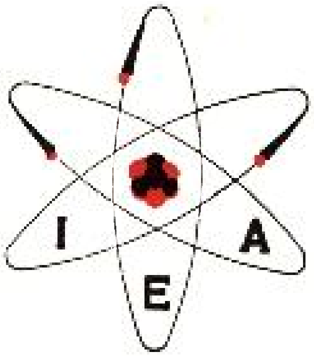

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EXPERIENCE WITH BRITISH NUCLEAR POWER STATIONS AND THE DEVELOPMENT OF THE ADVANCED GAS COOLED REACTOR (A.G.R.) AND THE STEAM GENERATING HEAVY WATER REACTOR (S.G.H.W.R.) SYSTEMS

by

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UKAEA Papers
delivered at Seminars in Brazil
during March 1969

U.K.A.E.A.,
Reactor and Production Groups,
Risley,
Warrington,
England.

June 1969.

FOREWORD

Seminars were held by representatives of the United Kingdom Atomic Energy Authority in the Institute of Atomic Energy, São Paulo, the Institute of Research in Radioactivity, Belo Horizonte and in the offices of the National Commission for Nuclear Energy in Rio de Janeiro during March 1969.

The speakers in São Paulo and Belo Horizonte were Mr. F. M. Greenlees and Dr. G. R. Bainbridge of the Reactor Group, and Mr. J. A. Waddams of the Production Group. In Rio the speakers were Mr. Greenlees and Dr. Bainbridge, the latter covering also the subject previously covered by Mr. Waddams at the other two seminars.

To assist those who attended these seminars, and others who were unable to attend on the days in question, the texts from which the lectures were given have been compiled into this brochure.

Clearly the wording of the texts will not be identical to the spoken presentations given at each centre but they have been prepared from the notes which each of the speakers used on those occasions. It is to be hoped that the brochure will be found both interesting and useful for future reference.

UKAEA,
Reactor and Production Groups,
Risley.

June 1969.

I RESOURCES OF THE UKAEA

INTRODUCTION

1. As you are no doubt aware, Great Britain is the largest single producer of nuclear power in the world. In 1968 approximately 176,874 million kWh of electricity were sent out, of which 27,145 million kWh (or some 15%) were produced by nuclear stations of the magnox type.

UKAEA

2. The design, development, commissioning and subsequent operation of the prototypes of this reactor system; of the forerunners of the second and third generation reactors, of which I will say more later; and of future reactor types, are the responsibility of the United Kingdom Atomic Energy Authority.

UKAEA GROUPS

3. The functional organization of the Authority is now built around four main Groups: - Reactor, Research, Production and Weapons. In addition there is a Centre for the production of radio-isotopes and an independent Health and Safety Branch. Of the four Groups I particularly wish to discuss the function and resources of the Reactor Group, of which my colleague Dr. Bainbridge, and myself are members. My other colleague, Mr Waddams, comes from our Production Group and will be talking to you on Fuel Services and other matters.

Reactor Group

4. This is the largest of the Authority's groups and consists of a headquarters at Risley with three main experimental establishments at Windscale in the north west of England, Winfrith in the south of England and Dounreay in

the extreme north of Scotland. In addition, the Group has four main research and development laboratories.

The Reactor Group of the Authority forms one of the largest organizations in the world for supporting major nuclear projects. It is from Reactor Group that design engineers are joining British Industry under the present re-organization. As you may know, two industrial organizations in the UK are being strengthened by UKAEA participation to form larger design and construction Companies. The Authority will still continue to give advisory and consultancy services as well as supporting Reactor Development.

Although the Reactor Group and the former Engineering Group, situated side by side at Risley, now work as one entity and have covered the whole range of reactor design, development and construction, the Reactor Group Headquarters also contains supporting commercial and scientific staff for formulating the general direction of the Group's activities and the work of its laboratories.

UKAEA REACTORS

5. This leads me to those functions of the Authority which are concerned with the development, construction, commissioning and operation of prototype reactor systems to the stage where they may be commercially exploited by the UK Electricity Generating Boards. Leaving out the Authority's magnox reactors at Calder Hall and Chapelcross, i.e. reactors using metallic fuel clad in a magnesium alloy, with which you are no doubt familiar, I would like to refer to the prototype reactors which the Authority has developed , or is in the course of developing, and which are of current interest.

WINDSCALE AGR

6. The Advanced Gas Cooled Reactor at Windscale, which commenced operation in 1963, is of 40 MW(E) gross capacity and is supplying power to the national grid. This reactor formed the basis for the second phase of the British nuclear power programme and its salient features are perhaps worth mention at this stage. The fundamental difference between this reactor and its magnox predecessors lies in the fuel, which is of slightly enriched uranium oxide clad in stainless steel. It will be appreciated that this permits the use of higher coolant temperatures and hence better steam conditions with consequent improvement in thermal efficiency. The higher fuel rating achievable with this design leads to the twin advantages of individual access to each channel of fuel and to a much more compact core with consequent saving in capital cost. I will discuss some of these points in more detail later.

WINFRITH SGHW REACTOR

7. The Authority site at Winfrith has both experimental facilities and operating reactors. It is there that the high temperature gas cooled reactor "DRAGON" was built by Authority participation with the European Organization for Economic Co-operation and Development. It is also the location of the 100 MW(E) Steam Generating Heavy Water Reactor which commenced operation in late 1967 and is now supplying power to the national grid. It is likely that this reactor system will be among those considered for the third phase of the British nuclear power programme and I will say more on this promising reactor later.

II THE UNITED KINGDOM NUCLEAR POWER PROGRAMME

II THE UNITED KINGDOM NUCLEAR POWER PROGRAMME

PHASE I

1. Historically, the first phase of the United Kingdom Nuclear Power Programme, as originally conceived in 1955 , was for an installed nuclear capacity of between 1500 to 2000 MW(E) by 1965. With the advent of the Suez crisis this was increased to an installed capacity of 5000 to 6000 MW(E) by 1965. As this situation became resolved, however, this programme was extended so that Phase I of the nuclear power programme was finally decided at an installed capacity of some 5000 MW(E) by 1968. As I previously remarked, this Phase of the programme is based entirely on the magnox reactor system.

PHASE II

2. The second phase of the nuclear power programme was announced in 1964 and it is intended to install a further 8000 MW(E) in England and Wales in the six years 1970 to 1975. This programme was intended to be flexible and to be reviewed at regular intervals in the light of later information. One of the items included in these reviews was the question of a further nuclear station in Scotland. In fact this Scottish station has now materialized in the form of Hunterston B with two reactors giving a total of ...... 1250 MW(E). The reactor system selected, in the face of international competition, for this second phase of the nuclear power programme was the Advanced Gas Cooled Reactor.

PHASE III

3. That, very briefly, is the programme for the production of nuclear power in Great Britain as achieved and definitely planned, but we must look ahead to our generation re-

quirements after 1975, to Phase III of the nuclear power programme. Although no official figures of required installed capacity have yet been issued, it is likely that some 40.000 MW(E) will be required by 1985, and active consideration is being given to the reactor system which will form the basis of the third generation of power producing reactors. The strong contenders for this role are a more advanced form of Gas Cooled Reactor and the Steam Generating Heavy Water Reactor, although we must not overlook the possible introduction by then of Commercial Fast Reactor stations.

A.G.R.

4. A likely form of advanced design of gas cooled reactor is one incorporating some of the features of the previously mentioned Dragon reactor at Winfrint. Such a reactor could employ coated uranium dioxide fuel particles in a graphite matrix or graphite tubes and use helium as a coolant. Alternatively, a variation on this theme would be the retention of a carbon dioxide cooling medium with coated uranium dioxide fuel particles in a silicon carbide matrix or tubes.

S.G.H.W.R.

5. The second contender I mentioned was the Steam Generating Heavy Water Reactor. The prototype of this reactor system at Winfrith achieved its full power of 100 MW(E) in January 1968 and is a direct cycle boiling light water reactor with partial moderation by heavy water. It employs slightly enriched uranium dioxide fuel clad in zirconium alloy. I shall discuss the design features of commercial reactors of this type later but it is perhaps worth mentioning at this stage that, although the prototype and the commercial design of Steam Generating Heavy Water Reactor for the United Kingdom

programme will employ enriched fuel, work is also proceeding on the design of a natural uranium fuelled steam generating heavy water reactor.

6. Before proceeding to describe some of the more interesting design features of the commercial versions of the Advances Gas Cooled and Steam Generating Heavy Water Reactors I would like to discuss the performance of our UK nuclear generating stations, and to review the operating experience we have had so far with the Advanced Gas Cooled Reactor at Windscale and with the Steam Generating Heavy Water Reactor at Winfrith.

PERFORMANCE OF OTHER UK STATIONS

7. You will recall, from what I said earlier, that in the year ending December 1968 approximately 15% of the total power generated in Great Britain was from nuclear power stations. As you know some of these stations have been in operation for many years and each station has made a valuable contribution during its operation to the electricity production in Great Britain. The large installed capacity of commercially operated gas-cooled reactor stations and the further extensive building programme under-way emphasizes the confidence in this system which experience in operation has given.

8. Following the operation of reactors built solely for plutonium production the United Kingdom Atomic Energy Authority were satisfied in 1953 that the gas-cooled system could be used in an economic nuclear power station, and , by 1956 the first Calder Hall reactor, while not optimised for power production, was supplying electricity to the national grid. This station, which now has four reactors , together with its duplicate at Chapelcross, has operated to date with average load factors of over 85%.

LOAD FACTORS

9. It is, of course, of paramont importance to the ...... Electricity Boards that their power stations having the lowest operating costs maintain high load factors. In this respect the UK gas-cooled reactors have performed exceedingly well. There are nine fully operative commercial gas-cooled stations (22 reactors) in the United Kingdom. Starting from Calder Hall in 1956, five stations (14 reactors) have already achieved average load factors of well over the 75% target originally set for costing purposes and two more stations (4 reactors) have average load factors of over 70%. There is no doubt that these, too, will in due course easily pass the 75% figure.

10. As with any other new venture it was expected that the first year or so of operation would show up any teething troubles. As these were cleared the load factor obtained on each station showed a considerable improvement. The original target load factor of 75% is beginning to seem pessimistic and a load factor of 80% or even 85% would seem a not unreasonable expectation from stations of this type operating on a network similar to that installed in the United Kingdom.

AVAILABILITY

11. In order to achieve these load factors, these reactor stations must have a high availability but, of course, like any operational plant they have suffered outage time. The Central Electricity Generating Board has carried out a provisional analysis of the causes of outage on their .... nuclear stations. This has shown that, in the early years of operation, faults on plant other than the reactor predominated. After this early period, availability is extremely high, unplanned outages becoming relatively insig-

nificant, and annual availability, including outages for planned overhaul, are regularly between 80% and 90%.

As an example of this, in the year 1965 to 1966, that is its first year of operation, the number one reactor unit and generating plant at Hinkley Point 'A' had an overall availability of 74.93%. Let me add some breakdown for illustration. Of the 25.07% of outage time, 2.70% was due to reactor outage for various reasons, 8.35% was for overhaul purposes and 14.02% was due to the outage of plant other than the reactor. Similarly, in the year 1964 to 1965, the third year of operation of the number two reactor unit and generating plant at Berkeley, an availability of 86.31% was obtained. The non-availability being due to reactor outage 1.10%, plant outage other than reactor 2.07%, and for overhaul purposes 10.52%. In passing, I would like to mention that in the year 1967 to 1968 this same reactor had an availability of 98.15%.

12. When I say that, for the purpose of this analysis, the reactor unit was taken to include the core, fuelling machinery and gas circulators, in addition to the control and instrumentation equipment, I am sure it will be agreed that this is a most impressive performance.

III THE ADVANCED GAS COOLED REACTOR

A) SIX YEARS OPERATING EXPERIENCE OF THE WINDSCALE ADVANCE GAS COOLED REACTOR

1. In February 1963 the Windscale Advanced Gas Cooled ... Reactor was taken to full power. In order to provide infortion for commercial designs as rapidly as possible, experimental programmes on graphite, fuel endurance and physics behaviour have been carried out concurrently with any necessary modifications to the reactor and experimental

facilities, whilst as far as possible maintaining the reactor at the highest power and availability. As a result of the basic reliability of the reactor design and its fuel these objectives were achieved.

2. In 1963 the reactor was operating at the design power level of 100 MW thermal and 33 MW electrical. Since then a maximum reactor output of approximately 129 MW thermal and 40 MW electrical has been obtained and over 1,300 million kWh have been exported to the National grid. The steady progress in conventional plant availability is illustrated by a yearly improvement from 71.9% in 1963 to 95.2% in 1968.

3. Fuel performance has been exceptionally good. Different fuel element designs have developed along the lines necessary to provide the final simulation of fuel for the UK Nuclear Power Programme, and has resulted in a progressive increase in the nominal maximum can temperature from 650°C to 725°C and in the peak rating (fuel and graphite sleeve) which has risen from 18.5 MW/te to 23.0 MW/te. Experience with the original Mark 2 fuel element charge continues to be excellent and there have been no failures in the 30,000 original fuel pins. The Mark 2 driver charge (i.e fuel which "drives" the reactor and is non experimental) has attained a peak pin irradiation of 26,000 MWD/te. [Mark 2 fuel 10.16 m/m dia. pellet 2 x 508 m/m long] The fuel of highest burnup in the core has reached 20,750 MWD/te, mean; (29,000 MWD/te peak pin) and the highest burnup of Mark 3 [Mark 3 14.5 m/m dia. pellet by 1067 m/m long pin] prototype fuel has attained 20,000 MWD/te (peak pin).

4. The majority of the more important plant items have performed extremely well and this, together with the control rod system and associated safety circuits which have been extremely reliable in operation, has contributed to the

high station availability.

5. An important consideration encountered in developing the Advanced Gas Cooled Reactor has been the reaction between carbon dioxide coolant and the graphite which becomes more pronounced at higher gas temperature and pressures. The problem has been solved by adding a small quantity of methane to the coolant gas, and it has been proved experimentally in the reactor that methane as an inhibitor is sufficient to ensure satisfactory behaviour of the core for at least 30 years at 80% load factor.

6. The pressure circuit has been subject to annual statutory inspections and entry into the top dome of the reactor with the fuel charge in place has proved possible as a result of the neutron shield, which was provided above the core as part of the original design. No serious problems associated with the pressure circuit have come to light from their inspection. No boiler leaks have been experienced in the six years of operation.

7. The gas circulators have proved extremely reliable and their availability has been around 98%. Since installation the circulator powers have been uprated from 1,500 BHP to 1,900 BHP.

8. In common with experience on Magnox stations a number of vibration problems have been encountered, such as sections of control rod sleeves becoming unscrewed, and impact absorbing mechanisms giving trouble when subjected to empty channel flow for a significant lenght of time. One of the bellmouth sections at the inlet to the cold duct from the heat exchangers became detached as a result of vibration. All these problems were overcome relatively easily.

9. In conclusion I would like to say that six years operation of the Windscale Advanced Gas Cooled Reactor have proved the fundamental concept of the system to be extremely satisfactory and reliable. It is flexible and easy to operate. This confidence, together with the large amount of experience and data accumulated, will prove of enormous benefit to the Phase II programme of advanced gas cooled reactors.

B) THE GENERAL DESIGN OF THE COMMERCIAL ADVANCED GAS COOLED REACTOR

10. The general design of the commercial Advanced Gas-Cooled Reactor Stations follows the development of the magnox reactor stations, but it is a very real advance in many ways. The use of uranium dioxide fuel in stainless steel cans has enabled an increase to be made in the fuel ratings and , with the fuel concentrated in relatively fewer channels,has increased the power densities. This fuel has also enabled higher reactor outlet gas temperatures to be reached,producing steam conditions similar to those obtaining in modern conventional stations and resulting in station efficiencies of over 40%.

11. Efficient design has resulted in a very compact reactor layout which has an output per square foot of plan area for the station buildings four times greater than that of a magnox station.

12. There are, however, many advances in the design of the advanced gas-cooled reactor, and it is to some of these design aspects that I would now like to refer.

13. One of the problems associated with the increased gas temperatures, which now reach about 670°C, is that of maintaining the graphite moderator at a relatively cool temperature level. This is achieved by changes to the gas

flow pattern within the pressure vessel as compared with the magnox reactors. After leaving the gas circulators the carbon dioxide gas path divides. Part of the gas flows directly to the fuel channel inlets below the core, and part passes upwards between the radial neutron shield and the inner vessel shell to the top of the upper neutron shield. From this point the gas flows down through various passages in the graphite core to the diagrid, where it mixes with the gas coming directly from the circulators to pass up through the fuel channels and thence to the boilers or heat exchangers. In the Dungeness B Advanced Gas Cooled Reactor the concrete pressure vessel is cylindrical, and is pre-stressed by circumferential and vertical cables in the barrel and by looped horizontal cables in the two end caps. Its inner boundary is sealed by a water cooled ..... membrane of mild steel. There are shields around and above the core to prevent excessive activation of the boilers and circulators so that these can be reached and maintained, and also to reduce neutron streaming upwards to the charge floor. Under certain conditions it is also possible to enter the space above the core.

14. The boilers surrounding the core within the main pressure vessel are of the once-through type, usually with a single reheater stage. The tube ends are led out in such a way that access is available for testing, isolation or even plugging, without entry into the pressure vessel. In the case of Dungeness B the boilers are grouped into four units, each with a corresponding gas circulator.

15. Each gas circulator is a centrifugal blower, the working parts of which form a cartridge unit mounted in an opening at the base of the pressure vessel wall. A simple sleeve valve enables the circulators to be isolated from the main gas circuit and enables the whole cartridge unit

to be removed from the pressure vessel for maintenance , after depressurisation, without permitting air ingress to the main vessel. If necessary, the other three circulators can be brought back to load with the fourth penetration blanked off.

16. A further development in the design of the Advanced Gas Cooled reactors, which will be introduced at Hartlepool,is the introduction of a pod boiler design. In this concept the boilers are standardised, factory built, tested units inserted in 2.74 m diameter vertical steel lined and insulated shafts in the wall of the cylindrical pre-stressed concrete pressure vessel. The number of boilers used depends upon the output, but they remain a standard unit. For Hartlepool each of the two reactors will have eight boilers housed in the 6.4 m thick vessel wall. This pod boiler scheme allows the boilers to be inspected in position and also to be removed and replaced in a straightforward manner without major work on the vessel structure.

17. In addition to this advantage, pod boilers need no apecial shield between them and the core, as is necessary when they are arranged round the core, and as steam and feed lines are taken through the steel cover over the pod, the usual penetrations for pipework through the wall of the vessel are almost eliminated. Design of the pre-stressing of the vessel is therefore simplified by allowing the use of wire winding to apply circumferential pre-stress.

18. As in the case of magnox reactors the power output is controlled by varying the coolant flow which, in the commercial Advanced Gas Cooled Reactor, is achieved by automatic adjustment of the circulator speed or vane position and by regulating the reactor gas outlet temperature by means of an auto control rod system. Anticipatory signals

are also provided to the boiler feed-water pumps.

19. The control rods are essentially stainless steel tubes containing boron steel or stainless steel inserts depending on their absorber functions. They are actuated by means of induction motors incorporating a direct current operated spring loaded brake.

20. The control rods are divided into two main groups, the auto-control rods which regulate the coolant outlet temperature, and the coarse rods which are sub-divided into two groups for sequential withdrawal during reactor start up. Both types of rod can be finely adjusted for trimming purposes.

21. Under fault conditions, all control rods are dropped into the core and their combined capacity is such that the reactor will remain safely shut down even if any two rods fail to enter the core.

C) A.G.R. SAFETY AND SITING ASPECTS

22. The principal safety features of the system may be summarised as follows:-

a) The uranium dioxide fuel and the stainless steel fuel can have high melting points and are compatible with each other and the carbon dioxide coolant. There are consequently no exothermic reactions and no possibility of a fire propagating along a channel.

b) The whole of the primary circuit is contained within a massive pre-stressed concrete vessel and sudden extensive failure of the primary containment without warning is inherently impossible. The loading on the vessel is carried by a multiplicity of steel tendons which are not subject to radiation and may be inspected and replaced if necessary.

c) Fracture of one of the minor external steel branch pipes would only result in a slow depressurisation. There would be no difficult in removing the shutdown heat under these conditions. Ample time would be available for corrective action.

d) The large thermal capacity of the moderator which operatesat a comparatively low temperature further restricts the rate at which fuel faults could develop and prevents the temperature reaching high values.

e) Heat transfer and heat transport under any fault condition can be analyzed with confidence bearing in mind particularly the ample passages for coolant flow.

23. It is considered that with its exceptional safety features and AGR station may be sited in an urban area with negligible increase in public hazard.

D) A.G.R. STATION AND SYSTEM POWER CONTROL

24. Station control may be carried out by the flexible control system which permits pressure governing, limited frequency governing, or manual loading of the turbo-alternators, to be selected as required. The system takes account of the requirements of the once-through boilers and for all loads down to 30%, is capable of maintaining stability, keeping the superheat and reheat steam temperatures nominally constant and the steam/water interface level constant.

25. Normal designs cater for load changes of up to 10% per minute and this is limited usually by turbine restrictions. There appears to be no difficulty in making these AGRs accept changes of 20% per minute and figures up to 30% might even be possible, but so far there has not been any reason to examine these alternatives in detail.

26. Basically, one should be able to vary the station output whilst maintaining steam temperature and H.P. steam pressures at their nominal value. In addition one should prevent boiling in the sections of the boiler made from austenitic steel while at the same time these sections must not operate at an unacceptably high temperature.

27. The primary variable which sets the reactor power is the coolant gas flow rate, which can be varied as I have already explained.

28. To achieve these requirements the control system comprises a minimum number of independent control loops performing the following functions:-

a) The station controller receives a power frequency signal and any deviation of this signal from the datum setting is used to adjust the coolant gas flow rate, and hence reactor power, and to provide anticipatory signals for the feedwater pump and the reactor auto-control rod system.

b) The reactor gas outlet temperature is regulated by the auto-control rod system which controls to a temperature datum determined by the superheat temperature. This temperature datum may be selected manually or automatically by the overall station controller.

c) A difference signal between the reactor inlet gas temperature and the pre-programmed outlet temperature value is used to trim the boiler feed flow from its pre-set value, and hence indirectly control the steam/water interface level in the boilers.

d) A reheat outlet temperature control is provided by controlling the amount of feedwater flow to a spray de-superheater at the reheat inlet.

29. The immediate extent to which the turbine will respond, through its governor gear, to a change in power frequency, is determined by the pressure over-ride facility which maintains superheater header pressures within pre-set limits, and by the speed with which the thermal output from the reactor boiler can be adjusted to the new conditions.

30. During start-up and shut down the turbine can, of course, be operated with the governor valves controlled by the stop valve pressure.

31. The boiler tubing in the critical regious of material transition is instrumented with thermocouples so that during commissioning and throughout the station life the movement of the steam/water interface can be monitored and the gas temperature control programmes adjusted as necessary.

E) A.G.R. FABRICATION ASPECTS FOR LOCAL PARTICIPATION

32. I would now like to refer to the ease of construction of the Advanced Gas Cooled Reactor. You may also be interested in the potencial I feel this reactor has for an appreciable level of participation by industry in your country.

33. Bearing in mind the Brazilian experience in complex reinforced concrete structures and other engineering fields, a considerable proportion of the Advanced Gas Cooled Reactor may possibly be manufactured here in Brazil.

34. To get down to individual items, the British design of pre-stressed concrete pressure vessel for commercial advanced Gas Cooled Reactors could, I am sure, be constructed by your own engineers, who would, no doubt, take responsibility for the detail design and supervision aspects of any British concept.

35. Similarly, the detail design, fabrication and .... constructional aspects of the heat exchangers, diagrid and much of the internal steelwork of the reactor, as well as the other conventional plant could, I am convinced, be accomplished by Brazilian manufacturing companies, some of which I had the pleasure of seeing during my last visit in 1964.

36. There are, however, certain items of plant such as the gas circulators, charge machine, and some of the control and instrumentation equipment along with, perhaps, the turbo-generators and the core graphite which you may consider it prudent or necessary to import.

37. To summarise, I feel sure that Brazilian participation in a commercial Advanced Gas Cooled Reactor, using a pre-stressed concrete pressure vessel of the type now being constructed in Great Britain, could be at a conservative estimate, between 45% and 50%.

IV THE STEAM GENERATING HEAVY WATER REACTOR

A) OPERATING EXPERIENCE DURING THE FIRST YEAR OF OPERATION OF THE WINFRITH SGHW REACTOR

1. Heavy water and fuel were loaded into the Steam Generating Heavy Water Reactor in September 1967 and criticality was first achieved on the 14th September of the same year. Electricity was first sent out to the national grid on the 24th September and sustained full power operation was first achieved on 25th September 1967. This was only a few weeks later than the target originally set when construction was first started in February 1963.

2. During the first year of operation a load factor of 44% was obtained with a generation availability of 50% and

381,000,000 kWh were generated. This, we believe, is a creditable performance for a new plant of this nature and particularly so far the first reactor of a new system.

3. The operating characteristics, including physics and hydrodynamics, have been found to be very close to prediction and we have encountered no unexpected features in operation. The plant normally operates on automatic control but manual control may be used if required, and control of the reactor and the plant as a whole has been very straightforward.

4. The heavy water moderator has presented no new problems. Since in a reactor of this type, the heavy water is used as a moderator, it is not under pressure. Thus losses from the heavy water system are negligible. In addition, there is a large amount of relevant experience on heavy water systems upon which we were able to draw. For example, the DIDO class of materials testing reactor of United Kingdom manufacture provided more than sixty reactor years of experience in handling this type of moderator.

5. In line with our past experience on nuclear plant this outage time has been caused by a number of faults which , individually, were of a minor nature. For example, the largest continuous source of leakage of steam and water from the primary circuit has been from valve glands and during each major shut down the glands of a number of primary circuit valves have been re-packed. During the year two other non-recurrent sources of steam or water leaks were encountered. One of these followed the failure of a 114.3 m/m diameter riser pipe between the channel top and the steam drum. This was caused by a 304.8 m/m file left inside the pipe during the erection period fretting away the pipe wall at a bend. I do not think we can blame the reactor for that, or for the second non-recurrent leak ,

which developed in a number of the small bore stainless steel experimental flux scanning thimbles which is attributable to the use of incorrect (non-annealed) tubing. This is also being rectified.

6. A further cause of loss in generation has been the circulating pump for the experimental channels, which is basically similar to the primary circulating pumps, and which boosts the coolant flow to four experimental channels to enable special highly rated or high pressure drop fuel clusters to be irradiated. In contract to the good performance of the primary circulators, five shut downs can be attributed to this experimental facility pump and its drive system. The clearances in the pump and its drive system have now been modified and these changes appear to have cured the difficulties.

7. A number of faults have arisen in the failed fuel pin detection system in particular in the non-return valves and steam traps and these also have now been modified to eliminate this problem.

8. A loss of some heavy water resulted from the incorrect assembly of a plate type heat exchanger which permitted a gasket to blow out and another small spill arose when the bonnet nuts on a small diaphragm valve became slack.

9. Other shut-downs have been caused by the necessity to remove fuel element assemblies with incipient failures from the core. This necessitated the reactor being shut down because the on-load refuelling machine had not been commissioned. However, since many of these fuel assemblies are of an experimental nature this is not considered to be particularly serious.

10. In general, our experience during the first year of operation of this novel reactor system has been good and we look forward to continuing improvement in load factor and

availability now that the early teething troubles on the prototype Steam Generating Heavy Water Reactor have been ironed out.

B) THE GENERAL DESIGN OF COMMERCIAL STEAM GENERATING HEAVY WATER REACTORS

11. The Steam Generating Heavy Water Reactor has been developed in the United Kingdom by the Atomic Energy Authority as the most promising type of water reactor. A size of 100 MW(E) was selected for the prototype as being adequate to prove the main features of larger commercial stations. Construction of the prototype was started in 1963. The reactor was built within the timescale and costs estimated at the start of the project.

12. Commercial Steam Generating Heavy Water Reactors are, like the prototype, direct cycle, light water cooled, heavy water moderated pressure tube reactors using slightly enriched uranium dioxide fuel.

13. The core of the reactor consists of an aluminium-alloy calandria, or tubed tank, containing heavy water, through which pass zirconium-alloy pressure tubes. The light water coolant which passes over the fuel element assemblies is contained in the pressure tubes which in fact from the fuel channels. The fuel proposed for commercial stations will be identical to that used in the prototype steam generating heavy water reactor at Winfrith.

14. During normal operation, reactor cooling is effected by the main cooling loops in which light water coolant is supplied by a circulator to the feeder header which distributes the coolant to the bottom of the pressure tubes and thus to the fuel channels, one circulator being used for each steam drum system. Saturated steam is generated

from the water passing upwards over the fuel which, after separation in the steam drum, is passed directly to the turbo-alternator set. The feedwater system used is conventional except that the heating required for the low pressure feed water is provided in part by the moderator cooling system, enabling one low pressure feed heater stage to be deleted.

15. The heavy water system operates at low temperatures and is unpressurised, it is of a design which has been demonstrated to be virtually free of leakage. There is no possibility of leakage between the light and heavy water systems as the design incorporates a gas filled gap between the calandria tubes and the fuel channel pressure tubes. To maintain the purity of the heavy water, the free upper surface is blanketted with helium.

16. Control of the reactor power is carried out by varying its reactivity, by adjusting the level of the heavy water moderator in the calandria. The heavy water may be pumped up from the drain tank to the calandria to increase reactivity or drained from the calandria to the drain tank when it is required to reduce power.

17. For rapid shut down a liquid absorber system is employed. Boric acid, in solution, is stored under high gas pressure outside the reactor and, upon receipt of a trip signal, valves automatically allow the liquid to be injected into shutdown tubes posiotioned interstitially throughout the reactor.

18. In addition, the heavy water moderator can be rapidly dumped to the drain tank to shut the reactor down in an emergency. There is also a small boric acid content in the moderator which can be adjusted for long term reactivity control.

19. It is proposed in commercial reactors that fuel be charged whilst the reactor is shut down and depressurised since sufficient batch refuelling can be carried out in less than 60 hours, that is, between any Friday evening and Monday morning. On load refuelling can, however, be provided if required.

20. In general, fuel will be replaced when it attains an irradiation of 21.000 MWD/te, and batch refuelling will take place at approximately 6 month intervals. The ability to refuel over a weekend is a valuable feature of the Steam Generating Heavy Water Reactor and may avoid the need to arrange refuelling operations with regard to seasonal variations in station loading.

21. The reactor is installed inside a double containment building to prevent the spread of fission products in the unlikely event of a reactor incident leading to their release from fuel. The building consists of a pressure resisting inner, or primary, containment constructed in concrete, containing the reactor core and the majority of the cooling circuit, and a secondary containment of substantially conventional construction. This secondary containment building would house the auxiliary plant and possibly also the turbo-alternator set. During operation, operators do not have access to the primary containment, but have access to the auxiliary plant in the secondary containment, and the turbine hall.

C) S.G.H.W.R. SITING AND SAFETY ASPECTS

22. The safety features of the SGHWR system may be summarised as follows:-

a) the use of pressure tubes which can be readily inspected after irradiation;

b) the restriction of any potential depressurisation fault due to a failure in the primary circuit pipework;

c) the avoidance of possible reactivity incidents because of the three methods of reactivity control, the near-zero void coefficient of the reactor and the ability to dump the heavy water moderator before refuelling;

d) the ability to inject emergency cooling water from a central pipe in each fuel element so that the effect of any delays in re-establishing effective cooling are minimized.

23. The above features ensure that the likelihood of any substantial release of fission products from fuel is negligible, and to reduce the size of any release of activity to the environment, facilities are provided to filter any leakage from the primary containment.

24. Safety is thus ensured not by any single measures, but by a number of different means so that any large scale contamination of the environment requires a series of failures, the probability of which can be demonstrated to be acceptably low.

25. Normal routine operation of an SGHWR does not impose any siting limitations. Siting, therefore, depends solely upon an assessment of potential hazards in accident conditions. Siting requirements for an SGHWR are consequently not stringent and no difficulty is foreseen for any site other than one in a fully built-up area. For such a site , consideration of additional safety features and an analysis of their effectiveness would be necessary, but the UKAEA are confident that the target of unrestricted siting can be achieved for this reactor.

D) SGHWR STATION AND SYSTEM POWER CONTROL

26. The behaviour of the Steam Generating Heavy Water ..... Reactor is determined primarily by the void coefficient (the fractional change in reactivity divided by the change in steam void fraction). The Winfrith reactor was deliberately designed to have a zero or slightly negative void coefficient with fresh fuel, which will become more negative with fuel irradiation, thereby limiting reactivity excursions.

27. Due to the absence of large heat exchangers, this type of reactor is capable of fast load changes and can be easily adapted to give automatic load following by feeding back the appropriate signals from the electrical network to the reactivity control system.

28. The Winfrith reactor is designed for 10% per minute load changes over the range 50 to 100% load, but this is capable of extension to 20% per minute, the main limitation being the permissible loading rate of the turbine.

29. Since larger output Reactors are achieved by increasing the number of channels, which are themselves similar, the boiling process and associated primary loop characteristics could be identical. Larger reactors using enriched UO_2 are therefore designed to have void coefficients very near to zero and similar overall control features.

30. The increased core sizes of commercial reactors can lead to xenon driven slow spatial modes of oscillation. This problem is very similar to that already met in Magnox ..... reactors, and can be treated in the same way by dividing the core into sectors. In one design for a 500 MW(E) Steam Generating Heavy Water Reactor, four core sectors are made by partitions extending part way down into the moderator, the moderator height in each sector being independently

regulated according to sector power.

31. As you will be aware, load following by grid frequency is normally initiated by the turbine governor, which opens or closes the steam valve from the speed setting depending on the frequency error. This movement is nominally proportional to the frequency error with 100% valve movement corresponding to approximately 2 cycles per second frequency variation. Power changes demanded for this type of load variation are usually within 10%.

32. If the steam valve is stepped open in response to a step change in frequency, the steam delivery to the ...... turbine is increased immediately, but it starts to fall off as pressure reduces, and more heat is taken from the steam drum. As the reactor power rises, and replaces the heat taken from the system, the pressure is re-established and the power delivered returns to the total demand. A typical transient of this type would be that an increase in demand of 10% would be met instantaneously, followed by a gradual fall to an increased load of 5% after, say 20 seconds, with total demand met after 60 to 70 seconds. The response could be improved by increasing the drum and .... circuit water heat storage, and also by increasing the maximum moderator pumping rates.

33. The initial immediate response in steam flow to a change in grid frequency is not normally essential and by changing the rapid governor response by reshaping the characteristic so that it opens exponentially the dip in load transient can be avoided.

34. Detailed simulation has shown that a 500 MW(E) Steam Generating Heavy Water Reactor could provide a grid load following characteristic in exponential form with a time constant of 15 seconds. For this simulation it was assumed

that the reactivity change rate was 3 MW/second and that the drum size was proportionally similar to the Winfrith reactor.

35. Following step changes in grid frequency which correspond to an additional power demand of 10% the system pressure variation is less than 0.7031 kg/sq.cm.

E) SGHWR FABRICATION ASPECTS FOR LOCAL PARTICIPATION

36. I would like to make the point that the manufacture of hearly all SGHWR components in factories, leads to ease of erection and also makes this reactor particularly suitable for participation by Brazilian industry.

37. All major building and civil engineering works, including the structural steelwork required for plant support , stairways, galleries, etc. could, of courses, be undertaken by Brazilian organizations. This phase of the work can also be completed before plant installation starts, thereby segregating the two basic types of engineering.

38. The permanent reactor crane, which must be positioned before plant installation starts, would handle all major components and minor items would be handled by temporary construction hoists. One large and several small openings in the buildings would be required to provide access during installation of the plant items.

39. All the plant items can be pre-fabricated in factories and the channels assemblies would be manufactured in groups of twelve or more leaving only the minimum of site welds.

40. Similarly, the calandria could be fabricated at a factory, the only limitation being that imposed by transport considerations. In the event of transport being the governing factor the calandria would be manufactured in

two or three segments. For the size of reactor under consideration for Brazil, the calandria would most likely be fabricated in two halves, leaving only the peripheral joint and service connections to be made at site.

41. From my previous visit I see no reason why all such reactor components, including the steam drums and primary circuit as far as the turbo-alternator, should not be manufactured in Brazil. However you may also, in this case, consider it prudent to have the pressure tubes, the primary coolant pumps, charge machine and some of the control equipment imported from firms who already have the appropriate experience. Once again I assume you would import the turbo-generator.

42. I feel that the extent of Brazilian participation in a Steam Generating Heavy Water Reactor project of the type I have described could be at least 50% and may even be higher.

F) GENERAL

43. In assessing a degree of Brazilian participation in the construction of both the AGR and SGHWR reactor systems; I have assumed that the fundamental design concept and basic design schemes would be carried out in the United Kingdom, and that, at least for the first reactor, Brazil would be prepared to accept some degree of assistance, possibly in the form of an overall consultancy service such as the AEA provided for British reactors being built in Italy and Japan.

FACTORS AFFECTING THE COSTS OF NUCLEAR POWER STATIONS

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1. Introduction

On a previous visit to Brazil by the author in 1967, the trend of costs for nuclear power station plants to be on line during 1970-1975 was discussed, in the range Cr900/kW towards .... Cr600/kW through the period. The present discussion in this paper centres on the reasons why such a wide range of costs is inevitable, narrowing gradually as the specification of requirements for the plant is made clearer and firming at the time when tenders are submitted and the contract placed. The range of generating costs for those capital costs would be 2 Centavos/kWh to 1.5 Centavos//kWh, the breakdown being broadly in Table 1.

TABLE 1

Typical Costs Breakdown

A. Capital Costs	Cr./kW	
Prime cost, or plant cost	500	300
Contractor's on-costs	200	150
Customer's on-costs	200	150
Total Station Cost	900	600
Fuel Inventory cost	150	120
Total Capital Cost	1050	720
B. Generating Costs (25 yrs. amortisation, 7 1/2% p.a. interest rate, 75% load factor)	Centavos/kWh	
Capital (Station) component	1.26	0.84
Fuel inventory component	0.21	0.17
Fuel replacement	0.40	0.34
Other works costs (Operations, Maintenance & Insurance)	0.15	0.15
Total Generating Cost	2.0	1.5

The factors affecting the costs of nuclear power stations were outlined in a paper given to the I.A.E.A. symposium on the International Comparison of Nuclear Power Costs in 1967 by ...... Bainbridge et al. In this presentation a summary of that paper is made. The more important factors which affect the cost of a nuclear power station are set down here with a view to assisting potential buyers of nuclear power stations to choose between the available alternatives and minimise their essential outlay.

2. Factors Affecting Prime Cost

The main items determining the prime cost of a nuclear power station, and which often permit wide differences to arise between the costs for alternative designs, are:-

1. Specification
2. Extent of Supply
3. Site Conditions
4. Manufacturing Requirements

and 5. Contract Price Date

2.1 Specification

A clearly drafted specification can help to reduce wide differences in the standard or quality of the power stations offered, though a very detailed one should only be attempted by a well-staffed and experienced organization. It may be too late to consider this matter after a contract has been placed and detailed drawings become available. Terms in the specification such as "to the satisfaction of the Engineer" can be variously interpreted and lead to significantly different costs. Where there is limited past experience between the customer and the tenderer's price variation ..... clauses inevitably appear in the offers, which make comparisons almost impossible without detailed assessment of the designs.

2.2 Extent of Supply

2.2 Extent of Supply

It is natural enough for a customer to ask "What am I getting for my money?". To get an answer, a detailed examination of the extent of supply for each offer must be undertaken. Exclusion from an offer of items in the cooling water system, in the essential supplies, or in the area of the station and generator transformers might not be readily observed, but to make good the deficiency in these items could cost several pounds sterling per kilowatt. The basis of supply of the plant must also be considered since many items may be on a manufacture and deliver basis, leaving erection and setting to work to be arranged by the customer.

The output from a given extent of supply is also important. The actual design capability may be 30-40 MW different from the nominal output, and an adjustment to the specified output may be needed to get a true cost comparison between designs.

Other adjustments may be required for differences in the ... necessary fuel stocks, the stock of spare equipment to ensure that comparable load factors will be achieved, or the power which would need to be brought-in to replace any shortfall in availability due to some inherent design feature such as off-load refuelling.

2.3 Site Conditions

It is possible to delete from a comparison, though not from an absolute cost determination, some common site items. Significant cost differences can arise, however, between designs having different thermal efficiencies and hence different cooling water requirements; or different turbine speeds or characteristics requiring different ground support or transmission line matching equipment. If different sites are essential for alternative designs the costs of transmission lines and transmission of energy should be taken into account; this latter aspect is assuming more importance with the trend of siting some nuclear power stations near load centres.

The nature of the site, its location and access facilities may give rise to cost differences. Some designs could be more suited to a coastal site than to a river with limited flow; others may be more readily constructed on shingle or sand, while good load bearing rock would probably provide a cheaper construction for any design.

2.4 Manufacturing Requirements

Many countries have important industrial resources and are keenly interested in manufacturing as much as possible locally. In these cases the cost of a significant proportion of the plant is subject to local conditions, taxes and productivity. In similar situations cost comparisons cannot be based on the direct conversion of currency values, and prices must be built up bearing in mind local construction requirements and methods. At the same time the impact of additional features such as local practices and design codes can be incorporated.

2.5 Contract Price Data

Adjustments may be required to get a proper comparison between cost figures for different contract price dates. There has generally been considerable escalation of prices for plant in recent years, which has varied from country to country. This aspect could therefore be important in any international comparison of offers from different countries, as escalation post contract price date is generally paid by the customer.

3. Factors Affecting Contractor's On-Costs

Many items for which the contractor must include a sum of money in his tender price require careful consideration if the offer prices are to be kept low and comparison between designs is to be attempted.

These factors include:-

1. Conditions of Contract
2. Guarantee
3. Risks
4. Terms of Payment
5. Contract Handling
6. Construction Time
7. Construction Methods and Codes
8. Inspection
9. Commissioning

3.1 Conditions of Contract

There is no valid reason for making the general conditions of contract more onerous than those for a fossil or hydro-power ..... station. There are well established sets of such conditions available for international trading such as:-

(i) U.N.E.C.E. Conditions 188A
(ii) F.I.D.I.C. Conditions of Contract (International) for electrical and mechanical works.

3.2 Guarantees

The guarantees requested should be carefully related to the extent of supply. For a complete station the cost will be higher if separate guarantees are called for on components, because this can place unnecessary restraints on the designers as well as increasing the overall margins in the plant as a whole. Thus, the performance guarantees are better restricted to the output and efficiency of the whole station.

Any guarantee of the construction period should be associated with an unambiguous extension-of-time clause in the general conditions of contract, releasing the contractor from responsibility for delays which are beyond his control. Without such a clause the contractor will be encouraged to add a contingency amount to his price.

The only other necessary guarantee is the conventional cover against defects in design, materials or workmanship during the 12 months following the satisfactory completion of guarantee tests.

It is to be expected that the fuel supply contract will be a continuing one after the plant contractor has completed his obligations. It is therefore prudent to call for a separate guarantee of fuel life, which can be given in the form of a guaranteed fuel cost associated with a specified fuel management scheme.

Guarantees covering the availability of the plant are sometimes suggested. The form of these guarantees, and the precise wording to govern implementation, are of great importance if the guarantee is to be of any value.

The unit sizes of power plant have increased rapidly in recent years, and statistics on availability are not adequate to provide a suitable basis to determine what additional money is required to meet a specific guarantee.

3.3 Risks

There should be a clear point in time at which each risk passes from the contractor to the customer.

A special risk in the building of a nuclear station arises from the presence of radioactive substances. Most countries have legislated for this risk to fall on the reactor owner. The extent to which some part of such risk can be passed to the contractor during the time he is handling radioactive materials varies, but the division of responsibility can be made quite clear. In particular, reference can be made to the national legislation concerned (see International Conventions on Civil Liability for Nuclear Damage , I.A.E.A. Legal Series No. 4 - 1966).

3.4 Terms of Payment

Because of the large sums of money involved the contractor will require progress payments during construction. These will reflect the actual progress of work if they are to serve the purpose of assisting the contractor with minimum cost to the customer. It must be realised at the outset, however, that any advance estimate of the rate of progress can be inaccurate, and that checking the progress of work to assess payments due may involve a large amount of administrative work.

The contractor normally expects these progress payments to cover at least 90% of the price, with release of the bulk of any retention money at completion of construction and the remainder in two instalments (i) after the guarantee tests and (ii) at the end of the defects guarantee period.

Payments made during the construction period have a significant effect on the overall cost of the station, so the customer is advised to be in a position to assess what this cost will be.

3.5 Contract Handling

This is an expression often used in its widest sense, thus creating a pretext for contractors and customers to have large staffs. However, if regarded as a single financial function which can be operated by an accountant the costs are often considerably reduced.

3.6 Construction Time

Because of the interest paid during construction the length of the construction period has a significant effect on the ultimate cost of the station and the generating cost, particularly when interest rates are high. It should be noted, however, that if the construction period specified is unrealistically short the contractor is encouraged to add a contingency amount into his price for item delays.

3.7 Construction Methods and Codes

Where a choice exists experience so far has shown that it is cheaper and more efficient to manufacture in workshops rather than on the site, so that site construction will mean bringing together the largest pieces of plant that can be transported. Cranage is then required on site to lift the heaviest items and very probably some site assembly of large shop-fabricated items. The fact that cranage is available will influence the design of smaller items and the package form of manufacture becomes an advantage. Studies nevertheless indicate that it does not seem possible or sensible to plan for a construction period for a single reactor of less than about three years.

3.8 Inspection

Inspection should be limited to the minimum which is absolutely necessary after consideration of:-

(i) Effect on nuclear safety of subsequent failure.
(ii) Any novel features incorporated in the plant.
(iii) Compliance with accepted codes or national statutory requirements.
(iv) Accessibility for repair or replacement after failure.
(v) Design criteria and inbuilt safety factors.

Non-destructive testing can be very expensive, particularly for certain types and configurations of welds. Careful consideration of design details may therefore result in reduction in the cost of the testing procedures.

Inspection is also necessary to ensure that the plant can be built in association with other items of plant at the site. Hence the correct specification of terminating points and cross reference to adjacent items is important.

3.9 Commissioning

Nuclear data at the period when the first commercial nuclear power stations were designed was often tentative or incomplete . Considerable uncertainty existed regarding requirements for absorbers, the ability to shape neutron fluxes, temperature limitations and so on. Elaborate and lengthy commissioning programmes resulted.

Measurements can now be limited to those required to confirm predictions, and much of the plant testing is done during construction period, leaving only the co-ordinated performance testing for the commissioning period.

4. Factors Affecting Customer's On-Costs

These factors include:-

1. Interest During construction
2. Land Purchase and Site Development
3. Other Direct Contracts
4. Administration
5. Taxes and Insurance During Construction
6. Escalation

While some of these items can be estimated as a percentage of the contract price others, such as land purchase and administration, are definitely not. The practice of adding a percentage in early calculations is not advisable unless care is taken to arrange that the percentage will decrease as a function of station output and will also take account of design type.

4.1 Interest During Construction

The interest rate on short term loans may be more in favour of the customer than the contractor and so some careful thought about the way in which the progress of the project is to be financed can be repaid by reduced costs.

4.2 Land Purchase and Site Development

In many respects the considerations of ultimate site capacity for nuclear power stations with superheat turbines are now ... little different from those for fossil fuelled stations except for the differences arising from fuel storage. The advent of the reinforced concrete pressure vessel has led to an inherently safe reactor which creates no pollution and makes possible the economical use of sites very close to centres of population and industry. The purchase of an exclusion area round the site is not necessary for some designs of reactor.

4.3 Other Direct Contracts

This raises the general question of the wisdom of separating parts of the station for direct contract. Because of the integrated nature of the design and site construction it should be carefully considered whether any advantage obtained by placing such direct contracts is outweighed by the diminution of the responsibility of the nuclear contractor in design and site construction.

4.4 Administration

The decision on the extent to which a nuclear department is established is primarily an economic one, since a utility unable to do its own supervisory work will find that consultancy services are easily negotiated.

4.5 Taxes and Insurance During Construction

It is of great importance that the responsibility for the payment of taxes is made quite clear. It is sometimes possible for a purchaser of a major power plant to get some relief from import duties. It is worth considering whether these and other taxes, variously known as sales tax, transfer tax, transmission tax etc., are better handled centrally by or on behalf of the customer and removed altogether from the contractor's price.

There can be no doubt about the cost advantage in handling the site works insurance centrally, provided this can be achieved within local laws which are sometimes restrictive. As the contractor is fully responsible for the plant up to the time it is taken over by the customer this insurance should be covered by him. The contractor should make sure that there is a proper reflection in his sub-contractors' prices for deletion of what would normally be their insurance responsibility.

4.6 Escalation

In industrialised countries customers are generally familiar with formulae for price adjustment. It should therefore only be necessary to specify that formulae should be bazed on specified nationally published indices for both labour and material. The simplicity of the formula method of adjustment will outweigh the extra administrative cost of checking actual cost rises by more detailed methods. The check of civil construction cost rises is also well established routine in most countries.

5. Cost Implications of Operating Requirements

5.1 Operating Practices

These vary widely between different utilities, but there is a common operating and maintenance objective to get the maximum station output reliably and consistent with safety using normal power station engineering practices.

The specification of fully automatic control may increase the station cost, and so a view must be formed about the possible effect on plant availability and running costs. Specification of local controls, instrumentation, start-up and alarm systems can also increase costs and so requires careful thought.

Other factors affecting costs include the methods of implementing safety regulations and arrangements for shift working.

5.2 Operational and Periodic Maintenance

Current AGR designs have facilities for on-load refuelling and overhaul of many core components. This means that minimal plant outage is required, principally for the purpose of statutory inspection, e.g. of boilers, and overhaul of turbine-generators.

A large utility with a policy to provide a reliable service and to minimise capital investment in new plant may aim at high station load factors and reliability by providing generous standby equipment and extensive maintenance facilities with large numbers of staff. To reduce capital and running costs a small utility may arrange for contractors to do planned station maintenance and repairs; hence permanent workshops and maintenance facilities can be kept to a minimum.

5.3 Staff Complement and Other Works Costs

For most utilities a staff complement of 60 on a four cycle shift arrangement should be adequate for operation of a 300-1200 MW single unit station. Shift operators would need to be experienced to undertake control of day to day maintenance.

In such a case the works cost breakdown is roughly:-

		%
(i)	Wages	22
(ii)	Staff Expenses	2
(iii)	Contract Labour	8
(iv)	Specialist Services	3
(v)	Chemical Services, Oil and Water	10
(vi)	Stores and Replacements	20
(vii)	Nuclear Plant Insurance	35
		100

The total cost would, at U.K. cost rates, be £ 0.5 - £ 1M per annum.

The cost of specialist training, though usually an extra to the basic power station, is not large, involving a small number of key senior grades only in doing specialized training at contractor's works and at operating nuclear power stations.

5.4 Spares

Recommendations, with delivery periods, for maintenance and breakdown spares can readily be obtained from a contractor, and although some spares must be available prior to commissioning, the cost in the operating budget is modest.

5.5 Licensing and Insurance During Operation

Most contractors are prepared to support a utility to obtain the necessary licences for operation, at no extra cost. There will, however, be utility operating costs for nuclear risks insurance.

6. Total Cost Comparison

When comparing the likely cost of electricity from alternative generating stations with significantly different characteristics it is desirable to carry out a system analysis in which the effects of the alternatives on total system costs through the years are considered. This is based on year by year calculations of the total system cost of alternatively meeting the demand for electricity , and is worth applying when the alternative new stations have different cost and operating characteristics. However, it is only appropriate when the generating system is integrated through a transmission network. The method is unnecessarily involved when dealing with say two nuclear stations, which have fairly similar costs and operating characteristics, in a situation when the nuclear component is a fairly small proportion of the total installed capacity.

In comparing alternative nuclear systems it is normally sufficient to assume a common discounted average lifetime load factor (except in-so-far as different availabilities produce a variation) and to assess costs either by comparing the present values at the commissioning date or the cost per unit calculated on an annuity basis.

To arrive at the cost input data for these comparisons, great care is required to select appropriate economic assumptions or ground rules. These ground rules include:-

(i) The rates of interest on capital, including short term interest rates during construction.
(ii) The station life (i.e. the amortisation period) assumed.
(iii) The load factor.

Because nuclear stations are still more capital intensive forms of electricity generation than fossil stations, the rate of interest taken has a significant influence in a comparative assessment. Similarly, insufficient care in selecting other ground rules can jeopardise a proper comparison.

An illustration of how changing these ground rules can affect the generating cost is shown in Table 2.

TABLE 2

Station Selection Affected by Changes in Ground Rules

Station			A	B	C
Capital Cost		Cr/kW	750	600	450
*Fuel Cycle Cost		Cr/kWh	0.0033	0.0054	0.0075
*Operation, maintenance and insurance		Cr/kWh	0.0015	0.0015	0.0015
Interest Rate % p.a.	Amortisation Period years	Load Factor %	centavos/kWh		
10	20	65	2.1	2.0	[1.9]
* 7 1/2	25	75	1.5	[1.5]	1.5
5	30	85	[1.1]	1.2	1.2

[ ] Preferred design based on generating cost.

* Ground Rules applicable to Basic Costs.

The three ground rules, interest rate, amortisation period and load factor, affect the capital components of cost, that is station cost and initial fuel inventory. It is therefore essential to ensure when costs are quoted for different systems that common ground rules have been used; or at least where they differ they can be properly substantiated. Some of the other ground rules which affect the capital component were mentioned earlier, e.g. taxes, import duties, accounting conventions, insurance and capital investment rebates. Where capital or generating costs are claimed for a system a thorough examination of whether these components have been included is required.

There is also a range of ground rules mainly affecting the fuel cycle costs of nuclear stations which includes:-

(a) Those affecting the cost of fissile, fertile or moderator materials and their preparation for use in the reactor , e.g. ore prices, separative work costs, fuel fabrication costs, plutonium credits, heavy water prices, re-processing costs.

(b) Those affecting delivered prices of fuels, e.g. transport charges, customs duties, taxes, reserve stocks.

(c) Technical assumptions such as irradiation levels, fuel management techniques, refuelling arrangements and method of dealing with the last charge.

Illustrative figures for the effects of variations in ground rules are shown in Table 3, relating to a power station costing an all inclusive Cr.600/kW, at the date on power and having a generating cost of 1.5 Centavos/kWh including a fuel cycle (inventory plus replacement) cost of 0.54 Centavos/kWh.

The figures quoted are for variations from the basic conditions shown, which are not, of course, all cumulative in their effect.

TABLE 3

Variations in Generating Costs

		Basic Data	Variation	Effect Centavos/kWh
Amortisation Period	Years	20	+ 5	- 0.1
Load Factor	%	75	+ 5	- 0.08
Interest Rate	%	7 1/2	+ 1	+ 0.1
Ore Cost	Cr/kg	60	10	± 0.03
Separative Work Cost	Cr/kg	120	10	± 0.02
Fuel Fabrication Cost	Cr/kg	200	10	± 0.01
Fuel Reprocessing Cost	Cr/kg	50	10	± 0.01
Plutonium Credit	Cr/g	20	10	± 0.03
Irradiation	MWd/T	20,000	2,000	± 0.04
Mean Rating	MW/T	15	5	± 0.05
Enrichment Levels	%	1.7	0.1	± 0.03

7. Assessment Factors

When considering the purchase of a nuclear plant there is generally no satisfactory substitute for inviting tenders and thoroughly assessing the alternatives offered. This requires assessment work in four main areas:-

1. Engineering
2. Safety
3. Performance
4. Development Potential

In each area the assessment has the objective of seeking out the features which are inadequate or in excess of requirements, and hence have cost implications which in many cases can be quantified.

7.1 Engineering

It is important to realise that the assumptions with regard to load factor can have a significant effect on the costs assessed for a nuclear power station. High load factors are not obtained automatically with any nuclear plant, and an engineering assessment is required to decide the load factor likely to be achieved in practice, which may be different from what the supplier claims. The load factor attained by a station can be influenced by two basic considerations. Firstly its running cost, and its consequent position in the merit table. Because nuclear stations have low running costs they will be higher in the merit table than fossil fuelled stations, and there will be considerable incentive to run them at as high a load factor as possible. Towards the end of even a nuclear station's life it may, however, only operate at low factors if newer nuclear stations with even lower merit order costs have been introduced. Secondly, the availability of the station will affect the load factor it obtains. The availability will itself in turn be affected by fixed features of the design and engineering; for example, the size, type and spare capacity of plant, the maintenance requirements and refuelling requirements may all affect the load factor. The engineering aspect in the assessment of designs offered is therefore extremely important in any cost assessment.

Another important consideration is a close examination of the manufacture and construction procedures proposed for key plant to ensure that the station will be completed to programme.

When examining the reliability proposals it is convenient to consider the designs offered under various broad headings e.g.:-

(i) Plant in normal operating environments and at normal working conditions.

(ii) Plant and equipment which in the event of failure either cannot be easily reached for repair, perhaps because it is within a containment dome or behind radiation shielding, or can only be approached after considerable time delay and/or at considerable expense.

(iii) Plant and equipment which can be repaired or replaced fairly easily but whose failure leads to station shutdown.

(iv) Plant and equipment working in severe conditions, e.g. of temperature difference or cycling, or turbulent coolant flow.

It is axiomatic that simple and robust engineering is preferred and often marginal capital cost increases can be justified by reliable performance. A nuclear power station with low running ... costs but relatively high capital investment must be run to as high a load factor as possible and engineering reliability assessment plays a large part in giving confidence in an economic comparison made of different systems.

7.2 Safety

A price consideration for an electricity utility will be the siting of the station, since restrictions on the freedom of siting can be extremely costly. The utility will want to site the station as near to a load centre as possible and this is particularly true with a nuclear station where fuel transport to the station is a minor matter. In the case of a coal station, however, an economic assessment including fuel transport charges, cost of transmission lines and energy transmission costs may shown that the station should be sited close to the mine and away from the load centre.

This freedom of siting will be directly related to the safety of the station. For example, the Heysham AGR Station to be built by the CEGB in the U.K. is to be sited within a few miles of ..... Lancaster, the county town of Lancashire, with a population of about 50,000 people, and with a large chemical industry and the site of a new University. The Heysham site is also within a few miles of the large holiday town of Morecambe, with a fixed population of about 40,000 which is considerably increased during the summer months. A coal station, or a nuclear design with a less well proven power system, would be less acceptable there unless plant improvements could be included, possibly incurring appreciable additional cost.

This freedom of siting has two obvious advantages: one in the reduction in the cost of installation of long transmission systems to reach the load centre, and secondly, the reduction of transmission line losses (the station has to produce fewer MW).

7.3 Performance

The assessment of the claim made for the performance of a nuclear station can be a very complex matter, and the utility will partially safeguard itself in this respect by requiring guarantees of electrical output, with adequate penalty clauses should this not be met. On all U.K. stations to date design performance has been exceeded. Coupled with the actual output of the station will be an assessment of the fuel cycle proposed, the fuel enrichments and the effects on the costs of generation quoted, together with aspects of the control system. The guarantees offered may not compensate for a shortfall in output performance which may not be easily made good in a short time. A cost penalty may have to be debited against an inadequate offer.

7.4 Development Potential

A narrow approach concerning a single station only can be .... useful in some respects, but it can be seriously misleading to fail to consider later advances in technology. There are many less tangible credits which can be, and should be, placed in favour of a particular proposal and the fact that these cannot always be precisely quantified is no remit to ignore them. Amongst these is the question of development potential.

It may be helpful to consider this under two general headings. Firstly there is the potential in the system. For example, the early U.K. choice of the graphite moderated gas-cooled system took into account the development potential inherent in such a system. This potential leads to successive improvements, and it is necessary to make a careful evaluation to see if that system has the potential to give progressively lower operating costs, or if it has already been as fully developed as might be expected. Secondly, one can look at the particular plant and assess the potential it has to incorporate improvements as they come along, an aspect which is particularly relevant to fuel development.

8. Conclusions

Meaningful comparison of nuclear power station tenders depends upon adequate preparation at the enquiry stage to specify clearly what is required, particularly in respect of extent of supply, site conditions and manufacturing arrangements.

A comparative assessment will require cost adjustments for items such as the guaranteed power output and the contract date.

Positive directions for dealing with guarantees, risks, taxes and insurance will reduce the contractor's on-costs.

Early consideration of the customer's on-costs can be repaid by lower costs.

Pre-tender discussion between the customer and possible contractors can be advantageous and would ease the problems of subsequent comparative assessment of offers by minimising the cost adjustments needed for differences in interpretation.

From Engineering, Safety, Performance and Development Potential assessment a modification list should be prepared which must be applied to a comparison between tenders.

Comparison of cost of generation requires the selection of appropriate ground rules. This applies to rules affecting fuel cycle costs as well as interest rate, amortisation period and load factor.

POWER REACTOR FUEL SUPPLIES & SERVICES OF THE U.K.A.E.A.

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1. Introduction

My colleagues have described U.K. experience with reactors of the magnox, A.G.R., S.G.H.W. and fast reactor types. It is a function of U.K.A.E.A. to provide a complete fuel service for reactors of all these types in the U.K., and similar services are offered overseas. This paper describes the various components of the U.K.A.E.A. fuel service, and the facilities which are available at Springfields, Capenhurst and Windscale. The paper concludes with an indication of how the fuel service might operate in support of a reactor of British design constructed outside the U.K. though the services described are individually and collectively equally available (and suitable) for utilization by present and future operators of all other types of reactor.

2. Fuel Element Manufacture - Thermal Reactors

2.1 Supply of uranium ore concentrates

The fact that the U.K.A.E.A. have for many years had the responsibility of fuelling the largest national nuclear power ..... programme in the world, without any domestic resources of natural uranium, has made it essential for them to place long-term contracts with a number of different uranium suppliers. U.K.A.E.A. are, therefore, able to provide at competitive prices the natural uranium which is required for any fuel which they supply to overseas customers. Alternatively, the U.K.A.E.A. are able in direct association with the primary ore supplier, to convert concentrate to uranium hexafluoride as an approved enrichment plant feed stock. (see 2.2 below).

2.2 Uranium ore concentrates to uranium hexafluoride conversion

For the first U.K. nuclear power programme of 5,000 MW (E) Magnox reactors to be installed by 1970, it has been necessary for U.K.A.E.A. to provide capacity for the manufacture of over 2,000 tes of magnox fuel per annum. The first stage in the manufacture of this natural uranium fuel is the conversion of uranium ore concentrates to uranium tetrafluoride, and capacity of over 2.000 tes per annum is, therefore, required at this stage. In addition, material is also required for the second U.K. programme involving enriched uranium oxide fuel from 1970 onwards, and the total capacity for the production of uranium tetrafluoride will need to be upwards of 4,000 tes per annum almost immediately, and about 6,000 tes per annum in a few years' time.

For the production of enriched uranium for the second nuclear programme, it is necessary to convert the uranium tetrafluoride to uranium hexafluoride to be used as feed to the diffusion plant at Capenhurst. U.K.A.E.A. have recently commissioned a plant of over 2,000 tes capacity for this process and it is planned to expand this to over 4,000 tes per annum within a few years.

Some significant spare capacity is available for the entire uranium ore concentrate to uranium hexafluoride conversion process from 1969 onwards and overseas contracts are now being obtained. There will be no problem about making further additions to capacity as home and overseas requirements increase. U.K.A.E.A. are prepared to arrange all the necessary conversion and transport operations to deliver natural uranium hexafluoride to U.S.A.E.C. diffusion plants or elsewhere in the period before enrichment can be undertaken for overseas customers at Capenhurst, and indeed after if necessary.

2.3 Enrichment

The U.K.A.E.A. diffusion plant at Capenhurst was substantially closed down a few years ago when the requirement for highly enriched uranium came to an end. Since then, however, development work has been proceeding with a view to the establishment of the economic production of low enriched uranium for nuclear power reactors. Some two years ago, the necessary modifications to the plant were started and production of enriched uranium hexafluoride for the ... U.K. programme has already begun. In the first instance, enrichment will be made for the Dungeness 'B', Hinkley 'B' and Hunterston 'B' nuclear power stations and thereafter the plant will be expanded as necessary to meet the requirements of the U.K. programme. It is believed that this planned expansion of the Capenhurst plant is the first occasion on which a diffusion plant has been constructed with the minimum cost of production under commercial ground rules as the prime criterion.

The present estimate is that during the next four or five years the increase in capacity at Capenhurst will fairly closely match the rising U.K. requirement for enrichment, but thereafter spare capacity will become available for the supply of enrichment to overseas customers.

2.4 Fuel fabrication

The term fuel fabrication is normally used, in respect of enriched uranium oxide fuel, to include the following main processes:

(a) conversion of enriched uranium hexafluoride into uranium dioxide powder.

(b) the manufacture of the powder into pellets.

(c) the manufacture or procurement of the cans and components.

(d) the manufacture of fuel pins and the final assembly of fuel pins and the final assembly of fuel elements.

The fuel for the Windscale A.G.R., the Winfrith S.G.H.W. and other small reactors overseas, has been manufactured in relatively small facilities at Springfields which have been used to prove the processes involved. Large plants have recently been constructed for the production of fuel for the second U.K. nuclear programme, and capacity is being installed in 250 tes per annum units.

The first two processes, (a) and (b) above, are similar for most enriched uranium oxide fuel - and indeed UO_2 powder is being supplied to other fuel fabricators in Europe who are making light water reactor fuel - but there are greater differences in the later fabrication stages and separate facilities have been constructed at Springfields for the production of A.G.R. fuel and S.G.H.W. fuel. The S.G.H.W. canning and assembly plant, however, can, and has been, used for the manufacture of other kinds of water reactor fuel.

Plans are being made for the design and construction of the plant which may be required if there is a substantial demand for high temperature gas-cooled reactor fuel.

2.5 Fuel transport

U.K.A.E.A. have substantial experience of packaging and transporting fuel of all kinds, both within the U.K. and overseas. They undertake all the necessary arrangements with shipping agents , Health and Safety Authorities, etc and have their own standing insurance arrangements.

Unique experience has been obtained with the transport of irradiated fuel from many parts of the world, including Canada, Australia, India, Italy, France and Denmark. In some cases it has proved appropriate to charter a special ship, but experience of transporting irradiated fuel on ordinary cargo vessels is developing.

3. Fuel Management

In addition to their own considerable experience of reactor operation, e.g. in respect of Calder Hall and the Windscale A.G.R., U.K.A.E.A. have made extensive studies of the reactor physics and associated problems involved in the reactors, and optimisation of fuel management within the reactor core. These studies not only cover gas-cooled reactor but, through the development of the ..... S.G.H.W. extend to cover water reactor systems. The theoretical studies are supported by extensive zero energy physics facilities at A.E.E., Winfrith, where, in addition, high power rigs are available for burnout testing of water reactor fuels. It is recognised that each power reactor has to be optimised to meet the operator's specific requirements, and U.K.A.E.A. are able to advise on the general principles of operation, leaving the detailed arrangements to the operator who carries day-to-day responsibility.

4. Irradiated fuel Reprocessing

The modern automated reprocessing plant at Windscale which was designed to reprocess the irradiated fuel from the magnox reactors in the U.K. and overseas has a capacity in excess of 2,000 tes per annum. The throughput of magnox clad uranium metal fuel will probably level out at about 1,600 to 1,700 tes per annum during the 1970's and a substantial amount of capacity will, therefore, remain for the treatment of oxide fuels. It is merely necessary to add a head-end plant for break-down and dissolution of the fuel prior to reprocessing. Such a plant has been built at Windscale and is being commissioned. In it, oxide fuel element bundles will be chopped and the pieces fed to a batch dissolver in which the uranium will be leached out with nitric acid.

5. Recycle of Uranium and Plutonium

At least as important as the efficient reprocessing of fuel is the establishment of economic arrangements for the re-use of the contained uranium and plutonium. These materials are extracted in the first instance in the form of nitrates.

There are two main conversion routes for the extracted uranium. It can either be converted to uranium hexafluoride and then re-enriched at Capenhurst, or it can be blended with uranium nitrate of a different enrichment to produce material at the required enrichment for new fuel. The latter route is generally more economic in the U.K.A.E.A. system. The U.K. programme requires uranium to be available at a considerable variety of enrichment levels from natural upwards, and it will, therefore, normally be possible to find a fairly ready use for uranium extracted from irradiated fuel with only quite small losses in the blending operation. This consideration makes it possible for U.K.A.E.A. to offer attractive credits for such uranium. Alternatively, the material can be returned to the reactor owner, or delivered anywhere he chooses in any appropriate chemical form.

The question of the re-use of the extracted plutonium is more difficult. From about 1974 onwards there should be ample plutonium available commercially to meet all requirements for experimental purposes and for fast reactor prototypes. This being so, the choice for those organizations which own plutonium will be between stocking the material for eventual use in commercial fast reactors or arranging for it to be burnt in thermal reactors as an alternative to enriched uranium. The first of these two courses is likely to be followed in respect of most U.K. plutonium, but much depends on the timescale for the commercial operation of fast reactors in different countries, and it is at least possible that some plutonium owners will seek a more immediate realization of the value of their material.

U.K.A.E.A. have themselves paid considerable attention to the possibilities of burning plutonium in thermal reactors. Plutonium fuel has been made under co-operative arrangements for the Kahl reactor in Germany, Agesta in Sweden and Garigliano in Italy, as well as for the Windscale A.G.R. All kinds of plutonium fuel will in future be manufactured in the new plant at Windscale (see below).

6. Fast Reactor Fuel

Two types of fuel are required for the fast reactor; highly enriched uranium or plutonium fuel for loading in the core and natural or depleted uranium fuel for use as a blanket material. Fuel for the Dounreay fast reactor was manufactured at Dounreay , but a large plutonium fuel element plant for the prototype and commercial fast reactors is being constructed at Windscale while the breeder fuel will be manufactured at Springfields. The Windscale plant will be suitable for making plutonium oxide fuel for thermal reactors which, in view of the special equipment required for handling plutonium, must be carried out on a substantial scale to be reasonably economic.

7. Complete fuel Cycle Integration

The theme of economy in enriched uranium costs dominates fuel management schemes inside the reactor. Comparable savings can materialise, outside the reactor, by minimising "in process" stocks and making maximum use of recycle material. It is of considerable significance that the U.K.A.E.A. possess the full range of nuclear fuel manufacture and processing facilities; advanced operational research techniques are employed to study detailed "in process" scheduling within the plants, but also and perhaps more important, for the study of the inter-relation and overall integration of the Springfields fabrication plant and the Capenhurst enrichment plant on the one hand and the Windscale reprocessing plant and the recycle of material recovered from irradiated fuel on the other.

At Annex 1 to this paper is a chart showing in simplified form the main processes carried out in the U.K.A.E.A. fuel factories and the principal links between them.

8. Fuel Services in Support of a British Designed Overseas Nuclear Power Plant

The U.K.A.E.A. have established close relationships with the British Consortia who design and construct nuclear power stations for the British market. On the basis of this domestic co-operation, the overseas customer may receive a single package offer to design and construct a nuclear power station, including the provision of the fuel, and such an offer would have the full technical support of the U.K.A.E.A.. Specifically offers to construct further overseas nuclear power stations would include all the fuel supplied and services described above, and these offers can be made available in the form of a comprehensive service or in whatever manner is considered appropriate. U.K.A.E.A. are prepared to operate quite flexibly if the customer desires to provide some parts of the fuel service from other sources.

As far as guarantees of fuel performance and endurance are concerned, utilities with a great deal of experience and expertise in the operation of nuclear power stations may seek only minimal protection and rely on their own experience in satisfying themselves about the potential performance of the fuel. Others may, however, come to the conclusion that they require guarantee cover in varying degrees of completeness. U.K.A.E.A. working in full co-operation with the reactor supplier, are ready to fit in with customers' wishes in this respect. Guarantee would be available even if some parts of the fuel service are provided from other sources.

FACTORS AFFECTING THE COSTS OF SGHWR NUCLEAR POWER STATIONS

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1. Introduction

On a previous visit to Brazil by the author in 1967, it was possible to say that competitive SGHWR power stations in the size range up to 500 MWE could be offered with design features being fully proven by the operation of the Winfrith 100 MWE SGHWR power station.

New it could be reported that the Central Electricity Generating Board of the United Kingdom had, during 1968, studied with the United Kingdom Atomic Energy Authority the relevant design, operational, safety and economic features of a power station having two SGHWR reactors and two turbines giving a nett output totalling 1,200 MWE. That group of over fifty engineers and other professional staff had assessed such a station as having a generating cost some 7 - 10% below that of contemporary gas-cooled reactor designs and consequently more below other water-cooled reactor designs.

This would not mean that in the U.K. the utilities would in any way abandon the well proven gas cooled reactor installation programme in favour of the SGHWR, but in the 100 MWE SGHWR power station at Winfrith Heath there was already being accumulated sufficient evidence of good operational behaviour for it to be confidently offered in SGHWR power station designs to utilities not yet committed to a particular reactor type. This already included, as was well known, utilities in Finland, Greece and other parts of the parts of the world including Latin America and the smaller U.K.

utilities would also be included.

In the other talk being given by the author during the current visit to Brazil the factors affecting the costs of electricity from nuclear power stations generally were being dealt with and so, in this paper, it was not necessary to do more than summarise those points which appear to lead to good economics for the SGHWR design compared with others. These factors would be a mixture affecting capital costs and fuel cycle costs.

2. Capital Costs

2.1 No boilers

As shown in the illustration the SGHWR does not have any boilers external to the core, which is in effect the boiler. So, what is a high capital cost item on the pressurised water reactor and on gas-cooled reactors to date has been eliminated.

2.2 No thick envelope pressure vessel

The SGHWR does not require a thick steel envelope pressure vessel for the core, which avoids disadvantages of cost, problems and worries in construction, testing and operation, particularly concerning safety. It has individual pressure tubes for individual fuel channels.

2.3 No internal separators

Separation of steam to go to the turbines of the power station is outside of the reactor region and access to the core for refuelling is therefore simplified compared for example with the boiling water reactor.

2.4 Low D_2O inventory and replacement costs

As the heavy water moderator circuit does not need to be at high pressure, and its temperature is below 100°C, and there is appreciable moderation of neutrons by light water in the coolant channels, a small, compact and relatively cheap "calandria" and heavy water circuit results.

2.5 Factory pressure tube manufacture

Factory fabrication of individual pressure tubes, or now by design clusters of pressure tubes, can be done to high standards and it reduces the construction time at the site.

2.6 Clear civil work runs

Reduced construction time is also achieved by having the civil construction work virtually complete before plant erection commences.

2.7 Low interest payments during construction

Because of the reduced programme time the interest payments during construction are lower than for other reactor systems which might take six months to a year and a half longer to build.

2.8 Reduced enrichment requirements and fuel inventory costs

The heavy water lattice and the light water coolant together ensure good neutron economy and so the fuel enrichment costs are minimised.

2.9 Off-load refuelling

Simplification of the refuelling system has been possible because of the direct access to the fuel channels whish enable regular fuel replacements to be achieved on three to six days each year. The reactor would be shut down for only two short week-end periods each year. This enabled a low cost to be assessed for bought-in units during those periods and of course it avoids the cost of on-load refuelling equipment.

2.10 Ferritic circuit

The main offer would generally include a ferritic circuit which research work has indicated should be practicable compared with earlier reactors with light water coolant having stainless steel circuit arrangements.

2.11 Alternative containment arrangements by selection

The offer could include for either vented or envelope closed containment depending on the safety requirements of the customer within his national organizations.

2.12 No solid control rods

The control of the reactor is by means of liquid which absorbs neutrons when placed in the control tubes fixed in the reactor system. Such liquid can be injected at high speed and withdrawn to suit the reactor operator's normal changing requirements.

3. Fuel Cycle Costs

3.1 Immediate fuel process economies of scale

The same UO_2 pellet route could be used as for the advanced gas-cooled reactor fuels already being produced on a large scale and hence the costs for fuel would be kept low from the beginning.

3.2 Economies of fuel component manufacturing scale

Minimum welding would be required of full length fuel pins made of Zircalloy 2 as in other water reactors.

3.3 Good plutonium by-product production

The lower power station efficiency (32%) than on gas-cooled reactors (42%), coupled with the heavy water lattice arrangement, gives good plutonium production. The system optimum burn-up in the U.K. could be as low as 15,000 MWD/T, not 18,000 - 20,000 as previously thought likely.

4. General Aspects

An important factor which should be considered where SGHWRs are to be installed is the heavy water price which will probably be upwards of Cr.200/kg in the early years, i.e. greater than \$44/kg or \$20/lb. Heavy water plant and resources are under review wherever heavy water reactor power stations are being built throughout the world. It seems likely that the production of heavy water will be rapidly increased in several places, including ..... Europe and Canada and India, so that the heavy water price will come down.

The arrangements for supply of either the advanced gas-cooled reactor or SGHWR power station can be made such that the whole station could be supplied on a turn-key contract or parts of the station could be individually supplied by the prime reactor contractor and other parts supplied by other sub-contractors to the utilities' requirements.

As was made clear in the other talk given by the author on this occasion in Brazil the total station cost, including .... customer's costs, is difficult to know for many reasons not least of which are that the specification and other conditions of supply are not yet clarified. Undoubtedly such clarification from the Brazilian utilities primarily interested in receiving nuclear power station tenders would come before long. It seems likely however that the arrangement for supply of either an SGHWR power station or an AGR power station could be such that these stations would be very competitive with other designs which might be offered from countries other than the United Kingdom.