5. CONCLUSION

We are pleased to be able to state that the licensing and quality control procedure concerning the manufacture of the steam generators has been extremely successful on the technical side. One example to show the high quality of the work performed:of the more than 17'000 tube to tube welds not one was found leaking after having performed the non-destructive testing.

However, the procedure was time-consuming and costly in consequence.

We shall not advocate the introductions of a cost and time criteria for licensing and quality control, since it might lead to reduced quality. However, we would wish that a certain cost awareness be permitted and accepted. This to avoid the spending of taxpayers money and the delay of vitally important projects for no real safety benefit.

ADVANCED GAS-COOLED REACTORS (AGR)

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1 GENERAL

The Advanced Gas-Cooled Reactor System is a development of the earlier natural uranium Magnox type reactor which, in various forms was the basis of the first nuclear power programme in the United Kingdom. Hunterston 'A', one of the first Magnox type stations, was commissioned in 1964 and has achieved a lifetime load factor of 83%, a record as good as any nuclear station of any type in the World.

Like the Magnox reactors, the AGRs employ a graphite core and carbon dioxide gas coolant, Fig. 1. The fuel however is enriched and encased in stainless steel cans. The whole of the core and the boilers enclosed in a concrete pressure vessel, a concept that was first developed for the later Magnox reactors. The blowers to circulate the gas through the core and the boilers are installed in the pressure vessel wall.

The AGR fuel ratings, gas pressures and temperatures are significantly higher than in Magnox reactors leading to smaller and more economic designs. Steam pressures and temperatures are the same as for coal and oil fired generating stations allowing the use of a standard 600 MW sent out turbine generator unit.

The amount of cooling water required for a given electrical output therefore is the same as for coal and oil stations. In contrast, water reactors, because of their lower steam conditions, require about 40% more water.

2 CONSTRUCTION OF HUNTERSTON 'B'

Construction of Hunterston 'B' with 2 x 600 MW units, commenced in 1968. It is of similar design to Hinkley Point 'B', a CEGB station built at the same time. The Nuclear Power Group were main contractors for both these stations and both commenced operation in February 1976. Construction of the reactors did not present a particularly difficult task. The field experience gained by the contractor at the Oldbury Magnox station was relevant to Hunterston 'B'. The vessel liner, the gas baffle and the diagrid were fabricated on site adjacent to their final position and then rolled on to prepared foundations, as had been done at Oldbury, except that there was no gas baffle in Magnox reactors. Although the site work content of the AGR is somewhat greater than that of LWRs, in the AGR system there are no components that require a high degree of precision.

The delays that occurred were due to the prototype nature of the design, but were contained to 2 years. The greater part of this delay was due to the insulation fitted to the inside of the concrete reactor pressure vessel. Laboratory tests after the installation of the insulation started on site showed the need for design changes and extensive areas of insulation had to be dismantled and rebuilt. The redesigned insulation has, however, performed without problems in service. The remainder of the delay was due to vibration problems with the fuel stringer. During the preliminary commissioning phase after the construction was complete, it was noticed that the fuel stringers were suffering from vibration at certain settings of gags which control the gas flow through the fuel elements. Extensive investigations were carried out to determine how best to stabilise the stringers. The problem was solved by a simple modification of drilling a few holes in the gag unit to make it aerodynamically asymmetrical, thus producing a lateral force to hold the gag unit against the side of the channel and preventing vibration of the stringer.

3 CAPITAL COST

When the AGR system was first adopted for commercial use, there were 3 reactor companies each with a different design of the same generic features of the AGR. There is an erroneous impression that all the AGRs have greatly exceeded the original estimates. This is certainly not true of Hunterston 'B'. At the start of construction in 1968, SSEB estimated that Hunterston 'B' would cost £97m, excluding initial fuel. The outcome on completion was £143m. About £30m of the increase was due to inflation and £16m due to the prototype problems and delays. The Hinkley Point 'B' figures were of the same order.

4 OPERATING PERFORMANCE

After the manufacture of boilers had reached an advanced stage tests on steels showed that the corrosion rate in hot CO_2 of 9% Cr. steel used in the evaporator section of the boilers was higher than had been expected. Some design changes were made to reduce the operating temperature of the 9% Cr. steel parts and the steam cycle was re-optimised. As a long term insurance of the life of the boilers it was further decided to restrict the outlet gas temperature from the reactor to 575°C which limits the output to 500 MWe. The reactor output has provisionally been limited to this figure since commissioning. The corrosion tests which are still continuing are encouraging and indicate that it will be possible to increase the gas temperature without shortening the life of the boilers. The reactor has been operated at its full output for a short period to demonstrate its capability. The design output from the reactor was achieved without difficulty. If the corrosion tests continue to confirm the present rates of corrosion, it will be possible to increase the output.

Bearing in mind that the Hunterston and the Hinkley AGRs were the first commercial AGRs to go into service, their performance has been satisfactory and the load factors of the units have been increasing progressively.

Unit R3

Figure 2 shows the annual load factor of the first unit at Hunterston designated R3, since it was commissioned in 1976. In April 1980 it was shut down for its routine 2 yearly statutory survey. All the reactor components were found to be in a satisfactory condition.

When the teething troubles of the AGRs have been overcome, it is expected that they will achieve LFs comparable with those of the Magnox reactors. This confidence is based on a detailed analysis of the reasons for the loss of output from the reactor to date. A summary of the analysis is shown in Table 1 and each item is briefly discussed.

TABLE 1

Hunterston 'B' - Reactor 3

Analysis of lost output

	%
Statutory Inspection	14
Off Load refuelling	10
Gas circulators	7
Other reactor items	5

Statutory Inspection

Each reactor has to be inspected every two years under the terms of the operating licence. The main features inspected are the pressure part and the reactor components. Inspection is carried out either by man access, for example, into the boiler annulus, or remotely by television cameras. These surveys take about 10-12 weeks, and on a 2 yearly basis represent a loss of availability of 10%. They are planned to take place during the summer months when the electricity demand in the UK is lower. Other known repair and maintenance work as far as possible is planned to be carried out during the same period.

Gas Circulators

There are 8 circulators per reactor, each driven by a 4.2 MW electric motor. The complete motor-circulator unit is mounted within the wall of the concrete pressure vessel and operates in the pressurised reactor environment. Early operation of the units has been encouraging but not unexpectedly with the first of an advanced design, detailed difficulties have had to be resolved and on a number of occasions it has been necessary to depressurise the reactor to remove and replace the units. After some detailed modifications confidence is growing that a higher degree of reliability is being built into the machines, and that the 7% loss of output due to the circulators will be greatly reduced in future.

The boilers are divided into 4 quadrants, each quadrant being served by 2 circulators. This provides flexibility in operation, as it is possible to continue to operate the reactor at reduced output with 3 quadrants, in the event of a failure of one of the circulator units, until it is convenient to shut down the reactor and to replace or repair the unit.

Refuelling

Unlike water reactors, gas cooled reactors can be refuelled with the reactor on load. The operational and economic advantages of this feature are obvious and cannot be emphasised too strongly. In the Magnox reactors on-load refuelling is a matter of routine, and in the 2 reactors of the 'A' station over 1000 channels are refuelled every year in this way. The AGRs are also designed for on-load refuelling, and the operation of the fuelling machine at the 'B' station has been demonstrated. The duty required is about 2-channels per week. For the time being however only vacancy channels are being loaded with fresh fuel on-load, and spent fuel is being changed off-load. This arises from considerations of the extremely unlikely possibility of dropping a fuel stringer into the reactor. In such an event, provided the reactor is tripped immediately after the fall, no nuclear hazard should arise. Automatic tripping devices, triggered by the fall, are now being investigated and will be installed in due course. Until then spent fuel will be changed off-load. It is planned to seek the approval of the Licensing Authorities and to introduce on-load refuelling next year.

Other Reactor Items

This heading covers various minor component failures that have caused some loss of output. A few examples are given below.

Relays used in the control rod withdrawal sequence were found to be insufficiently reliable for this particular application. As the system is designed to fail safe, relay faults caused hold-up in starting up the reactor. The relays have now been replaced by another type better suited for this duty, and a satisfactory performance is now being achieved.

The operating temperature limits on the superheater and reheater penetrations were initially set tight as a precautionary measure until some operational experience was gained. The output was reduced in any operating mode if the temperatures reached the set limits. As a result of the experience gained the limits have been relaxed with confidence.

Again as an initial precautionary measure the instruments that detect the rate of change of the coolant pressure and trip the reactor at a predetermined figure were set at a high sensitivity. As a result some unnecessary trips occurred. The sensitivity has now been relaxed, with satisfactory results.

Faults have occurred in the auto control loops which delayed startup and achievement of output. The problems have been identified and the faults are being eliminated.

It will be seen that apart from planned outages and the gas circulators the whole of the reactor plant proved to have a high order of availability - 95% over its life.

Conventional Plant

The conventional plant is similar to that used at coal and oil fired stations, but there have been some teething troubles which are not likely to recur. For instance, during commissioning in 1976 instability was experienced in the deaerator at about 50% power. This was found to be due to flow oscillations between two deaerating towers. These oscillations were large enough to cause damage to the deaerator supports and for the deaerator conservator to move physically. Modifications were made to the spray trays in the towers and changes made to steam supply pipework which overcame the problem. This accounted for 5% of loss of output from the station.

There were also a number of minor teething troubles. There is every confidence that the remedial measures taken will greatly improve the availability in future.

Unit R4

The second unit, designated R4, was commissioned in April 1977. From May to the end of September of that year it achieved an availability of 56%. In April it was discovered that there was some leakage of CO_2 into the labyrinth cooling water of one of the circulators. The labyrinth acts as a seal round the circulator shaft where it passes from the motor compartment into the reactor vessel to prevent leakage of oil from the circulator bearing into the vessel. The block containing the labyrinth is cooled with demineralised water in a closed circuit which itself is cooled by sea water in a heat exchanger. The presence of the small amount of CO_2 in the labyrinth cooling water indicated a defect in the labyrinth weld.

To repair the crack would have been a simple matter but it would have required shutting the reactor down, depressurising it and removing the circulator unit, thus interrupting operation for about 2 weeks. As it had already been planned to shut the plant down in October to carry out some rectification work on the conventional plant, it was decided to continue operation until October and to repair the circulator at the same time. The CO_2 in the closed circuit demineralised cooling water would have formed carbonic acid. To avoid this the labyrinth cooling water outlet flow was diverted and discharged to a convenient point on the sea water inlet side of the heat exchanger as shown in schematic form in Figure 3. The circulator continued to operate with this arrangement. In July it was found that the cooling of the labyrinth was not essential and therefore the inlet and outlet valves were closed, thus completely isolating this part of the cooling system.

On 2 October 1977 the reactor was shut down and the pressure gradually reduced from 38 bars. On 11 October the pressure had come down to below 3 bars, the pressure of the sea water inlet of the heat exchanger, when sea water began to leak into the depressurised reactor through the defective labyrinth weld, as the outlet valve from the circulator labyrinth which had been turned off in July, and logged as such, was in fact found to be partly open. About 8000 litres of sea water entered the space below the boilers. When the sea water evaporated it left salt deposits on the stainless cover plates, the mineral wool insulation and the mild steel liner. About 10% of the insulation was affected and was replaced. A thorough and detailed survey was carried out and many thousands of specimens were taken and analysed to ascertain the full extent of the damage before refurbishing started. This phase took 5 months. The removal and the replacement of the affected insulation, cover plates, studs and the cleaning of the liner took a further 20 months. The reactor was then commissioned and went into service in February 1980; its load factor since then is shown in Figure 4.

The total cost of the repair was about £15m. In engineering all experience has some value. This particular costly experience demonstrated that it is possible to enter the reactor and to carry out remedial work in the boiler annulus, with radioactive fuel in the core. The radiation dose levels were less than per day in the reactor in shifts. Each shift, instead of working continuously for 6 hours, worked on a 3-hours-on, 3-hours-off and 3-hours-on pattern, another shift taking over in the 'rest' periods. In this way a higher productivity was achieved. This was particularly reassuring in view of the delays caused to the original construction programme by the insulation problems. It is clear that provided the necessary components are available when required, the insulation of the vessel is not a critical activity in the construction programme and does not present a major problem.

5 SAFETY CONSIDERATIONS

Intrinsic Features

There are certain intrinsic features of AGRs which are unique compared to other types of reactor and which enhance its degree of safety.

1 The prestressed concrete pressure vessel with some 2860 tendons each with 7 separately tensioned strands cannot fail suddenly. The maximum rate of depressurisation would be caused by the fracture of a gas pipe 20 cms in diameter, which circulates some of the reactor gas through filters and driers and returns it back to the reactor. It would take about 30 minutes for the pressure to fall to near atmospheric.

2 There is no phase change of the coolant, and the performance of the fuel at all pressures, in air or CO_2, can be reliably predicted.

3 The fuel rating is relatively low and the mass of graphite acts as a heat sink. As a result, the fuel element temperatures under fault conditions rise slowly.

10 mrem/hr. People working 6 hour shifts and 6 shifts per week throughout the refurbishing work received an average dose of 0.3 rem. At the peak a workforce of 340 industrial and supervisory staff was employed. Each man worked 6 hours

Engineered features

As in all types of reactor the most important considerations are to ensure that the reactor is tripped with certainty under all fault conditions, and that the decay heat in the fuel is removed with certainty. It is a feature of the design that with the reactor tripped and pressurised, the decay heat could be removed even by natural circulation of the gas through the core and the boilers. Measurements on a shut down reactor indicate that there will be some margin of gas flow, over the minimum flow necessary to maintain safe fuel can temperature.

If under an accident condition the reactor lost pressure, it would be necessary to run some of the circulators to cool the fuel. Figure 5 shows a curve of the fuel can temperature transient after the rupture of the 20 cm gas pipe, with 5 out of the 8 circulators running. There are several alternative supplies to run the circulators: the electrical grid and 4-11 kV diesel generator sets which are automatically started on reactor trip, and any one of which is capable of running 6 of the circulators.

The rupture of the 20 cm gas pipe is considered to be the Maximum Credible Accident (MCA); this would depressurise the reactor with a time constant of 8 minutes. However calculations have been carried out for a hypothetical case of more rapid depressurisation with a time constant of 3 minutes, and with 5 circulators as before. The fuel can temperature transient is not dissimiliar from the MCA case, and is shown in Figure 6. Further hypothetical cases have been considered in which only 1 circulator is run. The final fuel can temperature would reach a higher figure than 650°C but it would still be well below the melting point of the can, 1350°C. Even with no circulators running radiative heat transfer to the large mass of the graphite moderator would prevent the can temperature reaching the melting point for some hours, about 4 or 5; which would allow time for extraordinary measures to be taken to reinstate some forced circulation.

In all cases it is of course essential to have water in the boilers to reduce the gas temperature. Each reactor has a steam turbine driven 100% flow feed pump and 2-50% flow standby 11 kV electric motor driven feed pumps. With the reactor tripped one of the 50% flow pumps would be more than sufficient to remove the decay heat. However in addition to these feed pumps, there are 5-415V electrically driven emergency feed pumps to serve 2 reactors. Three of these pumps would be sufficient to remove the decay heat from both reactors simultaneously. The electrical supplies to the emergency feed pumps are provided either by one of the four 11 kV diesel generators or one of two 3.3 kV diesel generators, or one of three 415V diesel generators.

The boilers of each reactor are made up of 12 units, which provide diversity under fault conditions, but in addition there is a decay heat removal system that is brought into operation half an hour after the reactor is tripped. Normally base load stations are not shut down frequently. However in view of the prototype nature of this plant, there have been a total of some 70 reactor trips of the two reactors. In every case the decay heat removal system has operated satisfactorily. These trips although contributing to the loss of availability discussed earlier in this paper, have demonstrated the high reliability of a vital engineered safety feature of the AGR system.

Operator exposure to radiation

The Magnox stations in the UK, particularly the later ones using concrete pressure vessels, have a very good record of low operator exposure to radiation. It is evident that the AGRs will maintain and even improve on the record of the Magnox stations. Fig. 7 gives an analysis of the level of whole body exposure of the station personnel during the last 5 years for the 'A' and 'B' stations. Fig. 8 gives the average radiation doses to station and outside personnel of both the 'A' and 'B' stations, together with the total station doses, for the last five years. It will be seen that the great majority of the workers received less than 1 rem per year, and that the AGR dose levels were considerably less than those of the Magnox station.

Environmental radioactivity

Routine discharges of gaseous and liquid radioactive effluent from the station are governed by authorisations issued to the SSEB by the Scottish Office of the UK Government under the Radioactive Substances Act 1960, and the methods of discharge and the means of monitoring the radioactivity have to be approved by the Scottish Office. Records are kept and are submitted to the Scottish Office, who also carry out independent random checks. All the figures have been well within the authorised limits. The gaseous radioactivity arises mainly from the impurities and additives in the reactor coolant CO_2. They are A-41, N-16, H-3. There is some S-35 released from the graphite and traces of I-131 from minor defects in the fuel cans. The liquid radioactivity arises largerly from the fuel storage ponds, in the form of Co-60 and Ca-45, and some H-3 from the driers in the CO_2 by-pass circuit. The radioactive liquid is diluted by the vast amount of the turbine cooling water and discharged to the sea.

There is regular monitoring of the water, fish, vegetation and milk up to 10(?) miles from the station. The readings have been consistently indistinguishable from the natural background radiation that existed before the 'A' station was built, but the background itself has varied with the fallout from nuclear weapons tests in the 1960s.

6 FUTURE DEVELOPMENTS

The Hunterston/Hinkley Point AGR design has been selected as the basis for the next nuclear power stations to be constructed in the UK: Torness in Scotland and Heysham 'B' in England. Naturally opportunity is being taken to improve some aspects of the design, based on the construction and operating experience. Also, since the existing design was prepared about 14 years ago, safety philosophy has undergone some changes. The new design will incorporate the present day thinking on these matters. The major changes are:-

The number of channels has been increased from 308 to 332 to give greater design margin.

The size of the main boilers and of the decay heat boilers have been increased to give greater design margin.

The prestressed concrete pressure vessel diameter and height have been increased to accommodate the larger core and to improve access.

To provide an additional diversity of secondary shutdown system, nitrogen injection into discrete channels from beneath the core has been added.

The Irradiated Fuel Disposal and maintenance cells have been duplicated and the number of buffer storage tubes has been increased.

A number of layout changes have been introduced to give further segregation of plant, and to meet seismic criteria.

The planned construction time for the first unit of the Torness station is 75 months which is not very different from the achievement at Hunterston 'B', excluding the delays due to the prototype problems.

Hunterston B power station. Cross section through both reactors.

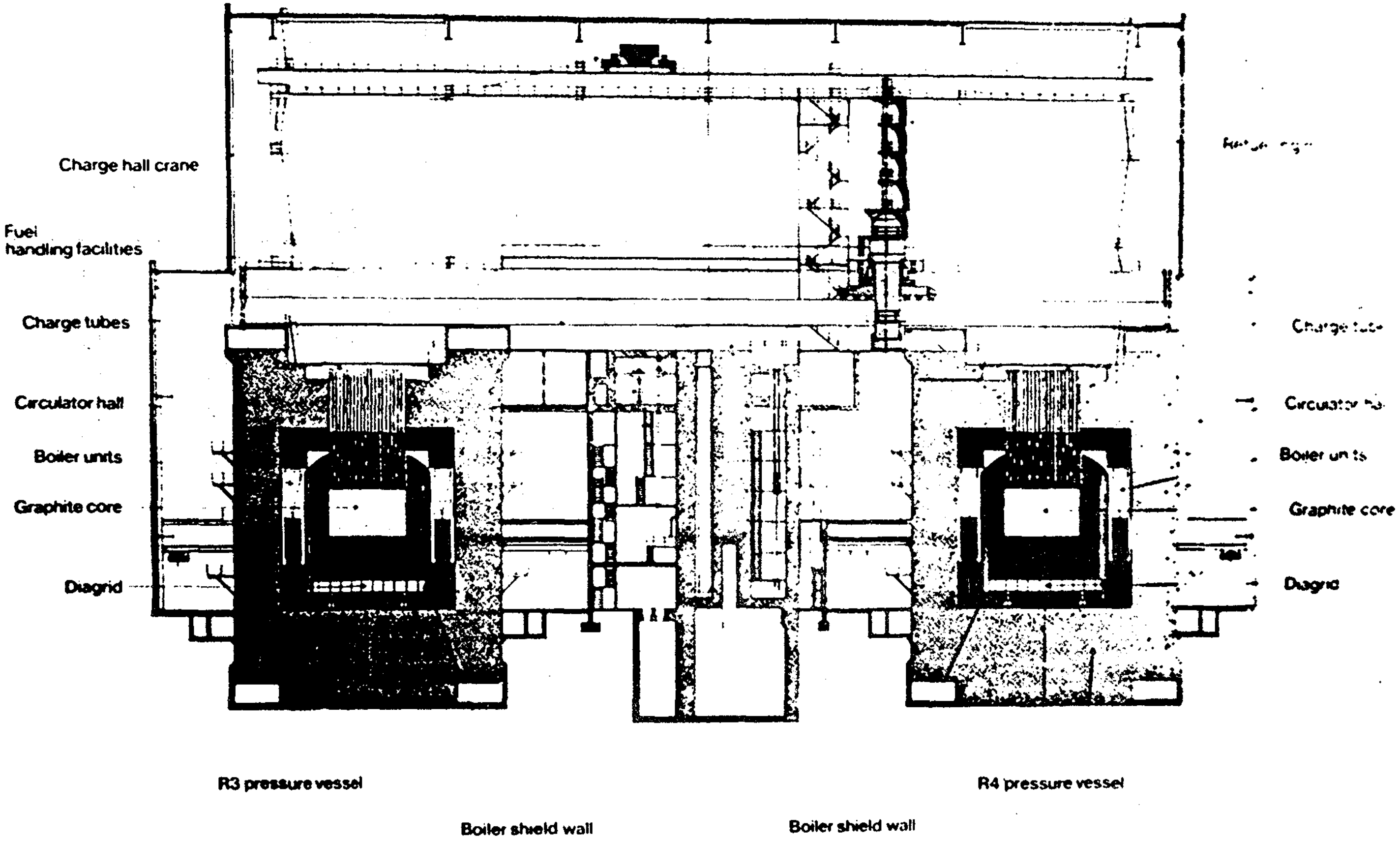


Fig.1

HUNTERSTON "B"

UNIT 3

LOAD FACTOR (%)

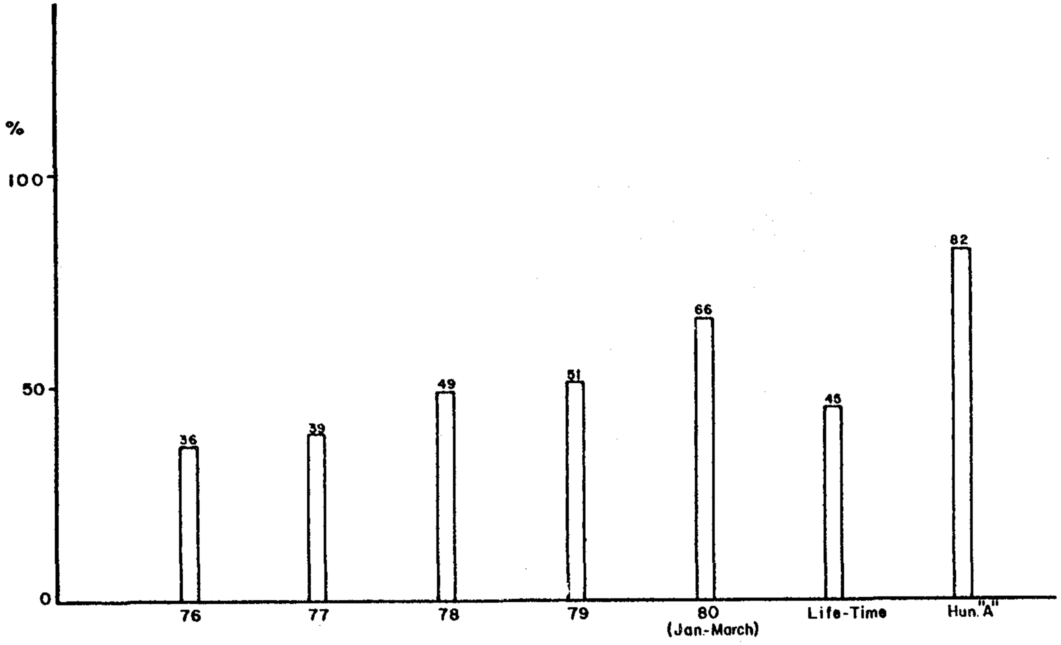
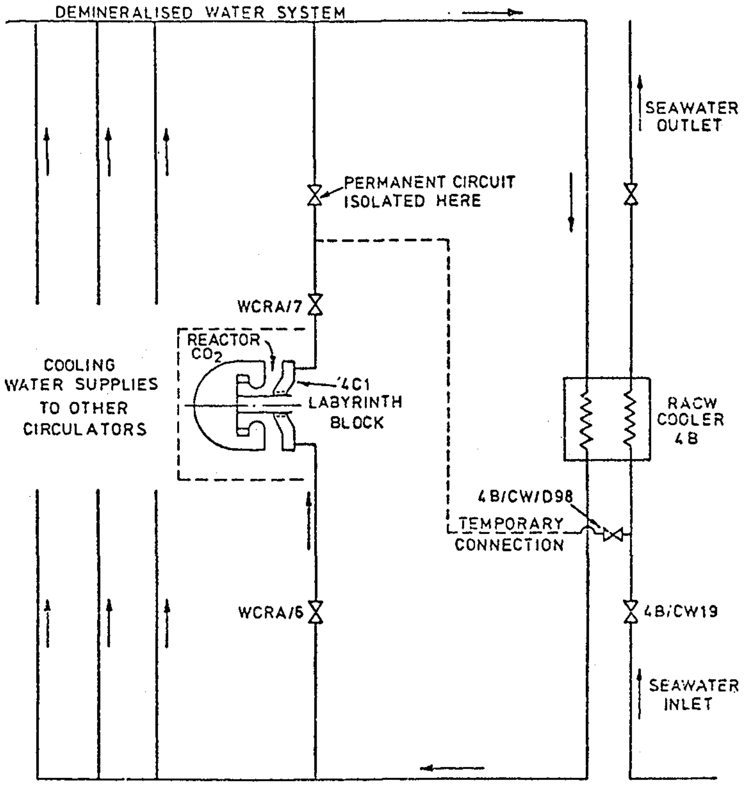


FIG. 2

HUNTERSTON "B" - R4



SIMPLIFIED DIAGRAM OF RACW SYSTEM
SHOWING TEMPORARY MODIFICATION

FIG. 3

HUNTERSTON "B"

UNIT 4 (Since re-commissioning)

LOAD FACTOR (%)

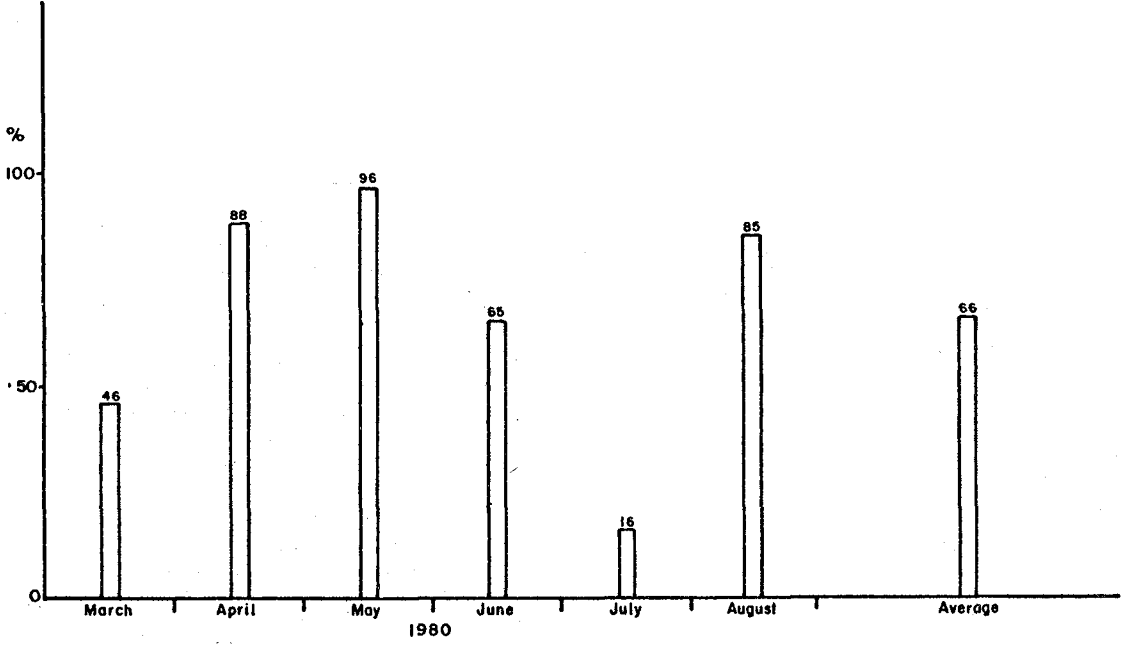
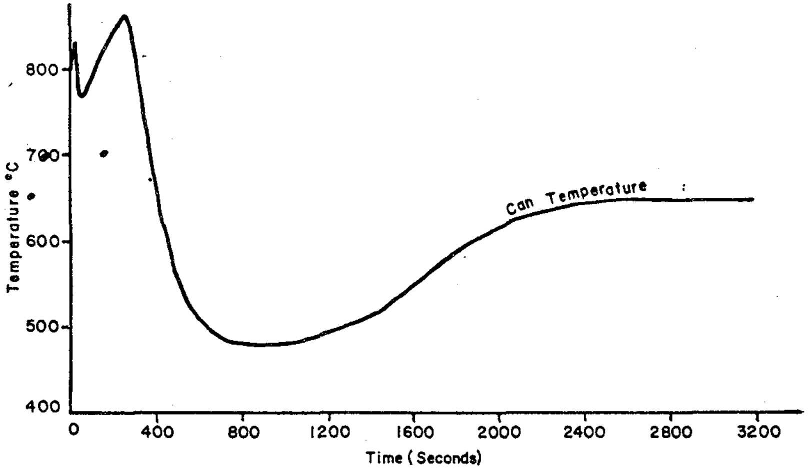
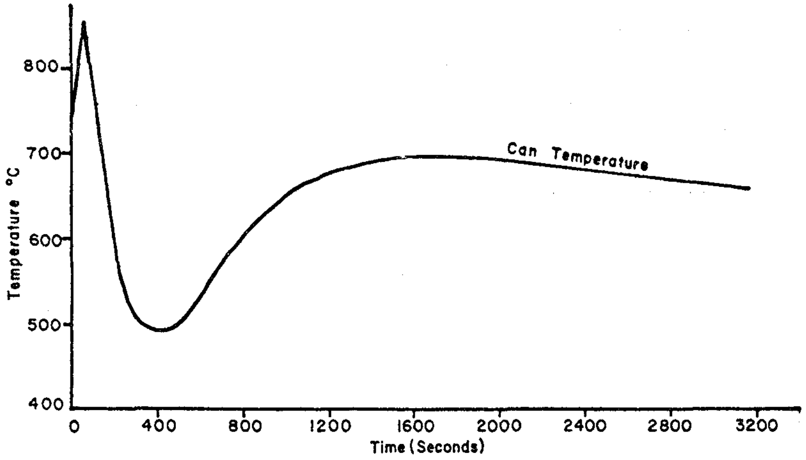


FIG. 4

HUNTERSTON "B"



MAXIMUM CREDIBLE ACCIDENT FIG. 5



MAXIMUM HYPERTHETICAL ACCIDENT FIG. 6

SOUTH OF SCOTLAND ELECTRICITY BOARD

HUNTERSTON 'A' AND 'B' POWER STATIONS

Analysis of Radiation Doses to Station Personnel

	.1975	1976	1977	1978	1979
NO. OF ALL 'A' STATION STAFF INCURRING IN THE YEAR:					
0 to 0.5 rem penetrating radiation	451	512	632	618	651
1.01 to 1.50 rem penetrating radiation	195	188	191	264	232
1.01 to 1.50 rem penetrating radiation	51	63	32	52	58
1.51 to 2.00 rem penetrating radiation	16	17	14	8	15
2.01 to 2.50 rem penetrating radiation	2	5	3	2	3
2.51 to 3.00 rem penetrating radiation	-	1	-	-	1
3.01 to 3.50 rem penetrating radiation	-	-	-	1	1
> 3.50 rem penetrating radiation	-	-	-	-	-
NO OF 'B' STATION STAFF INCURRING IN THE YEAR:					
0 to 0.50 rem penetrating radiation	125	198	211	202	220
0.51 to 1.00 rem penetrating radiation	-	-	-	2	6
> 1.00 rem penetrating radiation	-	-	-	-	-

SOUTH OF SCOTLAND ELECTRICITY BOARD

HUNTERSTON 'A' AND 'B' POWER STATIONS

Average and Total Radiation Doses for Personnel Designated to Hunterston 'A' and 'B' Power Stations

YEAR	1975		1976		1977		1978		1979	
STATION	'A'	'B'	'A'	'B'	'A'	'B'	'A'	'B'	'A'	'B'
Average Dose to Station Personnel (Rem)	0.53	0.08	0.57	0.13	0.47	0.15	0.48	0.14	0.44	0.15
Average Dose to Outside Personnel (Rem)	0.34	0.05	0.46	0.11	0.67	0.17	0.47	0.21	0.87	0.19
Total Station Dose Per Man (Rem)	398	10.6	480	42.8	446	87.5	541	128	532	133