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## DEVELOPMENT OF CO<sub>2</sub> CIRCULATORS\*

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### Abstract

The development of the basic machine types we have supplied has not been without problems. The Windscale AGR (the prototype AGR) was a small 1.2 MW vertically up circulator with an inlet temperature of 237°C (459°F).

Oil leakage problems occurred and were cured in the works test facility and the machine went into service with no other problems.

The Horizontal 5 MW machines for Hinkley/Hunterston were not so fortunate with vibration problems, interface corrosion problems (affecting the whole reactor) and material dimensional stability problems. Oil ingress problems did not show up in test work but were later reported from site. These reports were initially exaggerated due to the measuring techniques which took the operators some time to resolve.

In the vertical 5 MW machines for Hartlepool and Heysham 1 there are two interesting factors, firstly a spar failure and secondly shaft axial stability.

Many of the problems were due to modifications at site or our inability to model all aspects of site installation from which lessons for the future can be learned.

The latest stations Torness and Heysham II incorporate these lessons. The machines have been designed with so much margin that during the resolution of the reactor control rod gag problems the machines were run continuously at 20% overload (6.3 MW). From an initial accident case of 350°C inlet temperature, this increased to 458°C and now stands at 585°C. No modifications to the impeller were required. The site experience to date is good with no operational problems reported.

### INTRODUCTION

The Windscale (prototype AGR) circulators supplied in 1960 were the first in a series of submerged circulators supplied to British AGR reactor programme.

As each new reactor came along a different machine was required. Each machine type produced its own problems. The value of early development, followed by

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\* The author would like to thank James Howden & Company Limited for permission to present this paper.

full scale testing was demonstrated by the number of problems that were solved before delivery to site.

It is interesting to note that the final behaviour and performance of these complex machines is only established in the actual conditions of site operation and problems can occur as a result of modifications carried out at site or due to inability to model site conditions exactly. The lessons learned from the various development programmes carried through between 1958 and 1987 are hopefully useful in pointing the direction for future related projects.

#### WINDSCALE

This was our first submerged CO<sup>2</sup> Circulator (see Figure 1). Given the number of novel features, these machine proved remarkably trouble free, both in the test rig and at site over a period of 25 years. The prototype tests at full pressure showed bearing seal leakage into the motor compartment at an unacceptable rate. Modifications to the thrower/wind back geometry solved the problem and further back up modifications which were developed in parallel were not required.

It was established from this work that increases in reactor pressure for future reactors would adversely affect the problem and we were able to give it appropriate emphasis in subsequent AGR developments.

A point of interest in this machine is that the complete thrust bearing assembly is raised and lowered hydraulically, bringing the impeller into contact with the intermediate pressure casing, to form a standstill seal. The impeller, which is secured by a long central bolt is then released hydraulically, leaving the impeller in the gas circuit while the motor is removed for maintenance. Subsequent blind assembly of the motor to the impeller proved to be completely successful.

As an interesting aside, the central hub was gun bored over a 10ft (3.05m) length and deviated by only 0.003in (0.075mm)

#### HINKLEY POINT "B" - HUNTERSTON "B"

In many aspects this order reflected the problems experienced in building the early commercial AGRs in Britain. Competition was keen and orders for AGR's were placed when the designs were at the conceptual stage without, in hindsight, an adequate provision for an early design development phase.

This resulted in the circulators having to be designed almost as an afterthought and also having to absorb changes in duty and specification as the reactor design took shape.

Two typical examples were:-

(a) The duty was changed from one that required a 4500HP motor to a 6300 HP - this after the frame size was fixed with 1/8th inch clearance between the motor and the largest shutter tube possible. The motor consequently runs

hotter than is necessary. This is particularly noticeable when operating at low CO<sub>2</sub> pressures and has resulted in significant reduction in insulation life during the prolonged reactor commissioning period.

(b) The problem of interface corrosion was identified by the customer and the rules laid down had to be changed at a very late stage as the results from various tests became known.

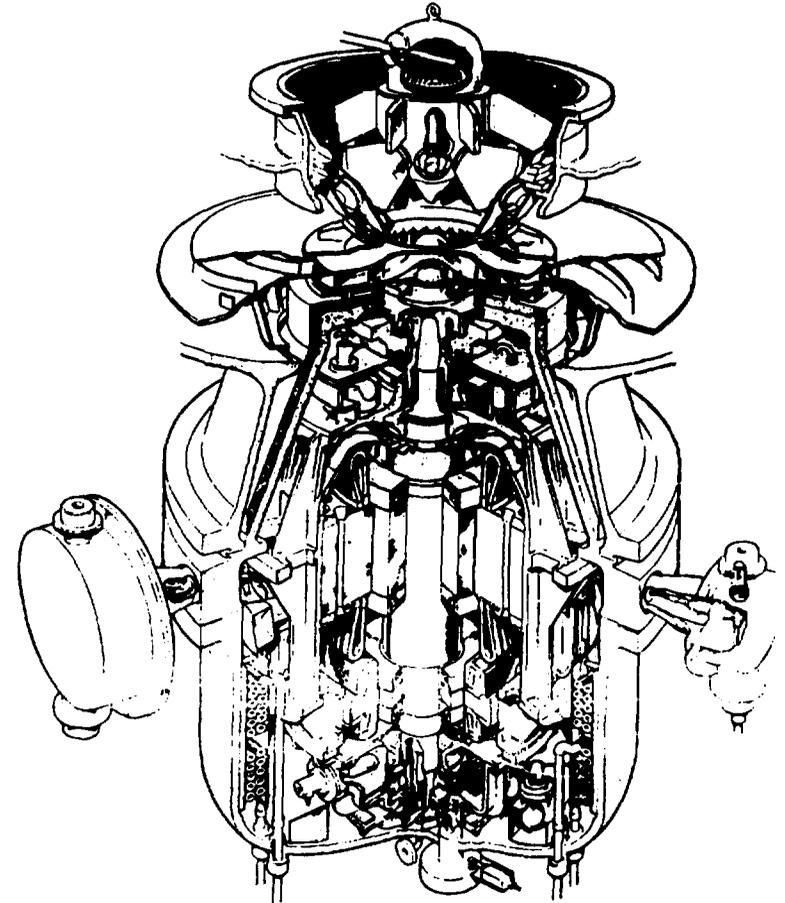


FIGURE 1.

The nature of the problem is that in CO<sub>2</sub> at temperatures above 250°C oxides form at interfaces. This oxide has twice the volume of the metal from which it is formed and jacks the faces apart.

The criterion for design is no longer stress, but that of accommodating the large strains which occur in the fasteners.

Since a bolted flange with lock washers has 10 faces, the amount of strain can be considerable. This must be accommodated by a waisted section in the bolt without exceeding 3% strain. Loss of thread profiles due to the same phenomenon must also be taken into account.

In addition to these specification change problems, there are bound to be some areas which cannot reasonably be dealt by the normal design process. A sensible development programme should aim to deal with these and also throw up any behavioural surprises which cannot reasonably be foreseen.

A few instances of the development process are outlined below.

#### Inlet Guide Vane Bearings

A special stainless steel roller bearing was developed for the Windscale machine and worked successfully.

The same bearing was used on the prototype machine for Hinkley but the IGV system became very stiff to operate after a few hundred hours. This was traced to a metallurgical instability in the bearing material resulting randomly in dimensional instability in the bearing components. An intensive investigation established the nature of the material structural change and the problem was resolved by modifying the manufacturing specification and applying stringent QA procedures. This bearing has now been used successfully on all AGR circulators.

In the course of this work a potential problem of wear and pick up at temperatures below 250°C was encountered but is not of significance during normal AGR operation. It does relate, however, to a similar potential problem in helium and will be given prominence in any helium circulator development programme.

#### Oil Ingress

There are two major problems associated with oil ingress, particularly on horizontal machines. Firstly that of controlling it and secondly that of measuring it. Both of these areas were at the limit of technology of the day.

The development task is that of controlling the intermixing of gas and oil mist in the presence of the vigorous turbulence which takes place in the various seal and labyrinth interspaces.

The measurement task is that of trying to identify a gram or two of oil in a high pressure test rig which can readily absorb several gallons of condensed oil on the water cooled surfaces and other cool areas.

An early mishap in the rig operation caused an inundation which continued to affect the readings for many months.

Oil entering the hot end of the rig due to ingress is broken down at a rate dependent on the temperature of the CO<sub>2</sub>.

Calibration of the rig for oil ingress measurements involves a complex procedure which enables the ingress oil to be identified against an equilibrium background of oil decay and oil evaporation from cool surfaces within the rig. This sounds impossible and at the time the first machines were tested oil ingress could not be assessed to better than about a tenfold accuracy.

Our joint best endeavours in co-operation with the customer resulted in an equilibrium reading of a few parts per million of oil in CO<sub>2</sub> being taken as the standard of acceptance, without knowing exactly what it meant in terms of oil ingress.

CEGB encountered similar problems in the reactor and the task was made more difficult by the fact, for instance, that a few micrograms of oil, condensing in the measuring system during cold periods could show up later as a false signal which looked like a 500 gallon slug of oil ingress.

An additional area of difficulty on these machines was the use of a common lubrication system to supply a pair of machines. This is satisfactory when both machines are running but when one machine is stopped, pressure balances are upset in the labyrinth system and a small amount of oil ingress can result.

Machines were only meant to operate as pairs, but the practicalities of site operations make it preferable to use machines singly if necessary.

As operating experience, discipline and measuring techniques have improved over the years, this problem has largely disappeared.

#### VIBRATION

In considering the design of the test rig for the Hinkley machines, it was obvious that we could not model exactly, the mounting stiffness of the pre-stressed concrete pressure vessel.

The estimated natural frequency of the machine at site was 56/58 Hz. In the test rig the natural frequency was just below running speed at about 45 Hz, and the overall vibration performance of the machines in the test rig was good.

When the first machine was run at site it became obvious that the natural frequency of the assembly was very close to running speed with consequent unacceptable levels of vibration of the circulator frame.

Measurements of vibration amplitude and phase relationships indicated that the vibration node was, as expected near to the mounting flange with the back end of the machine being very lively.

The conclusion from these test was that there was some unexpected freedom of movement of the forward end of the shutter tube resulting in the mounting stiffness being somewhat lower than had been estimated, resulting in a lowering of the pitching mode frequency to coincide with running speed. Delicate components at the back end of the machine such as IGV drive motors were at serious risk.

There was no possibility of the mounting stiffness being improved at this stage, but by good fortune, there was a self contained assembly at the back end of the machine which carried dome operating gear, IGV operating gear and other bits and pieces.

By de-coupling the mass of this assembly from the circulator and arranging for it to take its radial support directly from the shutter tube wall, it was possible to raise the natural frequency to the original intended level.

This dramatically improved the vibration behaviour and provided complete protection for the IGV drive gear and dome mechanism.

The modification has been in operation on all machines for some years now with complete success.

#### PERFORMANCE

It is fairly impractical to measure performance accurately under site conditions. Performance aspects must therefore be demonstrated beyond doubt at the development stage, modelling if necessary reactor circuit geometry in the region of the circulation inlet.

An apparent circulator performance shortfall showed up on the Hinkley reactors which could have proved difficult to resolve had the original development work not demonstrated the performance beyond reasonable doubt.

A simple explanation was in due course found for the apparent discrepancy and the machines were confirmed as being fully up to the claimed performance.

#### HARTLEPOOL/HEYSHAM I

These large vertical machines (see Figure 2) owe much of their design to the earlier Windscale machine. Bath lubricated tilting pad bearings were used with a main and pony motor mounted on the shaft. The pony motor is the safety related motor.

A major share holder in the consortium that ordered the circulator was GEC and we used GEC as the motor supplier in this contract rather than Lawrence Scott and Electromotors with whom we were working on the other contracts. With two

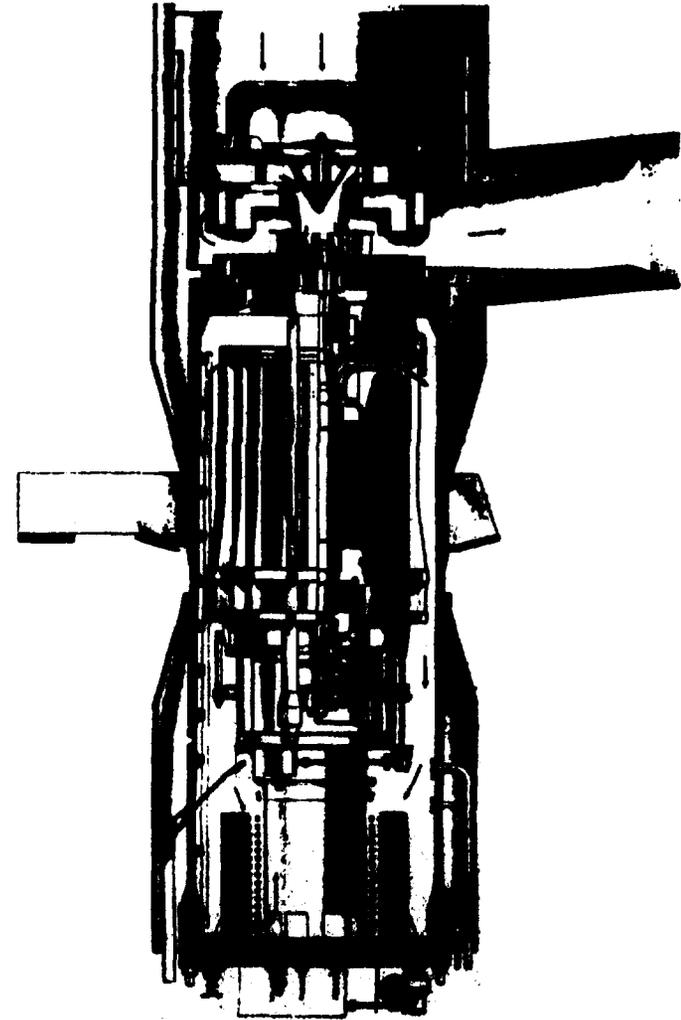


FIG.2. Sectional arrangement of vertical CO<sub>2</sub> circulator — Hartlepool and Heysham nuclear power stations.

such large contracts going through at the same time we were extremely busy and for that, and other reasons, the test rigs, although owned by Howdens, were located at the motor manufacturer's works. We believe this was a fundamental mistake as we were never quite in control of the work. In the most recent contract, we insisted on the test rig being in our works and there is no doubt that this arrangement is much more efficient.

The machines when first tested under full density conditions were found to have some lively components in the region of the inlet guide vanes. Some were excited acoustically and some aerodynamically. Bringing these under control was relatively straightforward, but it is unlikely that these problems would have showed up without a full density test facility.

One of the more interesting of these detail vibration problems was a classic self induced vibration failure of stiffening struts spanning the inlet passage.

As the IGV's close these struts are swept by a very wide range of gas velocities and consequently a wide range of Karman Vortex shedding frequencies. At some point the shedding frequency tunes into the natural frequency of the strut leading to classic failure.

This was Relatively easy to cure by machining spiral strakes on the surface of the struts but not the sort of problem that would be looked on kindly if it only came to light after 16 machines were installed at site.

During early reactor engineering runs, jacking oil supply pipes began to fail in fatigue without any external manifestation of distress. On investigation it

was found that the motor was being induced into a self sustaining form of vertical oscillation which cyclically interrupted the jacking oil supply and in turn induced cyclic pressures in the supply pipes of up to 7000 psi (480 Bar). Fatigue failure of the pipes naturally followed.

A very comprehensive programme of investigation involving all parties, was put in hand including instrumentation of machines at site, laboratory testing of components, and mathematical modelling, all of this at a most awkward time in the reactor programme.

In the end, the phenomenon was not completely subdued and the motor still oscillates harmlessly under some conditions. Use of rigid pipes and changes in some of the system stiffness and damping parameters enabled the system to be engineered for continuous safe and secure operation.

It is interesting that despite the lively behaviour of the motor, no thrust bearing failures or damage occurred.

#### HEYSHAM II/TORNESS

These machines (see Figure 3) were based on the Hinkley/Hunterston machines, incorporating the lessons learned from the operation of these reactors up to 1978 when the contract was placed. The changes were (i) a further increase in power up to 7000HP (5.25 MW) with a heavier shutter tube, (ii) the lubricating

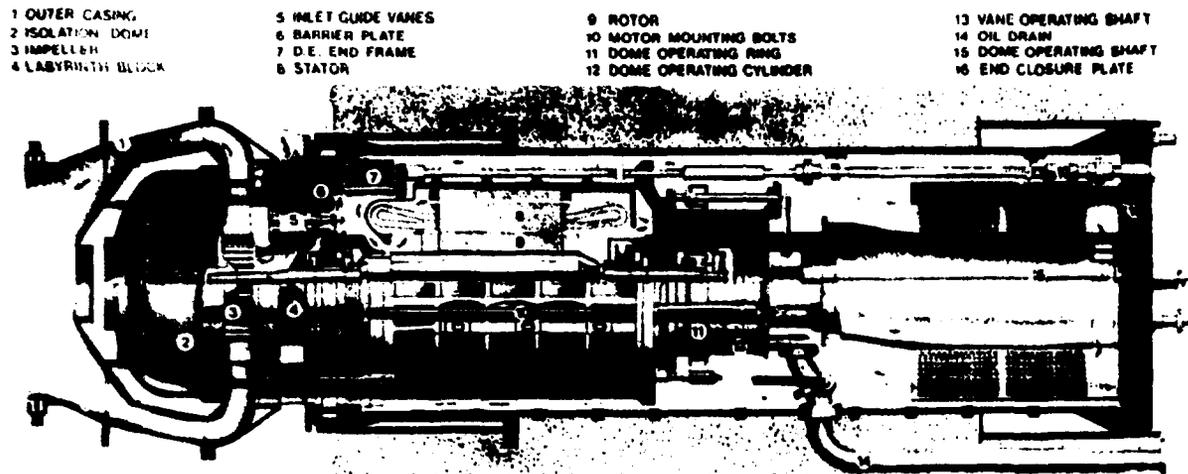


FIG.3. Howden gas circulator.

oil system was separated to one per circulator, (iii) the IGV drive was taken out of the shutter tube, (iv) the labyrinth system was changed to be the same as the vertical machine i.e. an external fan incorporated in the gas filter vessel which removes the need for water cooling of the labyrinth block.

The aerodynamics and the acoustic performance of these machines had been fully optimised for the Hinkley/Hunterston machines to give best aerodynamic performance, lowest obtainable noise levels and minimum aerodynamically induced shaft vibration.

In the new contract, the customer had a new objective for the noise spectrum, to enable him to optimise the gas circuit components design.

With the benefit of a high pressure test rig at a very early stage in the contract, it was possible to achieve further optimisation of the acoustic spectrum, while ensuring that shaft stability and aerodynamic performance were not adversely affected.

It must be said that this kind of optimisation is largely by trial and error and intelligent observation and experience.

A small, but worthwhile improvement was achieved using an inlet splitter vane which because of its peculiar shape became known as the hockey stick vane.

The opportunity was taken to make further improvements in shaft vibration by changes in bearing geometry giving a much improved second generation machine.

With the comparative luxury of a properly phased design and development period in the contract, and the early availability of a high pressure test facility, we were able to set new objectives in several important areas.

1. Oil Ingress - this was reduced to the threshold of measurement - a few grams per day. The measurement technique had in the intervening period improved to enable the improvement to be demonstrated.
2. Vibration - vibration level improvements were achieved both in the test rig and at site in line with our target objectives.
3. Thermal performance - motor winding temperatures were improved markedly.
4. Elimination of cooling water from the forward end of the machine while at the same time improving front end temperature.

#### Manufacturing Development

With the large time lapse between nuclear contracts, methods of manufacture have been moving ahead in rapid strides. It is important that new methods of manufacture are taken aboard without upsetting the design integrity of the product.

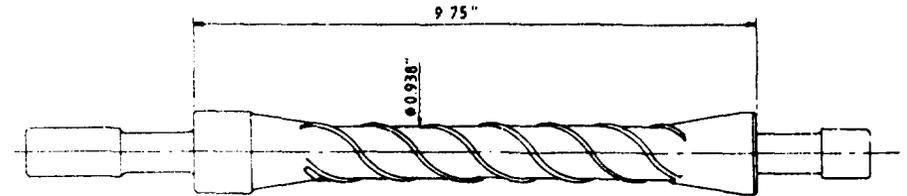


FIG.4. Modified inlet strut.

An instance of this is the impellers for Heysham II/Torness.

These are aerodynamically identical to the Hinkley Point "B" impellers.

The previous impeller had been fabricated from cast components, but casting suppliers had become increasingly resistant to taking on work to the very stringent quality assurance requirements which were being demanded. Consequently sources of supply had almost dried up.

For this reason, and also for the purpose of obtaining manufacturing consistency, we decided to change over to forged components.

With over one million operating hours on the cast impeller it was of utmost importance that any change should not invalidate this vast amount of running experience. The forged impellers were therefore kept geometrically identical to the previous cast impellers.

One factor which we considered worthy of exploring was the possibility that higher integrity, forged material might have less internal damping than cast material with consequent higher dynamic stresses.

Vibration response/decay tests were carried out on both impellers to demonstrate that there was no significant adverse effect. This was done using the calibrated hammer technique which scientifically examines decay of resonances in structures.

These tests were satisfactory, but as additional insurance, all likely sources of fatigue failure were profile dressed and polished.

In the meantime, having completed the design one of the reactor accident cases involving temperature excursion changed from 350°C with 10% overspeed, to 425°C and subsequently to over 500°C. With the design margin available we were able to accept these short term temperature excursions without failure.

The new machines, are installed at two stations and have accumulated several hundred running hours during reactor engineering trials. Some of the running has been done at 20% overload. To date no problems have arisen.

### Other Development

It must be evident that the items covered in the previous pages are chosen to represent some of the highlights and some of the transient difficulties typical of any complex development.

Few advances are made without minor setbacks and while we all wish that there were no set backs or difficult hurdles to surmount it is a fact of life that it is in these areas that the remembered lessons are learned.

In addition to the items of interest outlined there has been a vast amount of routine design, development and testing which does not have the spectacle of the test which goes wrong or the machine which misbehaves.

### Conclusions

One important lesson learned from the early AGR programme is that the design and development of a complex nuclear project should be carried out sufficiently early to avoid costly and time consuming changes during the manufacturing phase.

It is also important that reactor and circulator design and development go hand in hand to ensure compatibility.

These lessons were taken to heart in the later AGR programmes and an adequate design and development phase was included in the overall programme with excellent results.

## **TWENTY-FIVE YEARS OF BROWN BOVERI EXPERIENCE IN DEVELOPMENT, DESIGN AND FABRICATION OF CIRCULATORS FOR HTGR**

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### **Abstract**

BBC has been involved in the design and fabrication of circulators for helium circuits since the early days of German reactor technology. In the 60ies the activities in this field were started by the development of gas bearings for the circulators of the Dragon high-temperature reactor in Winfrith, UK.

As a next step, the two circulators for the AVR experimental reactor in Jülich, Federal Republic of Germany, were supplied. The circulators, which are equipped with oil bearings, have been operating troublefree since the start of commissioning in 1966. As a consequence of a water ingress into the reactor resulting from a steam generator damage one bearing was replaced in 1977 after 72000 operating hours. Up to the present date, each of the circulators has scored 115000 hours of operation, one of them without any disassembly.

In the THTR 300 in Schmehausen, Federal Republic of Germany, 6 BBC circulators are in operation. The insertable circulator units equipped with oil bearings have successfully proven their operating capability without any problems during the commissioning phase and the 100 % power operation which was started recently.

Currently active magnetic bearings are being developed for advanced gas-cooled reactors such as the HTR 100, the HTR 500 and the heating reactor after excellent results have been furnished by a small prototype in a test loop.

This ADI circulator has since scored more than 15000 operating hours without any trouble. A retainer bearing test stand also equipped with active magnetic bearings has been in operation for nearly 2 years. This test stand serves for developing the conditions for safe rundown of the rotors of even the largest circulators after the magnetic bearings have been deenergized unintentionally.

Development work is conducted on the prototype of a safety-relevant circulator held in magnetic bearings, to be used for decay