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Past experiences from gas-cooled reactors useful for VHTR

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Deliverable D-CT2-2 Past experiences from gas-cooled reactors useful for VHTR

Abstract

The aim of this document is to summarize the past experience in both German and British former HTR.

This document gathers 2 reports:

- Status and valuation of helium circulators of high temperature reactors (RWTH) LRST2006/14
- UK experience with circulators in gas-cooled reactors (NNC) 12820/TR/0019

RWTH report presents an overview of helium cycles and helium circulators in nuclear plants. It provides data on operating characteristics, design options and materials of helium and CO2 circulators in operated and proposed reactors. Magnetic bearings have only been tested on small machines nut were selected as a promising technology for proposed reactors. So we have no past experience of these components in large machines.

NNC report presents on overview of gas-circulators used in UK. It provides data on operated characteristics and design of operated reactors. It also gives a lot of information about issues such as failures, vibrations and oil ingress.

Revisions

Rev.	Date	Short description	Author	WP Leader	SP Leader	Coordinator
00	11/12/2006	First issue	Dominique CUCINI JEUMONT	Dominique CUCINI JEUMONT	Daniel BESSON AREVA NP	Edgar BOGUSCH A REVA NP

Status and valuation of helium circulators of high temperature reactors

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Lehrstuhl für Reaktorsicherheit und -technik
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Content: Status and valuation of helium circulators of high temperature reactors

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Abstract

Helium circulators are important components of gas cooled reactors to compensate pressure drops in the primary system.

In this report an overview is given on the helium circulator which have been operated in the helium cooled reactors AVR, Dragon, Peach Bottom, Fort St. Vrain, THTR, HTR 10 and HTTR. Additional information are given for circulator concepts, which have been worked out in different HTR-projects in Germany and USA. Further experience is available from helium circulators and helium compressors in large test facilities.

(KVK, EVO-Plant, HHV) Helium circulator technology in many cases is based on the broad experience with CO_2-circulators form Magnox- an AGR-plants in Great Britain and in France.

In these report technical descriptions, components data and available experience with these machines are summarized. Specific topics as design options, bearings, lubrication systems, control and drive systems are explained, too. In most cases one stage radial circulators with overhung wheel have been applied. The overall experience with these components is very good. Their availability was very high. For helium circulators for use in HTR plants with steam cycle of for process applications machines with power of drive of 2 to 3 MW, a pressurize of around 1.5 bar, helium inlet temperature of 250 to 350°C are state of technology. It is feasible form many design studies and using normal rules of extrapolation to realize machines with around a power of 4 MW of the drive. Helium compressors with power of around 50 MW and a pressure ratio of 1.5 to 1.8 have been operated with very good success in the EVO-plant, too. This is important for the application of the Brayton-cycle.

Ideas like magnetic or gas bearing have been tested in smaller machines; they still need some development and large scale testing, before an industrial application without technical risks is possible.

Content

1. Principle aspects of Helium cycles and Helium circulators in nuclear power plants [1.1 to 1.5]

1.1. Helium circuits in nuclear reactors

While helium-cooled nuclear reactors have different applications, their primary systems consist of a reactor core, heat exchangers and helium circulators. The helium circulators are used to compensate for pressure drops that occur within the main components and within the connecting gas ducts.

The principles of helium flow are demonstrated in the cycles in Figure 1.1 below. The simplest helium flow cycle is the generation of steam without reheating (Fig. 1.1a). The AVR, the Peach Bottom, and the HTR10 all use this type of cycle. In the THTR and in the Fort St. Vrain reactor, the cycle was modified by introducing a heat exchanger to reheat the steam leaving the high pressure turbine, as shown in Figure 1.1b. This process will be used in the next Chinese HTR. In the Dragon reactor and in the HTTR the nuclear heat was rejected by the cooling water.

Proposals for reactors using nuclear process heat for steam reforming, coal gasification, or hydrogen production via thermo-chemical cycles use either direct coupling with the reactor (Fig. 1.1c) or introduce intermediate heat exchangers between the reactor and the chemical processes (Fig. 1.1d).

In all cases the helium circulators have to compensate for relatively small pressure drops within the circuit. These pressure drops and the related pumping power are at the order of:

$$\frac{\Delta p}{p} \approx 2...3 \cdot 10^{-2} \qquad \frac{\Delta P_p}{P_{el}} \approx 2...3 \cdot 10^{-2}$$

In gas turbine applications the ratio of the power of the helium compressor to the total net energy production is much larger. Values of around

$$\frac{\Delta P_c}{P_{el}} \approx 0.2...0.3$$

are common and therefore different compressors have to be applied in these processes. A typical gas turbine cycle with two stages of compression is shown in Fig. 1.1e. The next Figure, Fig. 1.1f, demonstrates the principles of a combined cycle helium circuit consisting of a gas turbine and a steam turbine-cycle. Naturally the characteristic inlet and outlet helium temperatures in the reactor are different for each of the applications mentioned above. In Fig. 1.1 some of these values are indicated.

Inlet temperatures on the order of 250 to 300°C are advantageous as far as the design of the reactor is concerned.

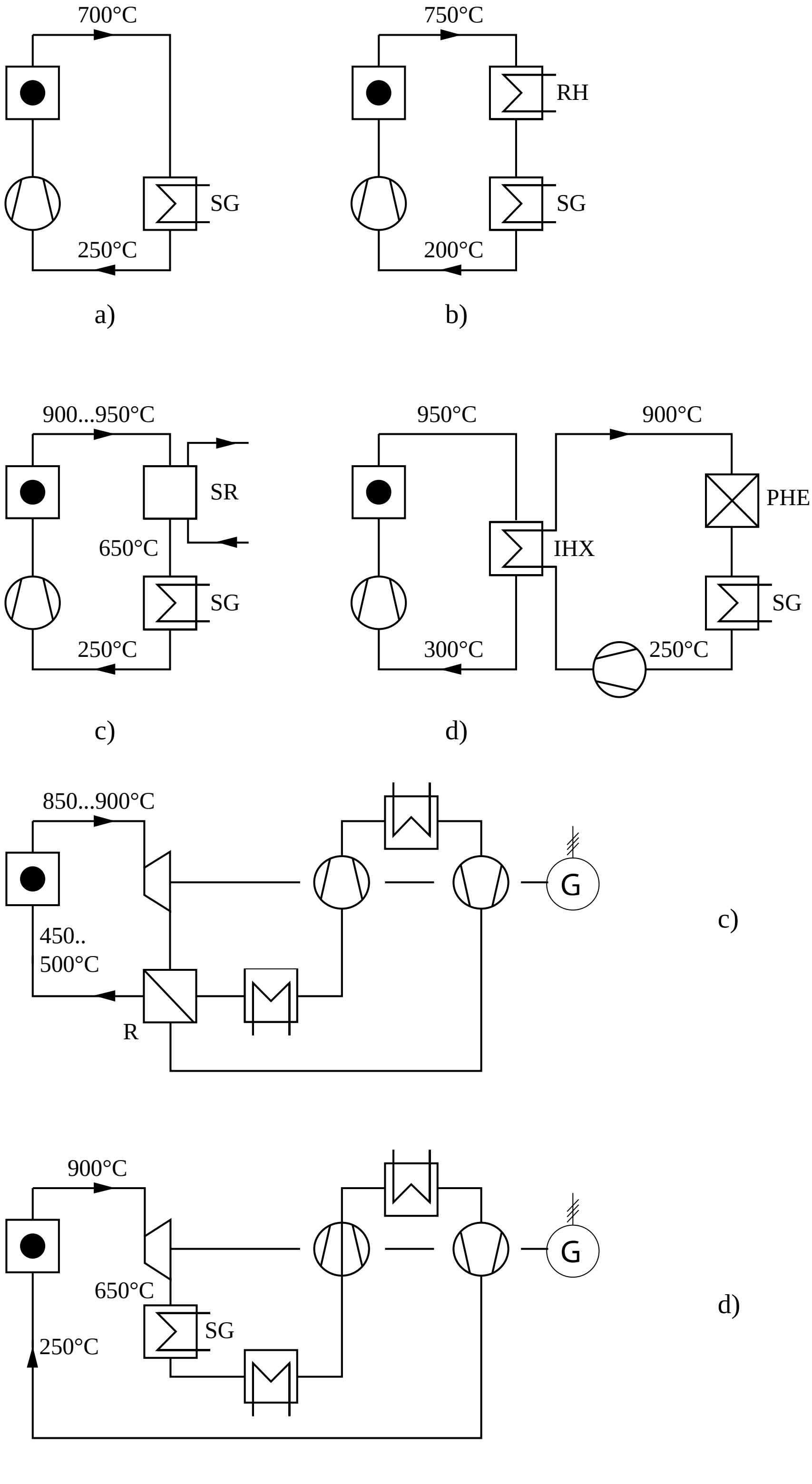


Fig. 1.1: Helium circuits for different applications of HTR

a) Steam generator (without reheat (RH))
b) Steam generator (with reheat)
c) Steam reformer (SR) for methane-steam conversion, direct coupling
d) Intermediate heat exchanger (IHX) supplies energy to process heat exchanger (PHE) and steam generator
e) Gas turbine cycle (two stage compression)
f) Combined cycle (SG = steam generator)

The following chapters examine helium circulators, which are suited to supply systems corresponding to Fig 1.1a through 1.1d. Chapter 5 contains some information on compressors that have been tested with respect to gas turbine cycles.

As a further example of large machines, the circulators of CO_2-cooled reactors (Magnox and AGR) are described in chapter 6.

1.2. Pressure Drops and Pumping Power in Helium Circuits

A mass flow corresponding to the thermal power of the reactor must be circulated through the core to remove the heat of the fission process.

$$\dot{m}_{He} = \frac{P_{th}}{c_p \cdot (T_{outl.} - T_{inl.})}$$

During the flow through the components and gas ducts of a helium circuit, a pressure drop occurs.

$$\Delta p = \sum_i \Delta p_i$$

The necessary pumping power for the whole helium circuit is then given by:

$$P_p = \frac{\Delta p \cdot \dot{m}_{He}}{\rho_{He}}$$

For a circulator with an inner efficiency η_i , the power P_{circ} is:

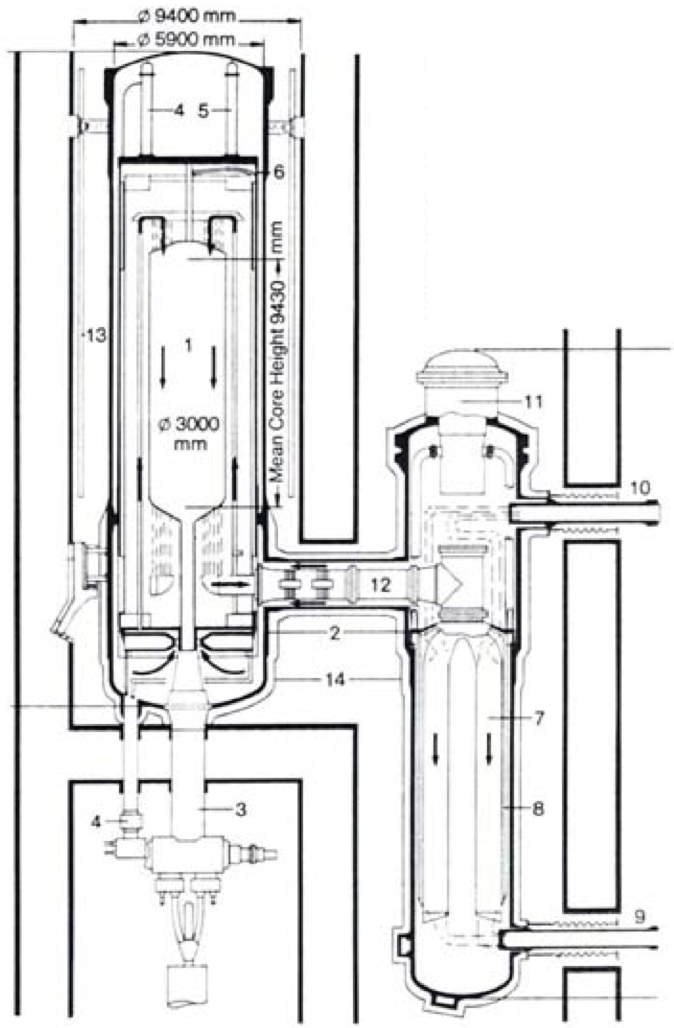
$$P_{circ} = \frac{P_p}{\eta_i}$$

The electric power P_{el} of the motor is dependent on the mechanical efficiency η_{mech} and the driving motor efficiency η_{mot} .

$$P_{el} = \frac{P_p}{\eta_i \cdot \eta_{mech} \cdot \eta_{mot}}$$

In all applications shown in Figures 1.1a through 1.1f a larger part of the püressure drop occurs in the reactor core. Figure 1.2 shows as a characteristic example the flow concept of the HTR-Module (200 MW_{th}).

The steam generator is connected to the reactor by a coaxial gas duct, in which the cold gas (250°*C*) cools the hot gas duct from the outside. All primary components, which are exposed to a high pressure of 70 *bar*, are cooled by the total mass flow of the cold gas.



$$\Delta p_t = \sum_i \Delta pi$$

Δp_1 : core

Δp_2 : bottom structure of reflector + hot gas chamber

Δp_3 : hot gas duct

Δp_4 : hot inlet to steam generator

Δp_5 steam generator bundle

Δp_6 upwards flow cold helium in steam generator

Δp_7 inlet to helium circulator

Δp_8 counter flow of cold helium in gas duct

Δp_9 upwards flow of cold helium in the reactor pressure vessel

Δp_{10} top structure of reflector

Fig. 1.2 Flow concept for the helium in the HTR-Module (200 MW_{th})
1: pebble bed, 2: pressure vessel, 3: fuel discharge, 4: small absorber balls, 5: reflector rod, 6: fuel loading, 7 steam generator, 8: outer shroud, 9: feed line, 10: live steam line, 11: blower, 12: hot gas duct, 13: surface cooler, 14: insulation

In this reactor the total pressure drop is around 1.5 *b*ar, of which 0.7 *bar* occur in the core, 0.3 *bar* are caused by the steam generator, and the rest occurs in the structures mentioned in Fig. 1.2. The pressure drop in the core may be written as:

$$\Delta p = \psi \frac{L}{d_p} \left(\frac{1-\varepsilon}{\varepsilon^3} \right) \frac{\rho V^2}{2}$$

The average velocity V in the core is calculated using the average velocity V_F between the pebbles corresponding to the free cross section of the pebble bed and the void fraction ε in the pebble bed.

$$V = \varepsilon V_p$$

The hydraulic diameter *D* is related to the pebble diameter d_F by the following relation:

$$D = d_p \left(\frac{\varepsilon}{1-\varepsilon} \right)$$

Using the following definition of the Reynolds number,

$$Re = \left(\frac{1}{1-\varepsilon} \right) \frac{\rho V d_p}{\mu} .$$

with $Re \leq 5 \cdot 10^4$, the experimental results for the friction factor can be approximated using the following equation,

$$\psi = 320 Re^{-1} + 6 Re^{-0.1}$$

where the two terms on the right side correspond to laminar and turbulent flow, respectively. Uncertainties come mainly from the actual value of the voidage, which is ε = 0.375 for an infinite bed and varies with distance from the bed wall, of the random packing of equal spheres

The variables in the equations above are as follows:

$$L = \text{core height}$$
$$d_p = \text{pebble diameter}$$
$$\varepsilon = \text{void fraction}$$
$$\mu = \text{viscosity of helium}$$

Naturally the core pressure drop depends strongly on the design, the dimensions, and the power of the core, as is shown in Fig. 1.3 for the example of annular core geometry.

Figure 1.3 represents a graphical analysis of the conditions of a pebble bed core with annular geometry in the case of a severe accident where a total loss of coolant and active cooling occurs. The maximum fuel temperature in this case mainly is dependent upon the generated power of the core before the accident. Decay heat produced by the core is dissipated into the environment by conduction, radiation, and free convection. A maximum fuel temperature of 1600°*C* is consistent with a thermal core power of around 400 MW_{th}, if the outer diameter of the annulus is chosen as 3.5 *m* and the inner diameter as 1.8 *m*. In this example, normally forged steel meets the specifications.

In this case, the pressure drop is relatively high in the core. Furthermore, this design would be suitable for gas turbine applications too. Generally, the core pressure drop is dependent on the average power density in the core ($\dot{q}'''$), the core height (*H*), the helium pressure (p), and the temperature difference in the core (ΔT):

$$\Delta p_c \approx \frac{\dot{q}'''^2 \cdot H^3}{p \cdot \Delta T^2}$$

Increased pressure and lager ΔT cause the pressure difference to decrease. Limited pressure drop ($\approx 1.5\,bar$) allows to use an one-stage compressor.

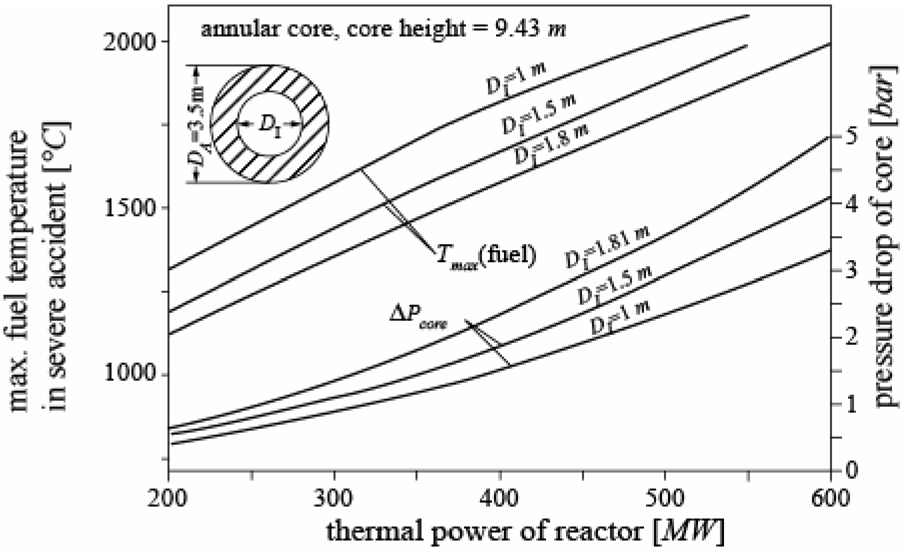


Fig. 1.3 Maximal fuel temperature in sever accidents (total loss of coolant and active decay heat removal) and core pressure drop dependent on thermal power in an annular core

The pressure drops in the heat exchangers and in all gas ducts must be estimated according to an optimization of the plant efficiency and total investment costs caused by design aspects of the plant. The choice of duct diameter and gap thickness for gas transport in primary system spacing in heat exchangers are important parameters.

In the case of prismatic cores, the pressure drop is determined from the following considerations:

The pressure drop equation for a single coolant channel serves to demonstrate the various losses experienced by helium coolant as it passes through the core:

$$\Delta p_t = \frac{1}{2\rho}\left(\frac{\dot{m}}{A}\right)^2 \left[K_v + K_1 + \frac{\Delta f L}{D}\left(\frac{\bar{T}}{T_1}\right) + \frac{T_2 - T_1}{T_1} + \sum_{j=1}^{n} K_j\left(\frac{T_j}{T_1}\right) + K_2\left(\frac{T_2}{T_1}\right)\right]$$

K_v is the loss coefficient of the flow control valve, K_j is the loss coefficient due to the offset at element interfaces, and T_j is the temperature at the bottom of the core element block *j*.

Characteristic values of prismatic cores are given in table 1.1.

Table 1.1 Flow resistance as a function of the region power factor

Region Power Factor $P(r)$	**1.6**	**1.0**	**0.4**
Velocity head in top reflector coolant holes [kPa]	3.8	1.5	0.24
orifice K_v	3.47	35.0	307.3
Entrance loss coefficient, K_1	0.36	0.36	0.36
Frictional resistance $\left[\frac{4fL}{D}\cdot\frac{\bar{T}}{T_1}\right]$	12.35	13.07	16.57
Acceleration due to the temperature rise $\left[\frac{T_2-T_1}{T_1}\right]$	0.74	0.74	0.74
Element interface offset loss coefficients $\sum_{j=1}^{n} K_j\left(\frac{T_j}{T_1}\right)$	0.50	0.50	0.50
Exit loss coefficient $\sum_{j=1}^{n} K_2\left(\frac{T_2}{T_1}\right)$	3.34	3.34	3.34

Different equations for friction factors are known and can be applied to prismatic fuel elements. In the laminar flow regime, $Re < 2000$, the expression for circular tubes is given by:

$$f = \frac{16}{Re}$$

For the turbulent flow regime, $Re \geq 5000$, there are various correlations to choose from, including the well-known empirical equation:

$$f = 0.046 \cdot Re^{-0.2}; \quad 5000 < Re < 200000$$

The Blasius formula can also be used:

$$f = 0.079 \cdot Re^{-0.25}; \quad 5000 < Re < 100000$$

The Koo correlation is often applied:

$$f = 0.00140 + 0.125 \cdot Re^{-0.32}; \quad 3000 < Re < 3000000$$

The von Karman-Nikuradse equation, derived from theoretical consideration and using the Nikuradse experimental data, can be applied to open channels as well as enclosed tubes:

$$\frac{1}{\sqrt{f}} = 4.0 \cdot log_{10}(Re\sqrt{f}) - 0.40$$

Depending upon the degree of accuracy required and the convenience in performing the calculations, a specific expression is chosen. The von Karman-Nikuradse equation is perhaps the most accurate for smooth pipes but requires an iterative type solution to evaluate the friction factor. The first two expressions are probably more commonly used but are less accurate than the Karman-Nikuradse equation. Another formula is known as the Colebrook-White correlation.

$$\frac{1}{\sqrt{f}} = 3.48 - 4 \cdot log_{10}\left[2\left(\frac{\varepsilon}{d}\right) + \frac{9.35}{Re\sqrt{f}}\right]$$

This expression correlates the data from hydraulically smooth to rough walls with ε being the root-mean-square roughness height and d the pipe diameter. This expression reduces to the von Karman-Nikuradse formula for smooth pipes; that is, when $\varepsilon/d = 0$. An even simpler relation is the Moody approximation to the Colebrook-White equation:

$$f = 0.001375 \cdot \left[1 + \left(20000\frac{\varepsilon}{d} + \frac{10^6}{Re}\right)^{1/3}\right]$$

In the HTR- prototype reactors THTR and Fort St. Vrain, the calculated pressure drops in the core, gas ducts, and heat exchangers had an uncertainty of around 10% compared to the measured values.

1.3. Concepts and characteristic parameters of helium circulators

In the HTR-plants, which have been built until now with one stage radial compressors, circulators have been installed with an electrical motor. Only in the Fort St. Vrain reactor an axial compressor with a steam turbine has been implemented.

Figure 1.4a shows the principle of a radial machine. The wheel is arranged on the shaft of the motor, which is normally integrated into the helium circuit. The bearings are usually oil lubricated and have a multiple stage sealing system. Figure 1.4b shows this type of gas circulator in a version which typically is applied in industry.

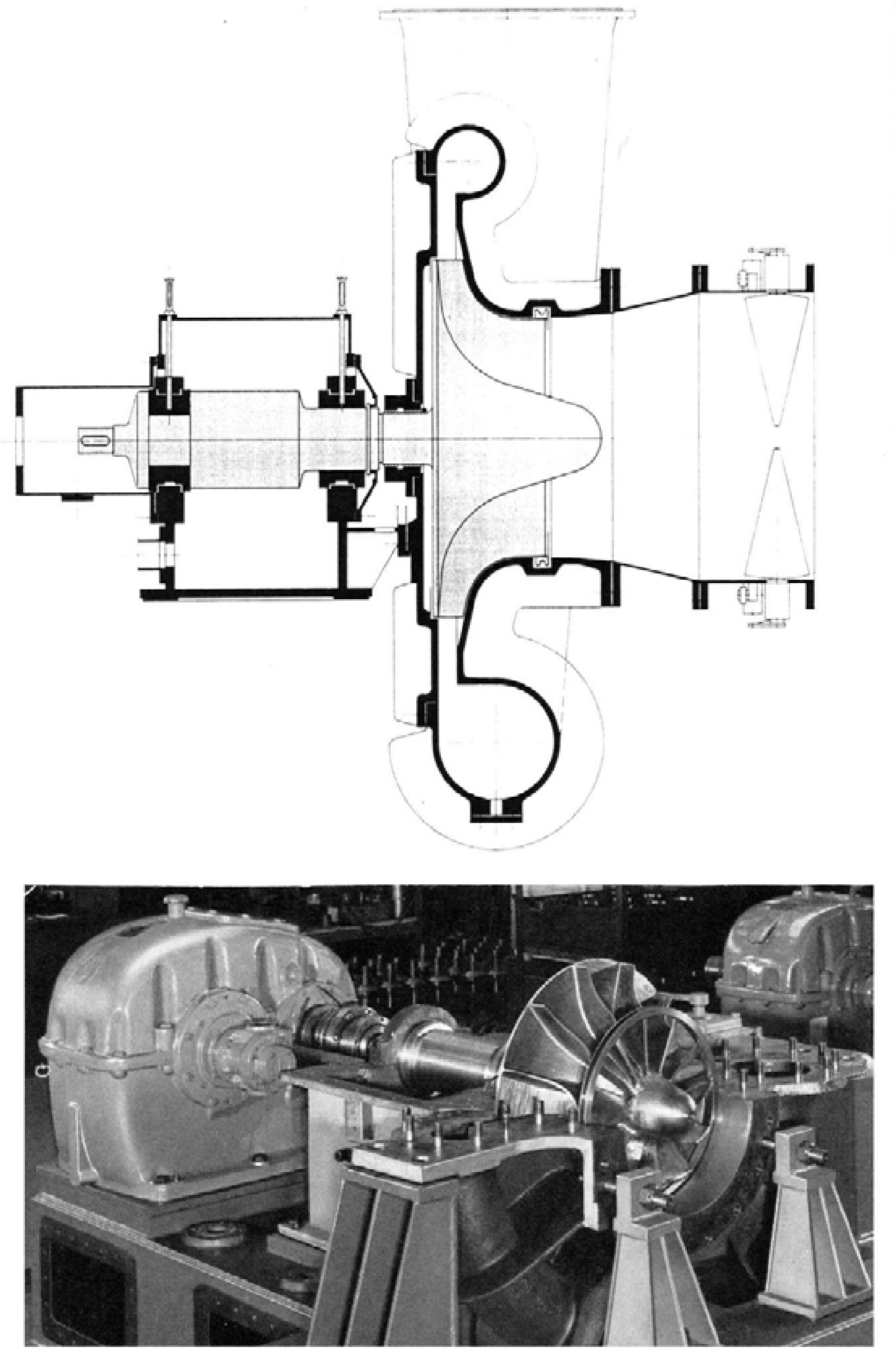


Fig. 1.4 Radial circulators

a) Priciple of a radial circulator

b) Picture of an industrial circulator ($p = 4.2\,bar,\ T = 405°C$)

There are some important connections between mass flow of helium, specific work of flow, specific rotational frequency and the specific diameter of the wheel.

The volumetric flow of helium is given by the equation

$$\dot{V} = \frac{\dot{m}}{\rho(p,T)}$$

The specific work of flow is defined by the expression

$$y = \frac{\Delta p}{\rho} = \eta_i \cdot c_p \cdot T_i \left(\left(\frac{p_2}{p_1} \right)^{\frac{R}{\eta_i \cdot c_p}} - 1 \right)$$

Approximately one gets for small values of $\Delta p / p$

$$y \approx \frac{R \cdot T_i \cdot \Delta p}{p} \cdot \left(1 + \frac{\Delta p}{p} \cdot \frac{1}{2} \left(\frac{R}{\eta_i \cdot c_p} - 1 \right) + \ldots \right)$$

where η_i is the inner efficiency of circulator, T_i is the inlet temperature, and p_2 / p_1 is the pressure ratio.

The specific rotational frequency can be calculated from the empirical relation

$$\sigma_{YM} = 2.108 \cdot n \cdot \frac{\dot{V}^{0,8}}{y^{0,75}} ,$$

and the specific diameter of the wheel can be determined from the empirical expression

$$\delta_{YM} = 1.054 \cdot D \cdot \frac{y^{0.25}}{\dot{V}^{0.5}} .$$

These empirical relations have been determined from the comparison of many compressors, which have been designed and used in different fields of industry.

In the Cordier diagram (fig.1.5), the specific diameter and the specific rotational frequency are shown with their dependence from each other. Optimally designed circulators are positioned on this curve.

This chart allows a distinction between radial- and axial-circulators. In the designs of the AVR, the THTR, and the HTR-Module, for example, radial machines have been proposed or implemented. These one-stage machines are positioned on the left part of the chart. Axial compressors, shown on the right side of the chart, have been chosen for other applications.

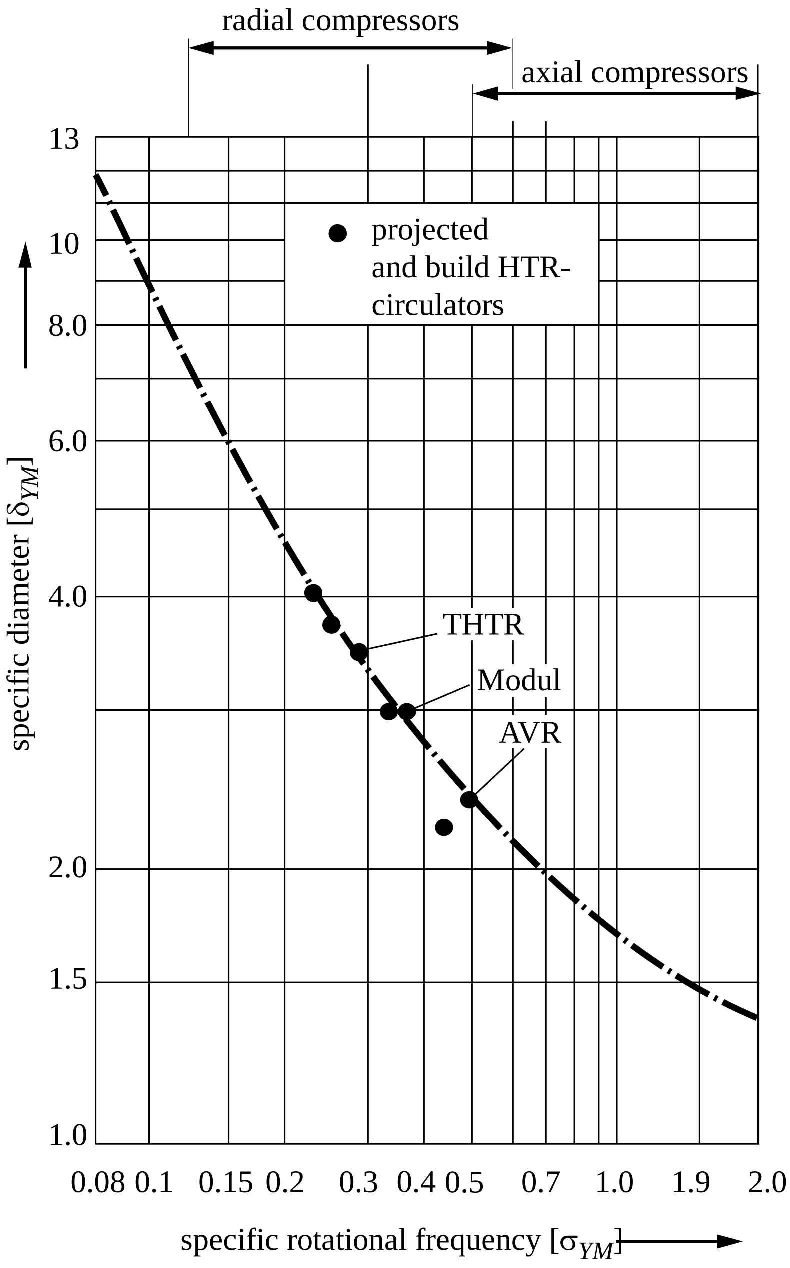


Fig. 1.5 Cordier diagram

The specific work of the fluid can be approximately calculated by the equation

$$y = \Delta p \,/\, \rho$$

in the case of relatively small pressure drops $(\Delta p / p \ll 1)$ or more exactly by applying the ideal gas law as given before.

$$y = b \cdot R \cdot T_i \cdot \left(\left(\frac{p_o}{p_i} \right)^{1/b} - 1 \right)$$

The parameter *b* than can contain specific aspects of the machine expressed by the dependence of inner efficiencies from further parameters.

The rotational frequency *n* is an important parameter for the optimization of the circulator because the diameter of the wheel decreases with *n* and therefore with the size of the component and the investment costs. On the other hand, with larger values of *n*, the tip speed of the blades increases. Strength and safety factors of this component then become more important. Machines with a speed of 3000 *rev/min* normally are applied if electrical energy is used for the drive.

The ratio of the diameter of the wheels is dependent on the related value of the rotational frequency *n*, as explained in Figure 1.6.

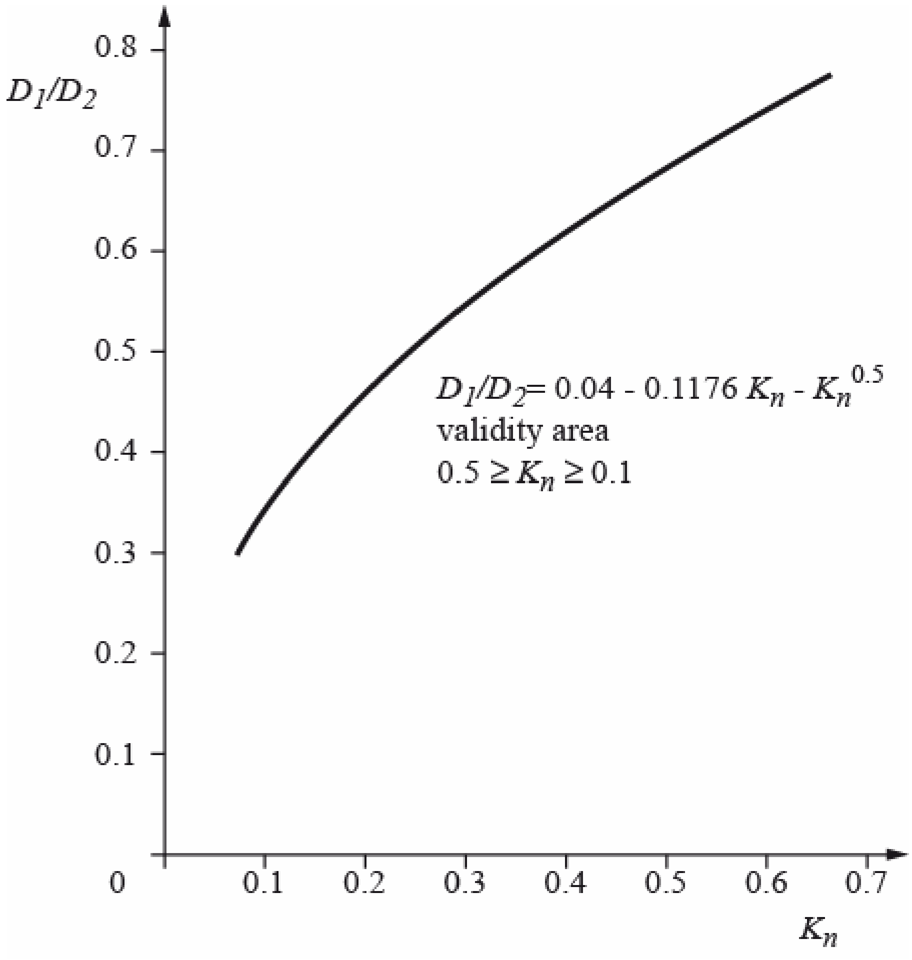


Fig. 1.6 Ratio of diameter of wheels (D_1/D_2) versus the value of related rotational frequency K_n

The following definitions are used in connection with the concept of the Cordier diagram:

$$K_n = \frac{6 \cdot 33 \cdot n}{1000}\left(\frac{\dot{V}}{H_{ad}}\right)^{1.5}$$

$$D_1/D_2 = 0{,}04 - 0{,}1176 \cdot K_n - K_n^{0.5}$$

By applying the afforementioned equations and graphs, different helium circulators can be compared.

1.4. Requirements of the component

Helium circulators in HTR-plants circulate the cooling helium gas through all primary components, cool them and compensate for all pressure drops. Some important design and operational requirements are:

- operation at full power
- part load of the plant
- start up of operation
- shut down of the plant following normal procedure
- shut down because of failures in plant
- decay heat removal after shut down of the reactor
- operation of the circulator because of decay heat removal during service and repair work

The circulator has to be operated in a wide range of part load. Figure 1.7 shows aspects in a graphical representation the conditions for part load of the THTR-circulators. The curves show the dependence of pressure dropson volume flow for the cases that the available 6 circulators change their load simultaneously and that just one of the 6 circulators is operated in state of part load.

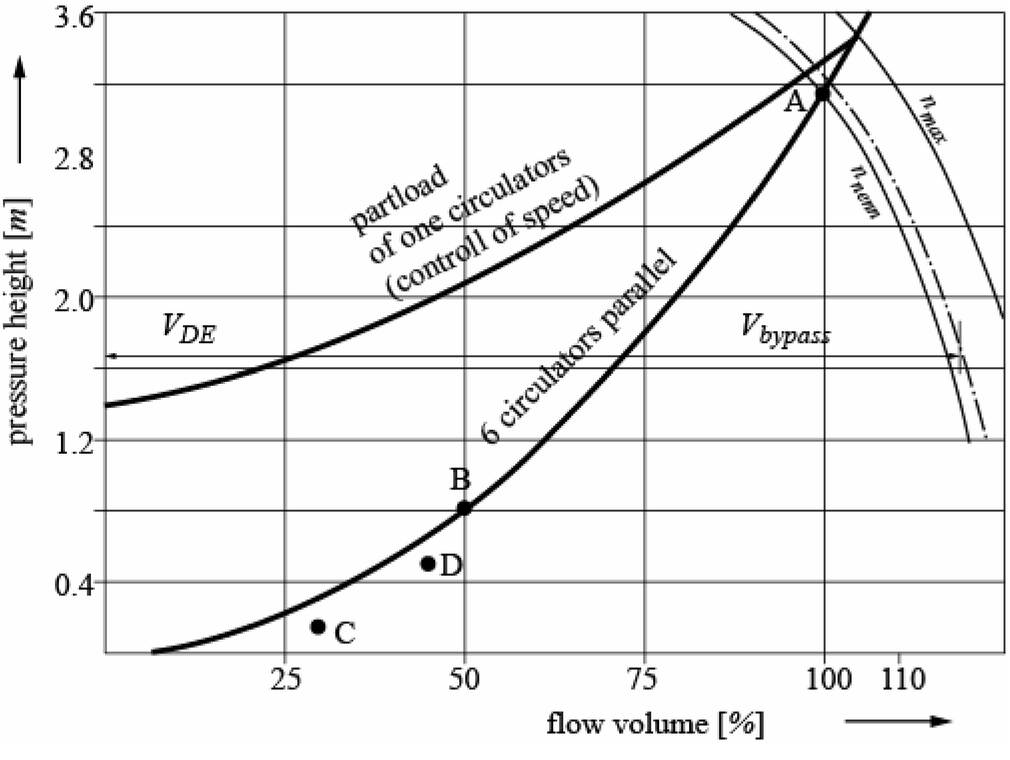


Fig. 1.7 Part load diagram of the THTR-circulator

Generally, there are many requirements for the operation of the plant, and therefore specific requirements for the circulators. Table 1.2 contains some numbers, which have been defined by utilities during HTR-projects in the past. The design of the circulator, the drive, and the necessary auxiliary systems for these components must be suited to fulfil these requirements. Further requirements for circulators are:

- Sufficient supervision of the main parameters of operation (*T*, *p*, $\dot{m}$, speed, vibrations, power, helium quality, oil supply)
- Design for a lifetime of 40 or more years of full power operation
- Easy access to the component, possibilities of inspection, maintenance and repair
- Positioning of the component out of fields of radiation of γ- and neutrons
- Possibilities to decontaminate the component

Table 1.2 Representative plant transients for HTR-systems as a basis for circulator design

<table>
<tr><th>procedure</th><th>state of plant</th><th>demand of time [h]</th><th>number of occurrence</th></tr>
<tr><td>start up</td><td>reactor cold and without pressure</td><td>17</td><td rowspan="2">{200</td></tr>
<tr><td>start up</td><td>reactor cold and under pressure</td><td>15</td></tr>
<tr><td>start up</td><td>after 10h after shut down</td><td>6</td><td rowspan="2">{600</td></tr>
<tr><td>start up</td><td>directly after scram</td><td>2</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>shut down</td><td>until reactor cold and without pressure</td><td>24</td><td rowspan="2">{200</td></tr>
<tr><td>shut down</td><td>until reactor cold and under pressure</td><td>5</td></tr>
<tr><td>shut down</td><td>reactor trip</td><td></td><td>250</td></tr>
<tr><td>shut down</td><td>turbine trip</td><td></td><td>250</td></tr>
<tr><td>shut down</td><td>other reasons</td><td></td><td>100</td></tr>
<tr><td>shut down</td><td>load rejection till until house load</td><td></td><td>400</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>load change</td><td>normal increase and decrease (3%/min)</td><td></td><td>20000</td></tr>
<tr><td>load change</td><td>rapid increase and decrease (5%/min)</td><td></td><td>2000</td></tr>
<tr><td>load change</td><td>step load increase and decrease (± 10%/min)</td><td></td><td>2000</td></tr>
</table>

2. Overview of existing and planned helium circulators and CO_2-circulators

2.1. General overview [2.1 to 2.9]

In addition to the detailed data of the layout of circulators shown later in Table 2.1 through 2.4, there are many different design options as explained in Fig. 2.1. According to this figure, there are theoretically a number of possible combinations. However, in practical application, only some systems have been executed in nuclear plants and test facilities.

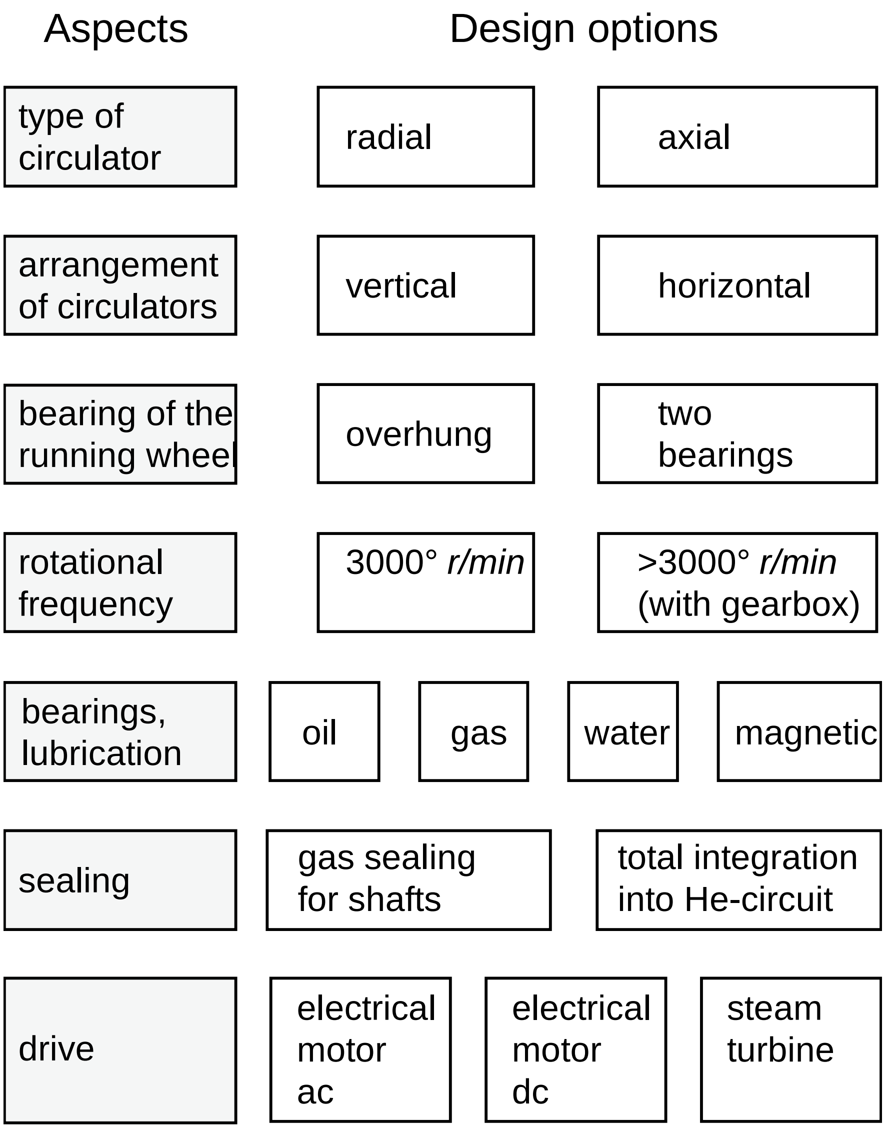


Fig. 2.1: Design aspects of helium circulators

2.2. Helium circulators in built and operated reactors

The main data of these components are summarized in table 2.1. Some additional information on the technical concepts is contained in chapter 3.

Table 2.1: Data of helium circulators that have been built and operated

Plant / Aspect	Dimension	Peach Bottom	Dragon	AVR	THTR	Fort St. Vrain	HTTR	HTR 10
country	--	USA	GB (OECD)	GER	GER	USA	Japan	China
thermal reactor power	*MW*	110	20	46	750	842	30	10
number of loops	--	2	2	1	6	8	1	1
number of circulators	--	2	2	2	6	4	1	1
power of circulators	*MW*	0.17		0.095	2.3	3.95		0.06
helium inlet temp.	*°C*	351		254	250	394		250
mass-flow	*kg/s*	30		7.5	46.25			4.3
pressure	*bar*	30		10	39.2	47.3		30
pressure drop	*bar*	1		0.065	1.1	1		0.06
circulator	--	radial		radial	radial	axial	radial	radial
drive	--	electr. motor		electr motor	electr. motor	electr. motor	electr. motor	electr. motor
arrangement	--	horiz.	horiz.	horiz.	horiz.	vertic.		vertic.
rotat. freq.	*1/min*	3475		4400	5600			
lubrication	--	oil	gas	oil	oil	water	oil	oil
sealing	--	helium	helium	helium	helium	water, helium	helium	helium
support of wheel	--	over-hung	over-hung	over-hung	over-hung	over-hung	over-hung	over-hung

2.3. Helium circulators in proposed reactors

Based on the results of operation of the components contained in table 2.1 in many reactor studies and detailed planning work, helium circulators have been designed and offered by component manufacturers. Table 2.2 contains the principle data used in some of these projects.

Table 2.2: Data of helium circulators planned HTR

Plant / Aspect	Dimen-sion	PR 500	HTR modul	HTRK	HTR 500	PNP 500	MHTGR	HTR 1160	MHTR
country	--	GER	GER	GER	GER	GER	USA	USA	China
thermal reactor power	*MW*	500	200	3000	1250	500	350	3000	450
number of loops	--	3	1	6	6	2	1	4	1 (2)
number of circulators	--	3	1	6	6	2	1	4	1 (2)
power of circulators	*MW*	2.4	2.5	6.6		27	3.2	10.67	
He inlet temp.	*°C*	250	250	260	250	293	255	311	250
mass-flow	*kg/s*	53.5	85.5	220		73.8	158		
pressure	*bar*	40	59.5	60		40	62.9	48.5	
pressure drop	*bar*	1.1	1.5	1.3		1.15	1	1.45	
circulator type	--	radial	radial	radial	radial	radial	axial	axial	axial
drive	--	electr. motor	electr. motor	electr. motor	electr. motor	electr. motor	electr. motor	electr. motor	electr. motor
arrangement	--	vertic.	vertic.	vertic.	vertic.	vertic.	vertic.	vertic	vertic.
rotational freq.	*1/min*	3000	3000	3000	3000	3000	6200		
lubrication	--	oil	oil	oil	oil	oil	magnetic bearings	water	oil
sealing		gas	gas	gas	gas	gas	gas	water heliu m	gas
support of wheel		over-hung	over-hung	over-hung	over-hung	over-hung	over-hung	over-hung	over-hung

2.4. Helium circulators in helium test facilities

The large helium test facilities that were built and operated in German HTR-projects contained helium circulators also. Table 2.3 contains some data of these machines. Additionally, two helium compressors that have been applied in gas turbine plants, the EVO and the HHV, are listed here.

Table 2.3: Data of helium circulators and helium compressors tested in large helium test facilities

Plant / Aspect	Dimension	EVO	HHV	KVK	EVA II	WKV
country	--	GER	GER	GER	GER	GER
thermal power of test facilities	*MW*	150	45	10	10	5
number of loops	--	1	1	1	1	1
number of circulators	--	1	1	1	1	1
circulator power	*MW*		45			
helium inlet temp.	*°C*			250	250	250
mass-flow	*kg/s*					
pressure	*bar*	30	60	40	40	40
pressure drop	*bar*					
type of circulation	--	axial	axial	radial	radial	radial
drive	--	turbine	electr. motor	electr. motor	electr. motor	electr. motor
arrangement	--	horiz.	horiz.	horiz.	horiz.	horiz.
rotational freq.	*1/min*					
lubrication	--	oil	oil	oil	oil	oil
sealing	--	gas	gas	gas	gas	gas
wheel support	--	2 bearings	2 bearings	over-hung	over-hung	over-hung

2.5. Circulators in CO_2-cooled reactors for technical comparison

Many circulators have been operated in CO_2-cooled reactors and are still in successful operation. Overall, the data of more than 100 machines of this type with many years of operation is available today.

Table 2.4: Data of circulators in CO_2-cooled reactors

Plant / Aspect	Dimension	Magnox 1	Magnox 2	WAGR	AGR
country	--	GB	GB (Hinkley Point)	GB	GB
thermal power of reactor	*MW*		250	100	1600
number of loops	--		6	4	8
number of circulators	--		6	4	8
power of circulators	*MW*		5		4,8
CO_2 inlet temp.	*°C*		180	250…325	273
mass-flow	*kg/s (m³/s)*			170	(12)
pressure	*bar*				39,5
pressure drop	*bar*				2,5
circulator	--		axial	radial	radial
drive	--	electr. motor	electr. motor	electr. motor	electr. motor
arrangement	--			vertical	
rotational freq.	1/*min*				
lubrication	--	oil	oil	oil	oil
sealing	--	gas	gas	gas	gas
wheel support	--	overhung	overhung	overhung	overhung

3. Detailed explanation of helium circulators in built and operated reactors [3.1 to 3.24]

3.1. AVR

The AVR has two helium circulators (Fig. 3.1). They are arranged in the bottom part of the reactor vessel (Fig. 3.2). Each circulator consists from an asynchronous motor in oil lubricated sliding bearings and a fan wheel in overhung position on the motor shaft. Labyrinths and a barrier gas system prevent the oil from making its way into the cooling gas circuit and the cooling gas from penetrating the motor housing. The speed is set via a frequency converter. The circulators are designed for maintenance-free operation. Apart from a bearing change in 1979, which made it necessary to dismount a circulator, these machines ran without any maintenance for 20 years without problems.

After a damage occurred in a steam generator, both machines were submerged to the axles in water. During maintenance work to repair the damage, cooling water made its way into the bearing oil system via a loose screw fitting. As a result, one of the circulators had to be dismounted. The dismounting of the blower and replacement of the bearing were carried out without any major problems. The blower showed no signs of damage due to age and was determined to be in very good condition.

Switching off the helium circulators was one of the methods applied to stop the reactor. This is the gentlest and slowest shut-down procedure. It was always used when a regular shut-down of the reactor was intended. The rods initially remained in their normal position and were not moved into the core until the reactor had cooled down substantially. As in other shut-down procedures, the feed water mass flow was set at approximately 40% and the circulator started up again step-by-step after approximately three hours.

Load alterations in the AVR only involved minor temperature changes in the core and the reflector, the boundary for the speed of the change being set solely by the maximum possible speed change of the blowers. The load reduction from 100 to 50% was performed in two minutes. In principle, changes would have been possible at the same speed if the output had been raised. However, the fact that changing the circulator’s speed determined the amount of energy to be withdrawn had to be taken into consideration. The core performance was then automatically adjusted via the negative temperature coefficient. Due to the inertia forces in the system, overshooting of the output occurred. If the output were raised inaccurately, this overshooting could lead to the boundary value for the maximum permissible output being reached and the reactor being shut down automatically.

It has been demonstrated experimentally that, after a simultaneous failure of the cooling gas circulator during power operations and the shut-down facility, the reactor shuts down automatically and remains sub-critical for approximately one day. The temperatures of the fuel remain within the range of temperatures prevailing during operation.

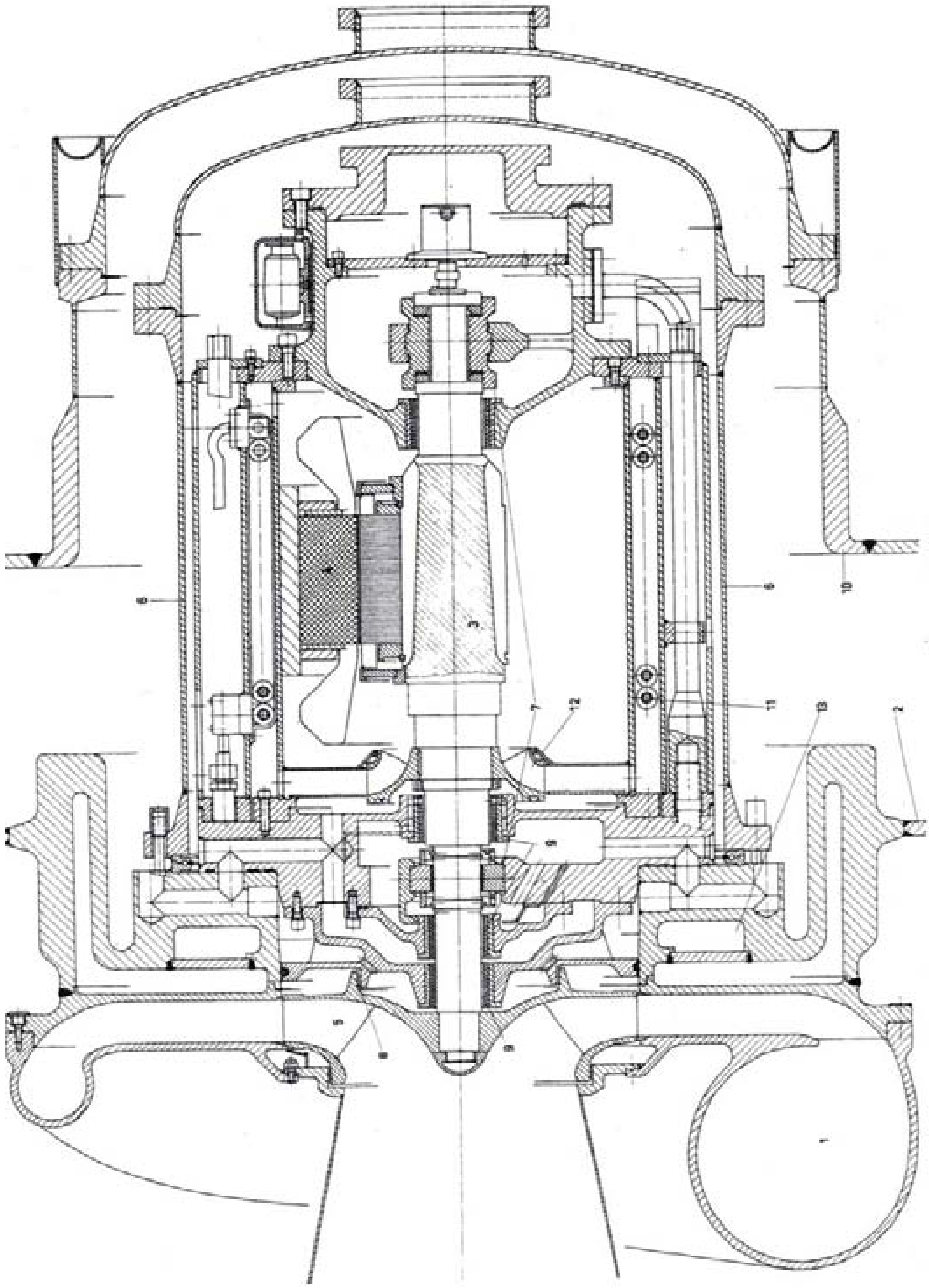
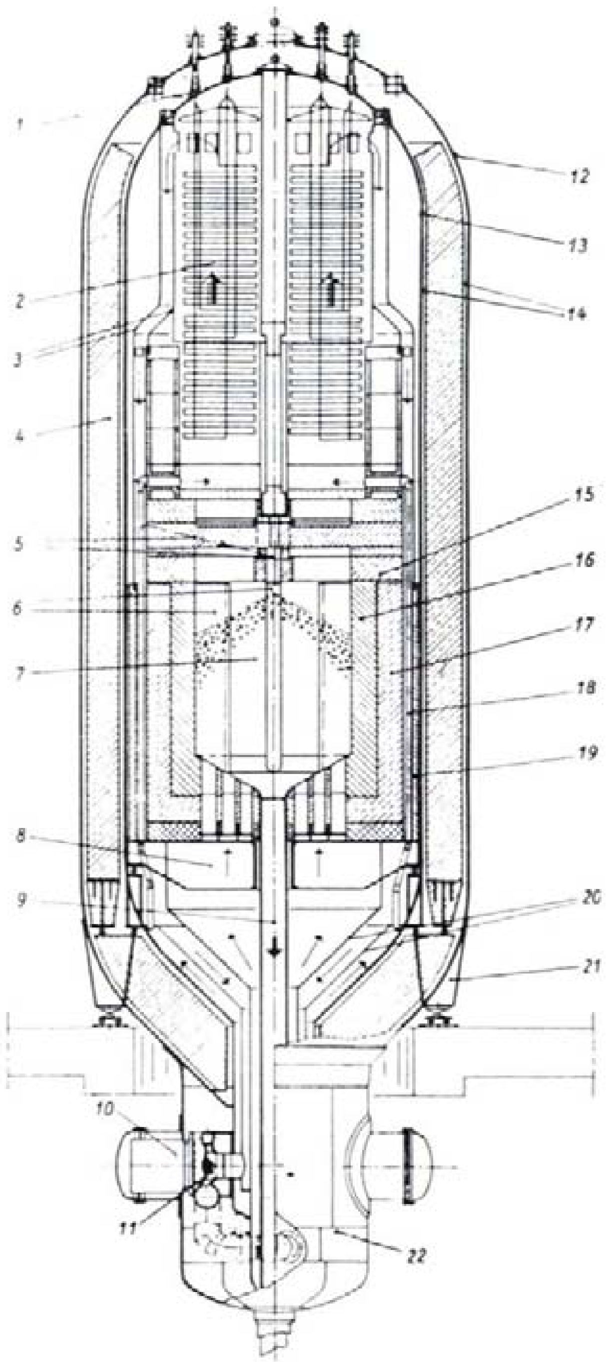


Fig. 3.1: Helium circulator of AVR

1: pressure spiral housing 2: inner dome of circulator 3: shaft 4: electrical drive motor 5: wheel of circulator 6: inner vessel of circulator 7: bearing 8: labyrinth 9: labyrinth sealings 10: outer vessel of circulator 11: water cooling of drive motor 12: wheel of circulation of sealing gas 13: room for water cooling



1 openings of sveral steam generators pipes
2 steam generator
3 cooling for gas ducts
4 biological shield
5 inlet for spherical fuel elements
6 lugs ofshut down rods
7 core
8 supporting grate
9 outlet for spherical fuel elements
10 driving motor
11 blower
12 reactor vessel II
13 reactor vessel I
14 gap für insulating gas
15 amorphous coal brigde
16 reflector graphite
17 amorphous coal shield
18 by-pass tubes
19 thermal shield
20 cooling gas ducts
21 footing
22 blower dome

Fig. 3.2: Arrangement of primary system of AVR and positioning of the helium circulators at the bottom of the reactor pressure vessel

Fig. 3.3 contains a view to the inside of the reactor building. When maintenance or inspection are necessary, accessing the two circulators is simple. Tools for maintenance and repair of the circulators have been developed and tested.

Overall the 20 year of operation of the AVR-circulators demonstrated, that this type of machines can be operated with very high availability and excellent load following characteristics in helium cycles.

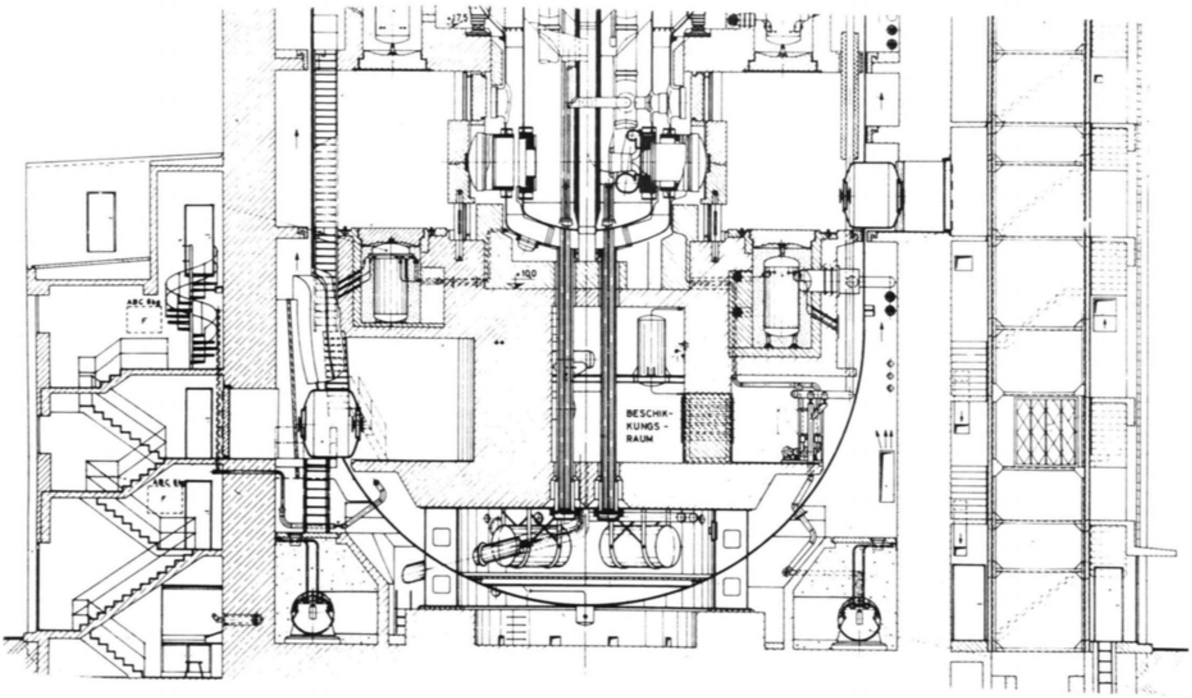


Fig. 3.3: Access to the helium circulators of AVR using lock system inside the reactor

3.2. THTR

In the THTR (Figure 3.4), the helium coolant gas is circulated by six parallel-flow coolant circulators, each connected to a steam generator. The circulators carry the coolant gas from the steam generator to the pressure space common to all circuits. The circulators are anchored radially to each steam generator via holes in the cylindrical PCRV wall. All system lines for coolant water, oil, gas, power, and measuring instruments are radially passed through a hole in the liner flange.

In the THTR, all surfaces of the primary pressure boundary are cooled by cold helium (250°*C*). To protect the liner and the and the concrete structure, the liner is insulated by a metallic foil insulation system with a metallic cover plate an the helium side. The circulator unit is shown in detail in figure 3.5.

The circulator rotor, the drive motor with coolers, and the shut-off and control valve, including the drive of each of the components, are integrated into one insertable unit. The motor operates in a helium atmosphere under the respective reactor pressure of around 40 *bar*.

The single-stage radial wheel is mounted on the motor shaft in an overhung position. The shaft bearings are lubricated and cooled by oil. A sealing gas system supplied with pure helium prevents oil from leaking into the primary coolant circuit as well as activated coolant gas from leaking into the oil circuit. The oil supply system, specifically the oil container, the oil cooler, and the valves, is located outside the PCRV. It works under reactor pressure and is connected to the circulator through service lines.

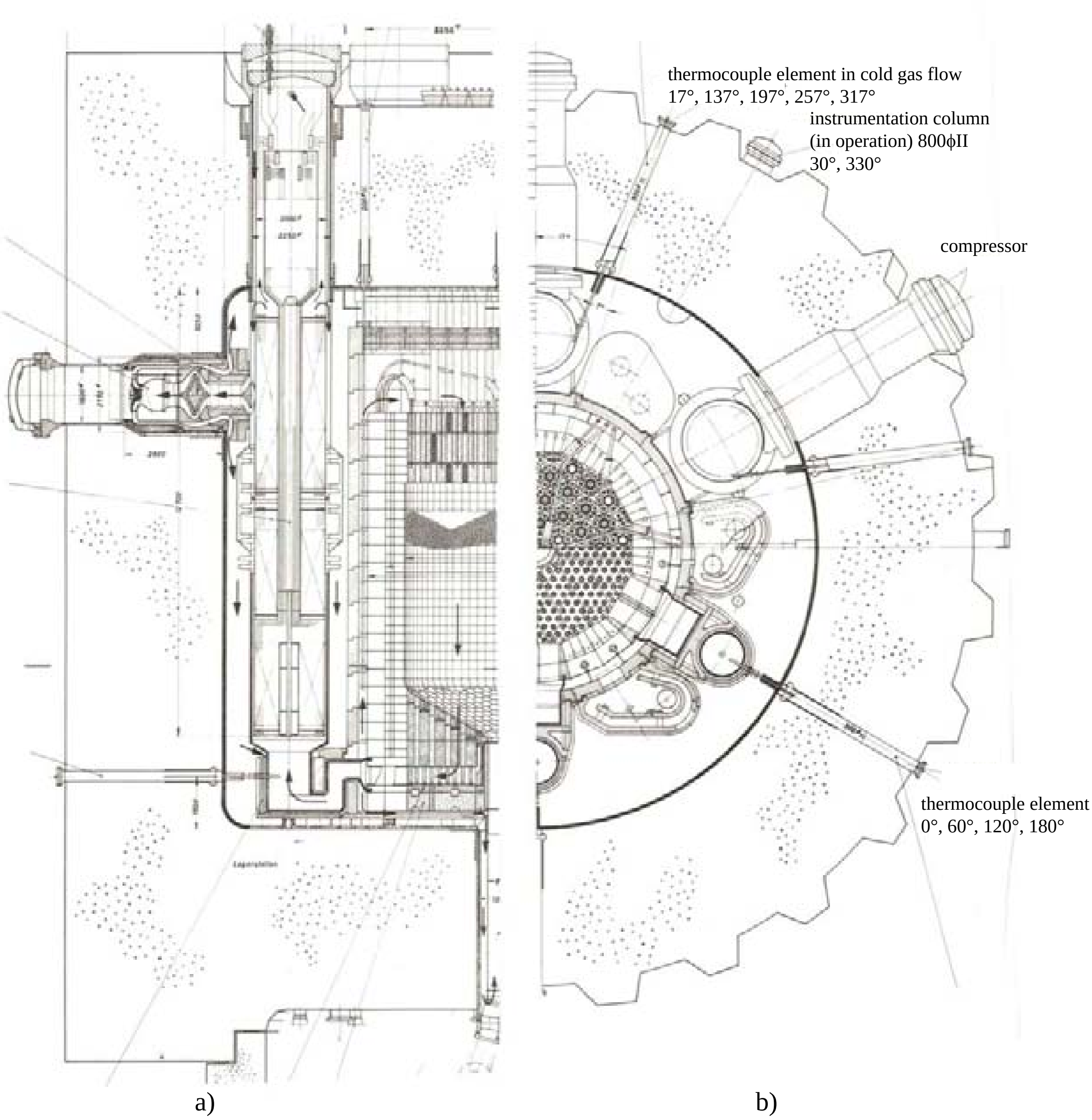


Fig. 3.4: Arrangement of helium circulators of THTR in the wall of the reactor pressure vessel: a) vertical section b) horizontal section

The shut-off and control valve located on the intake side of the circulator has a hydraulic drive mechanism. It serves for individual control of the delivery of the coolant gas circulator and ensures the following functions:

- setting of a minimum coolant gas flow during start-up of an individual steam generator – circulator unit during operation of the other units
- plugging of a shut-off steam generator-circulator unit on the coolant gas side, with the possibility of setting a regulable backflow of cold coolant gas through the shut-off steam generator
- throttling to a lower coolant gas flow rate through a steam generator at constant circulator speed, e.g. during removal of decay heat

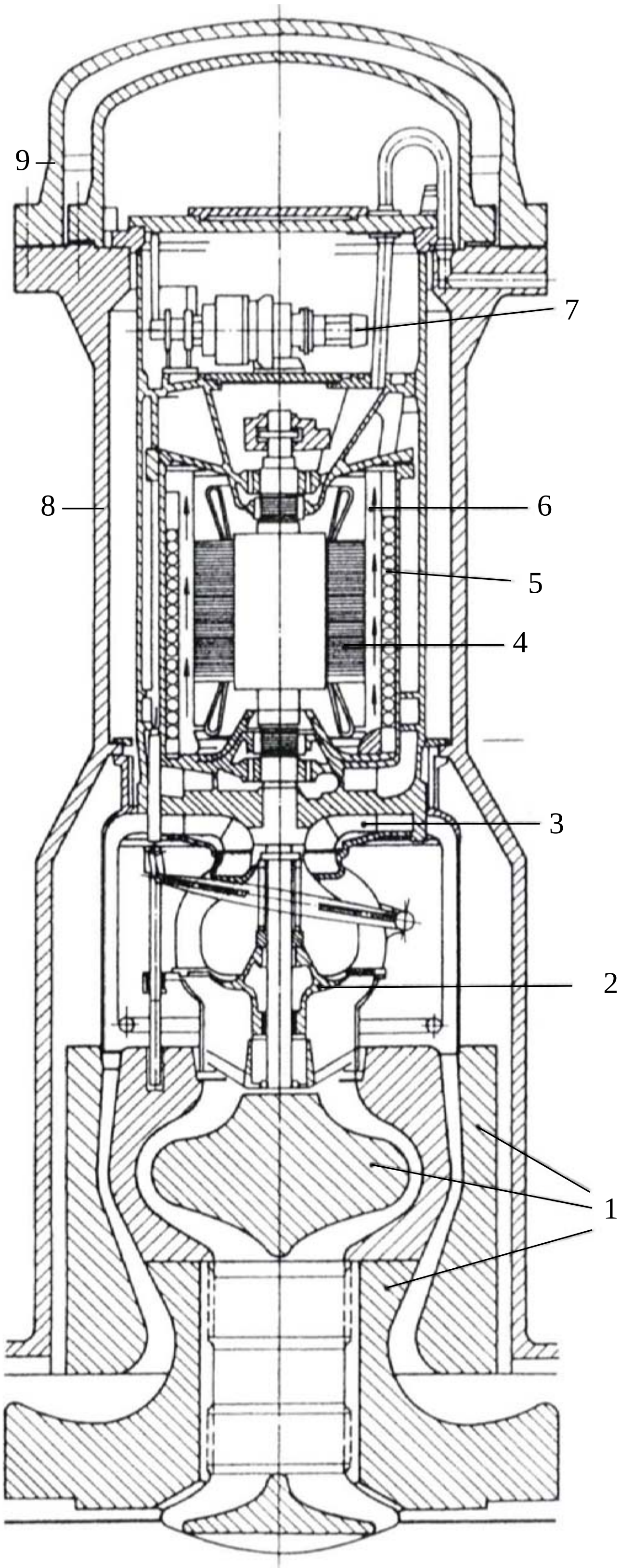


Fig. 3.5: Helium circulator of THTR: (1: neutron shielding 2: bypass flap 3: wheel 4: electromotor 5: motor cooler 6: cooling water channels 7: servomotor 8: shutter tube 9: double walled closure)

The circulator is driven by a bipolar three-phase squirrel cage motor characterized by a simple design and high operating reliability. In the power range of the nuclear power plant, the delivery of the circulators is controlled by varying the motor speed in the range of 3000 to 5600 min^{-1}. Three circulators are each fed by one turbo generator. In case of failure of the turbosets, switching-over to operation with electricity from other sources is possible (const. 50 *Hz*).

The circulator has an inner efficiency of 84.5% and an nominal electrical power of 2300 kW_{el}. All the criteria were fulfilled and the six helium circulators operated excellently during the whole operation of the THTR. Fig. 3.6 contains a comparison of calculated and measured values.

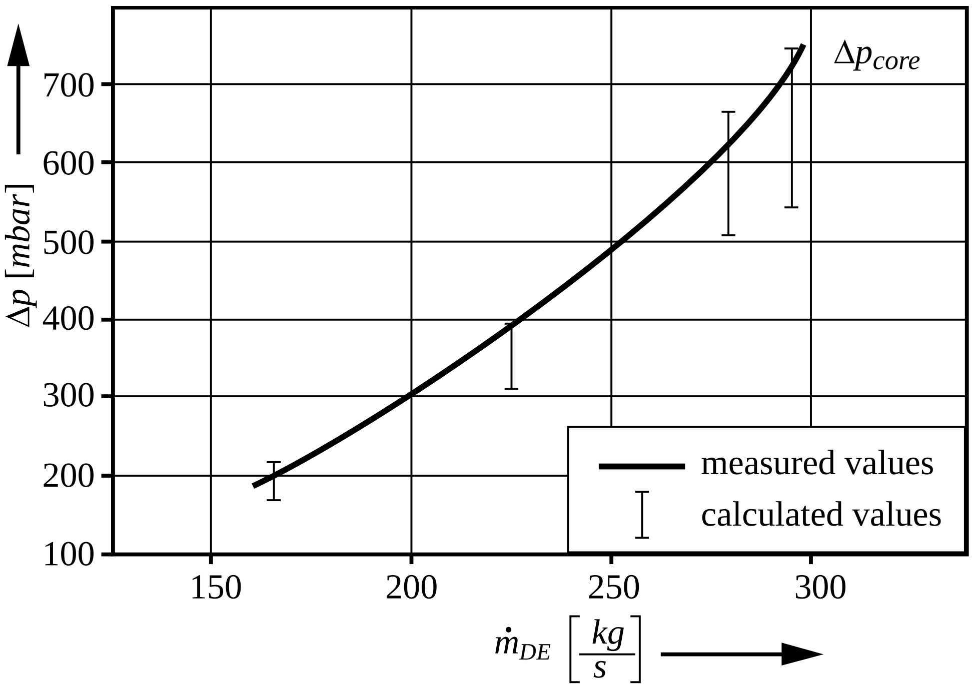


Fig. 3.6: Comparison of calculated and measured data of THTR with regard to pressure drop, helium mass flow, and power of circulators

The deviations between measured and calculated values of pressure drop dependent from the mass flow is relatively small. This knowledge allows the design of circulators for other helium cooled plants.

During the operation of THTR many experiments have been carried out.

Some characteristics of operation of the THTR-circulator are illustrated by Fig. 3.7. The point A is where the plant is working at nominal values. The power at the shaft (~ 2000 kW_{el}) is measured at a flow rate of 10 m^3 helium /*s*.

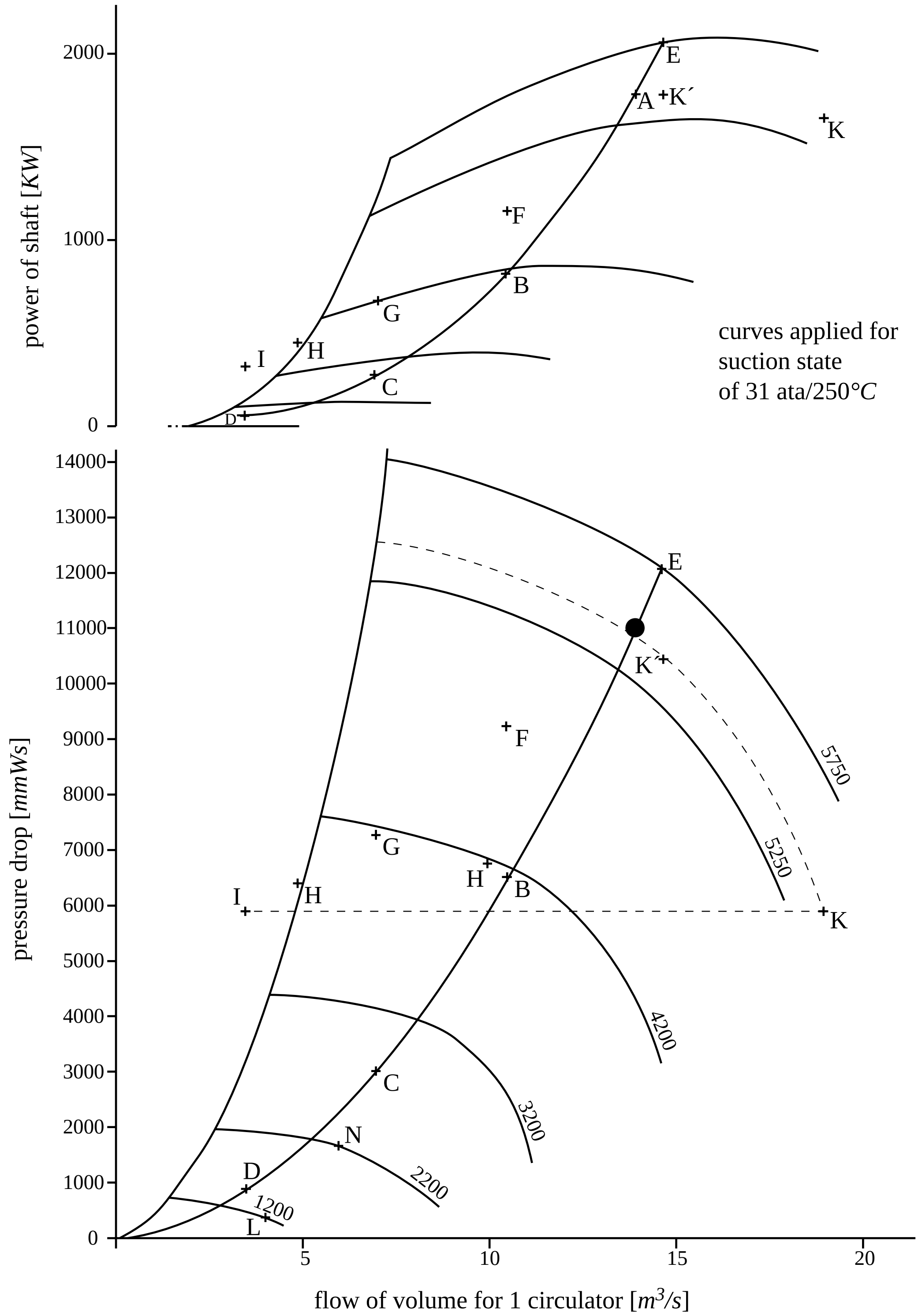


Fig. 3.7: Characteristics of the THTR-circulator (for the design point: $p_{inlet} = 38.9\ at$, $T_{inlet} = 250°C$, $\dot{m} = 49.25\ kg/s$, $\dot{v} = 14\ m^3/s$, $\Delta p = 11000\ mmWs$)

More details regarding the design of the circulator can be seen in Fig. 3.8. The technical details of the inlet part of the component, the flap for flow restriction, the wheel, and the bearing system are shown in this picture. Specific design conditions were determined by the integration of the circulator unit together with the drive into the wall of the reactor pressure vessel.

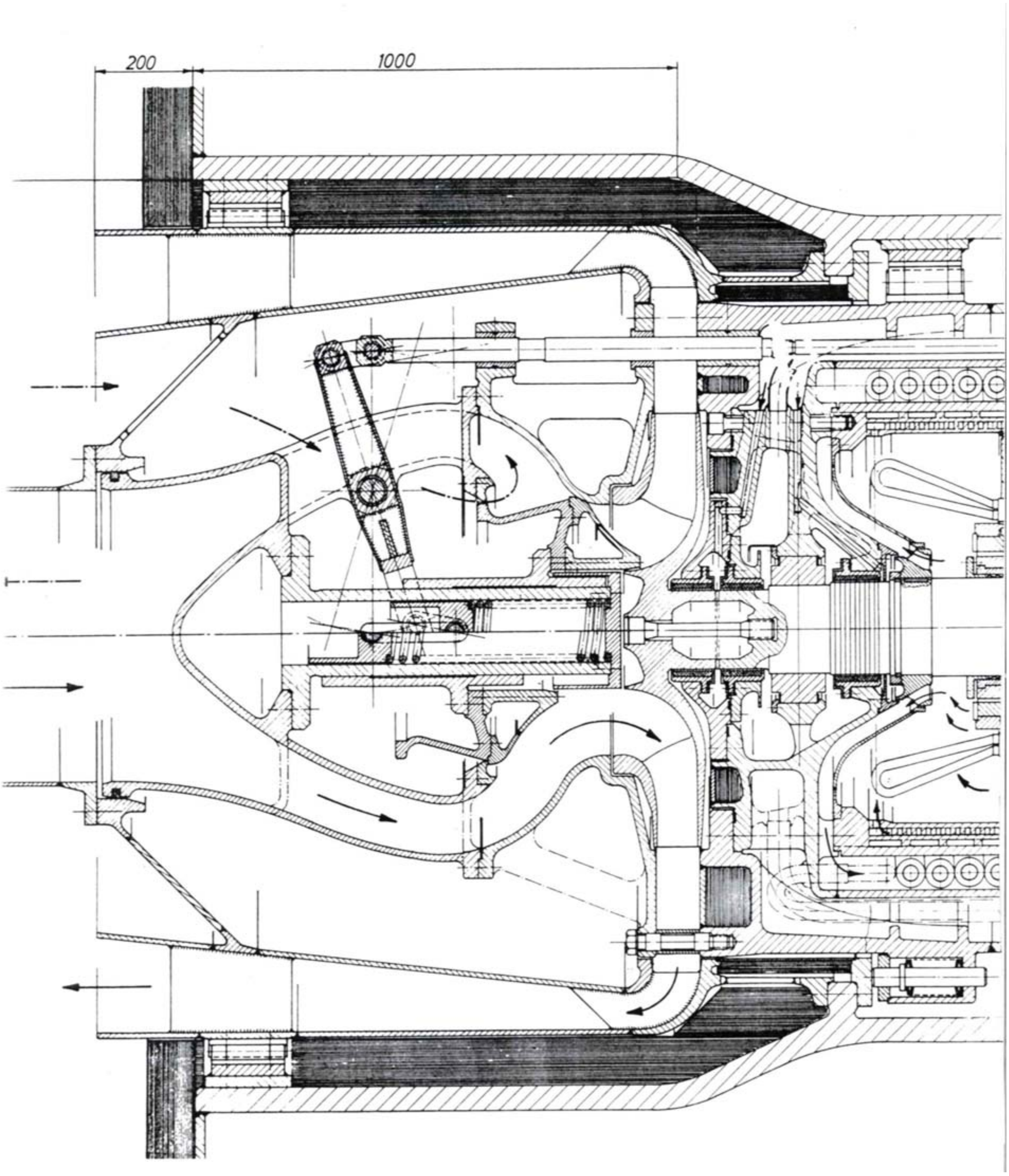


Fig. 3.8: Detailed drawing of the helium circulator of THTR

3.3. Dragon reactor

In the Dragon reactor, helium circulators with gas bearings have been used. Fig. 3.9 shows the component including the electrical drive device. It is also a one-stage radial compressor with a wheel in overhung arrangement.

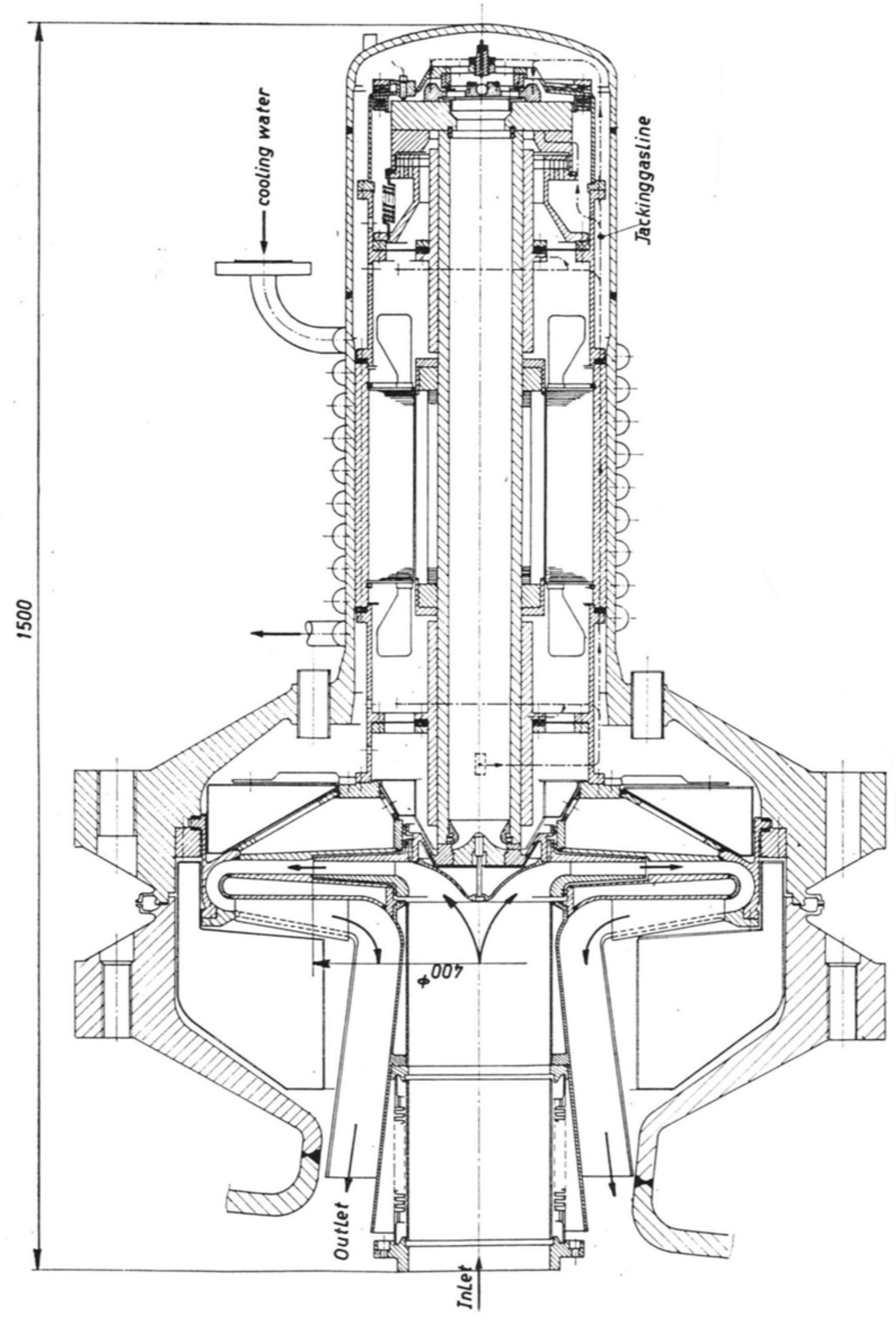


Fig. 3.9: Helium circulator of Dragon reactor

The electrical motor is completely integrated into the helium cycle. The reactor contains two steam generators, each connected to a separate helium circulator (Fig. 3.10a). The reactor (Fig. 3.10b) had been operated for more than 15 years successfully, and the new technology of gas bearings showed a very good operating behaviour and high availability.

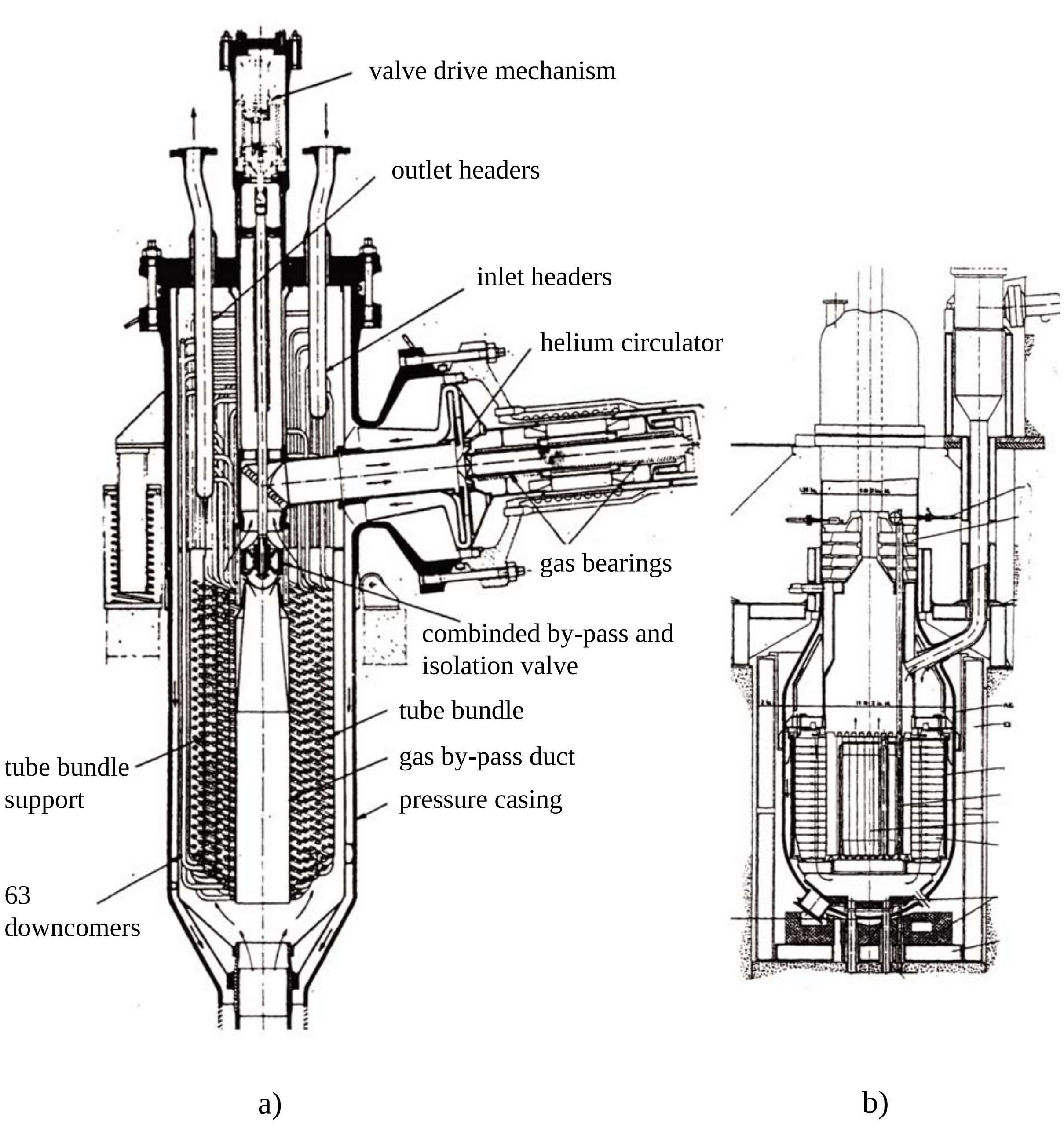


Fig. 3.10 Steam generator – helium circulator units in the Dragon reactor
a) unit consisting of steam generator and circulator arrangement of primary circuit
b) arrangement of the units in the reactor system

3.4. Peach Bottom

Peach Bottom was the experimental reactor for the HTR-reactor line un the USA.

The flow sheet of this first helium-cooled HTR is shown in Fig. 3.11. The total helium flow of around 60 *kg/s* is circulated by two helium circulators, which operate at an inlet temperature of 350*°C*. The design pressure is 35 *bar*. The two independent loops each contain a steam generator and a helium circulator (Fig. 3.12, Fig. 3.13). These components are designed as single-stage centrifugal machines. They are driven by an electrical motor and a variable-speed-fluid coupling. Small auxiliary motors are provided to run the compressors at slower speed, when the heat production in the core is low, or during phases where the core was shut down and decay heat removal took place.

There was a special solution for the transport of hot gas from the core to the steam generator compared to earlier gas cooled reactors. The steel piping connecting the reactor vessel with the steam generators is in the form of two concentric pipes, with the hot coolant flowing through the inner pipe and the cool helium returning to the reactor through the outer annular space. The inner pipes are lined with stainless steel and a thermal insulation to maintain the wall of the pipe at an acceptable temperature.

Isolation valves are provided in the coolant pipes so that either one of the main coolant loops can be shut off from the reactor in the event of malfunctions or for maintenance. Measuring systems are provided to monitor the concentrations of various impurities in the main coolant gas.

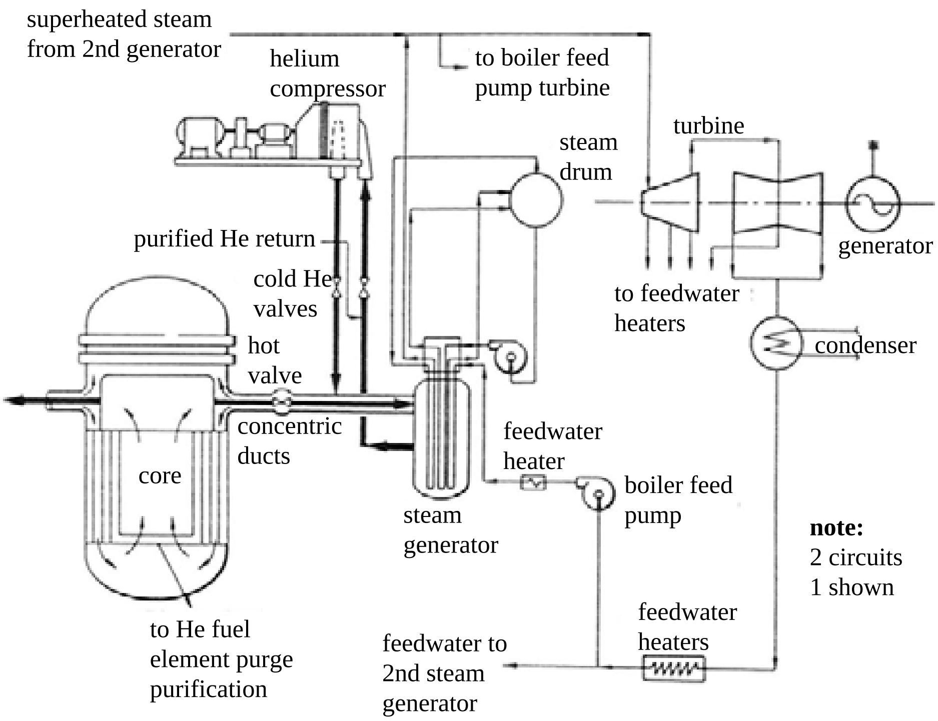


Fig. 3.11: Flows sheet of Peach Bottom reactor

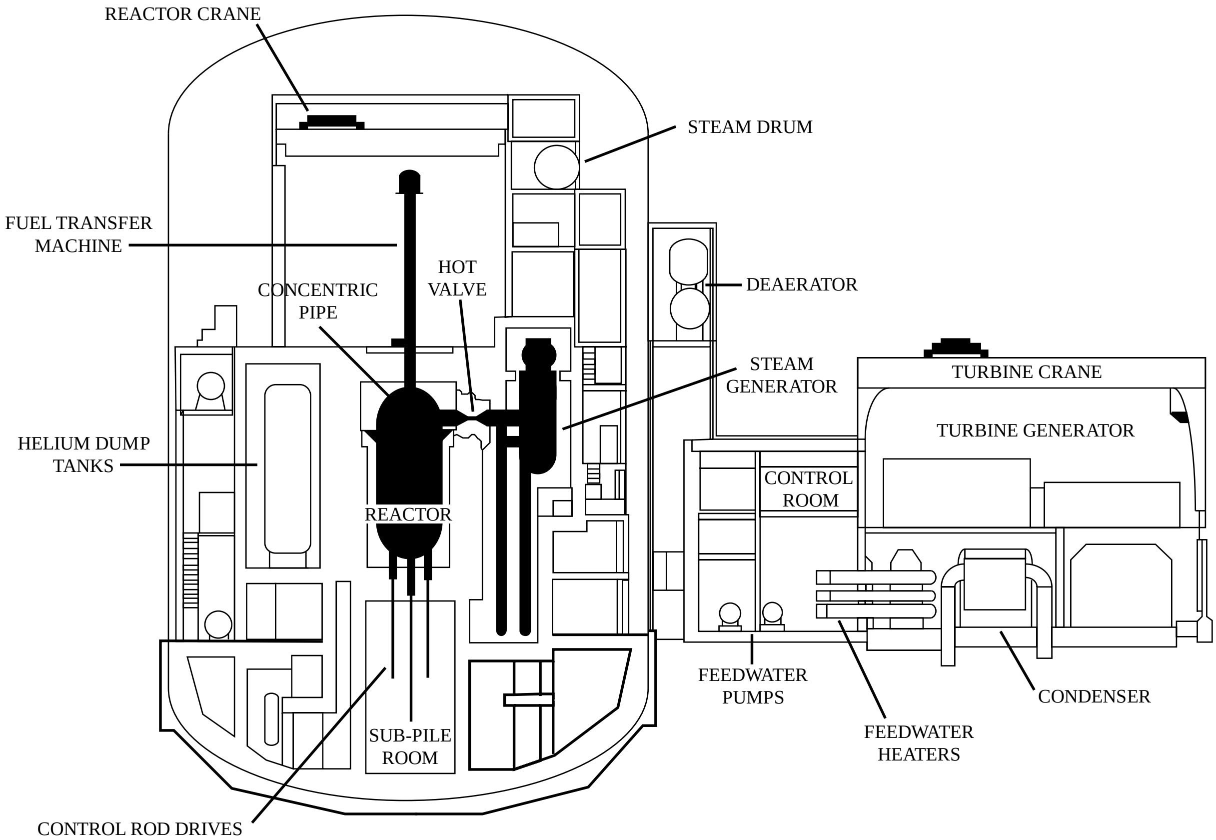


Fig. 3.12: Section through the total plant of the Peach Bottom reactor

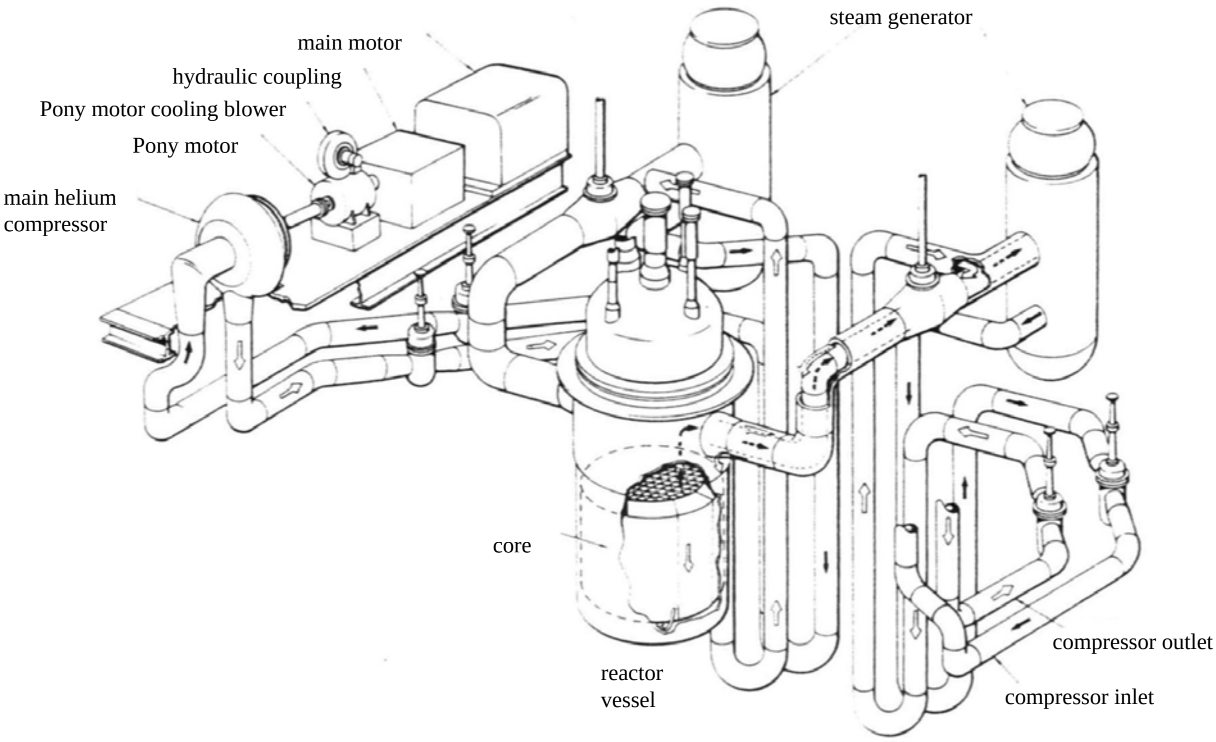


Fig. 3.13: Arrangement of primary components of Peach Bottom reactor

3.5. Fort St. Vrain

In the Fort St. Vrain reactor 12 steam generators were operated. Four helium circulators were installed to move the primary coolant through the reactor system. Fig. 3.14 shows the arrangement of these components at the bottom of the prestressed concrete reactor pressure vessel and indicates the flow of the helium.

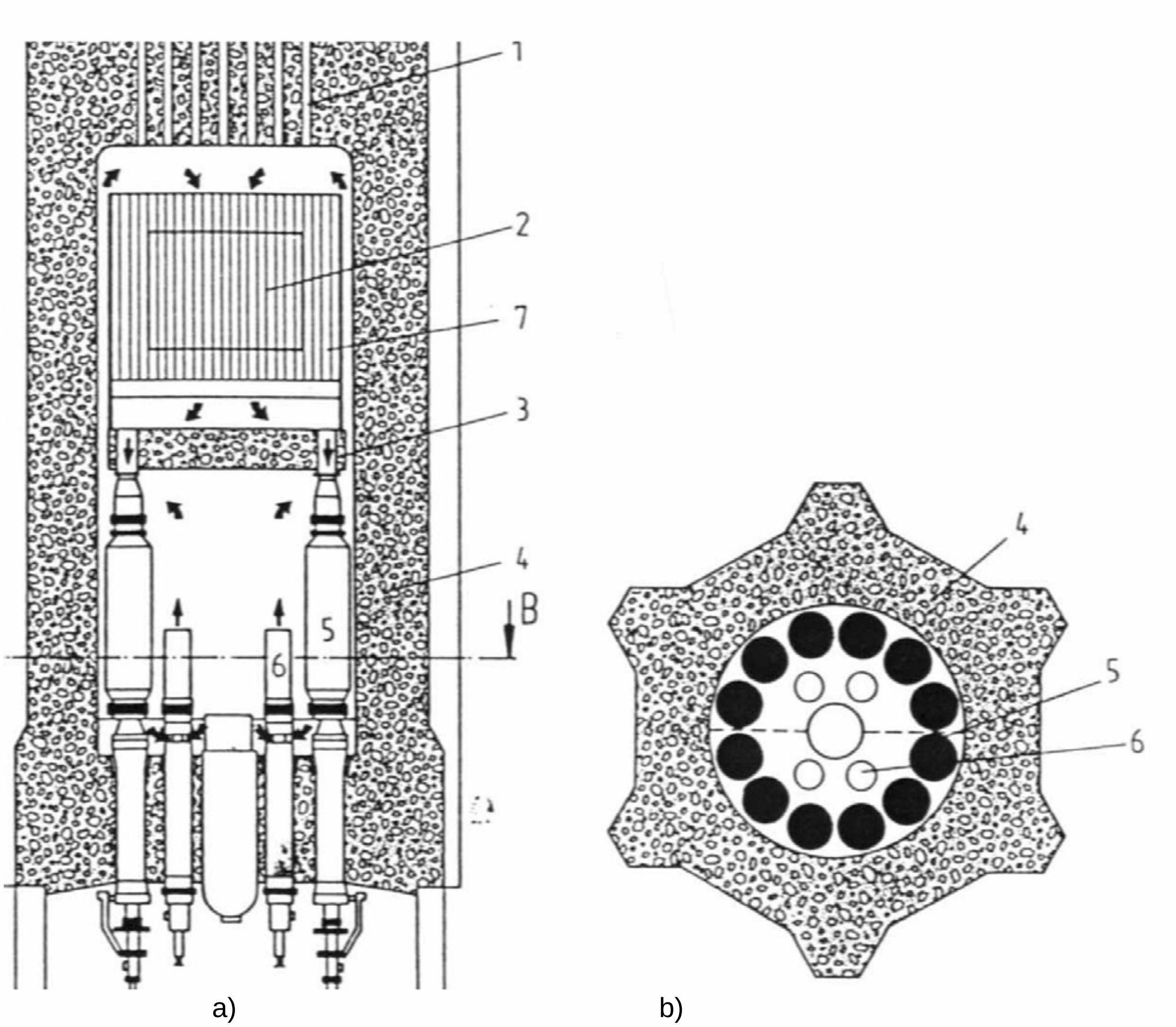


Fig. 3.14: Arrangement of primary components in the Fort St. Vrain reactor
a) vertical section
b) horizontal section
(1: shutdown rods 2: core 3: hot gas duct 4: reactor pressure vessel 5: team generator 6: helium circulator 7: graphite reflector)

Each of the four helium circulators (Fig. 3.15) consists of a single-stage axial-flow compressor, a single-stage steam-turbine as the main drive, and a single water-turbine as auxiliary drive. They are used to supply power to the circulator when the steam supply is either not available or not desirable. The steam-turbine drives are in series with the main turbine and normally operate on cold reheat steam with each circulator accepting an equal portion of the total reheat steam flow.

The helium compressor and the two drive turbines are mounted integrally on a single vertical shaft and overhung from a central bearing and seal section. A helium stop valve on the discharge side of each helium circulator prevents backflow through the circulator when it is not in operation.

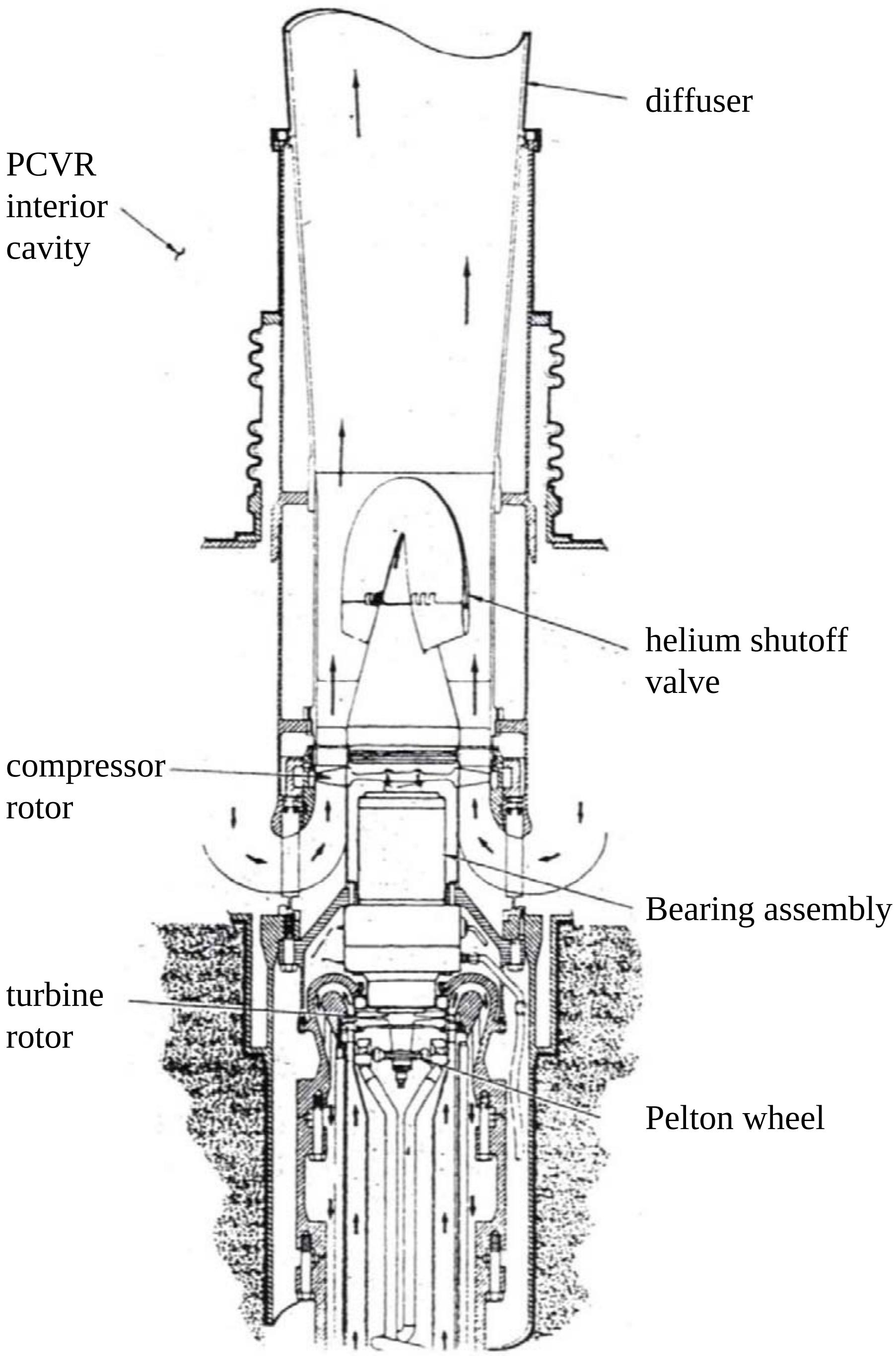


Fig. 3.15: Positioning of the helium circulator and the steam turbine drive in the wall of the reactor pressure vessel and in the primary circuit

The steam-turbine drives are normally supplied with cold reheat steam from the main turbine, but saturated steam from the bypass flash tank or steam from the auxiliary boiler may be used too. High-pressure water can be provided in emergencies from the feed water system, or if necessary from the condensate or fire water systems to the auxiliary pelton-wheel drive.

Circulator speed is controlled by a steam-turbine throttle and by several bypass valves in the circulators. The operating characteristics of the circulators are such that at part-load plant operation there is excess steam which must be bypassed around the circulator turbines. Thus, to achieve proper system control and to permit individual and independent control of each circulator, throttle and bypass valves are provided in the steam supply lines to the circulator.

The sealings between the helium circuit and the area of the steam turbine require special designs. For example, this system sometimes caused operation problems of the reactor. Fig. 3.16 shows the details of the positioning of the circulator together with this very special drive system. Fig. 3.17 includes a view to the axial flow compressor wheels and on the whole compeonent.

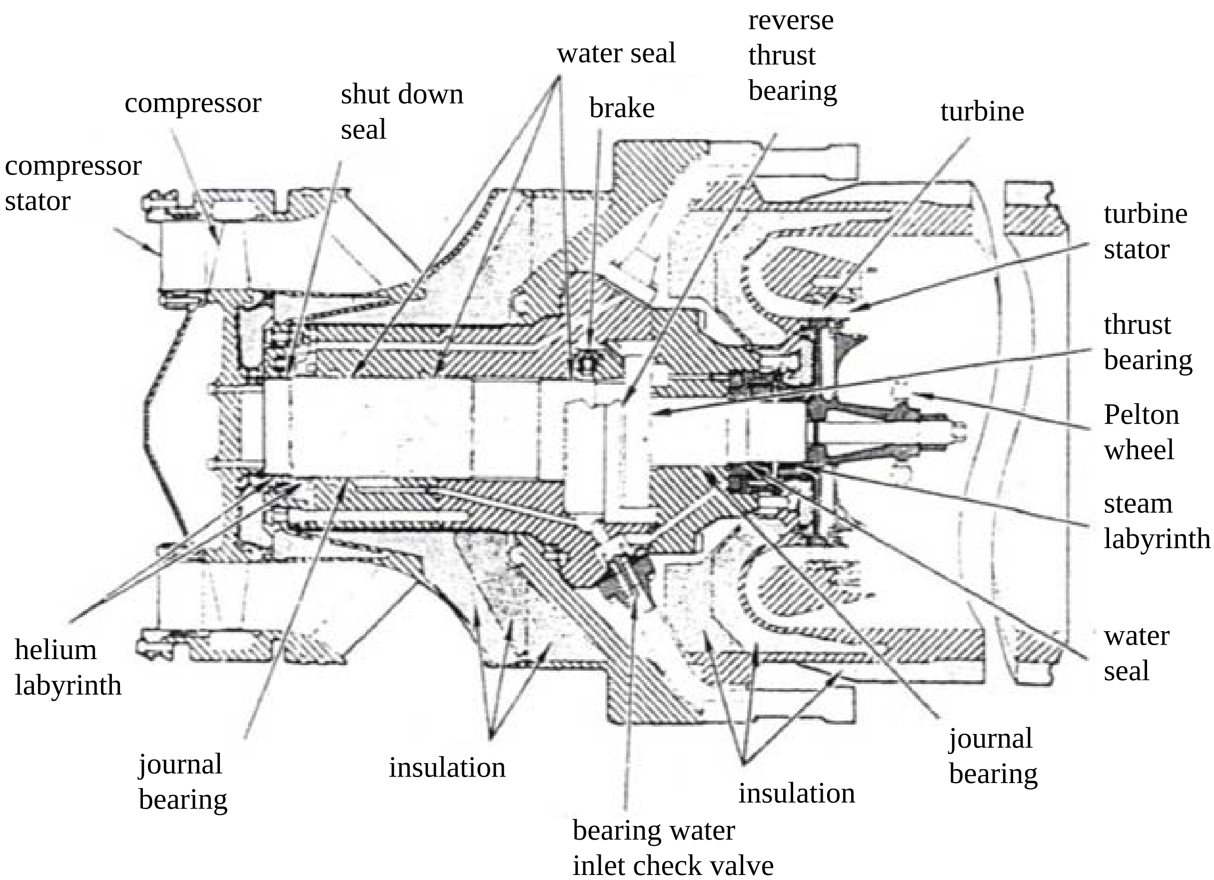
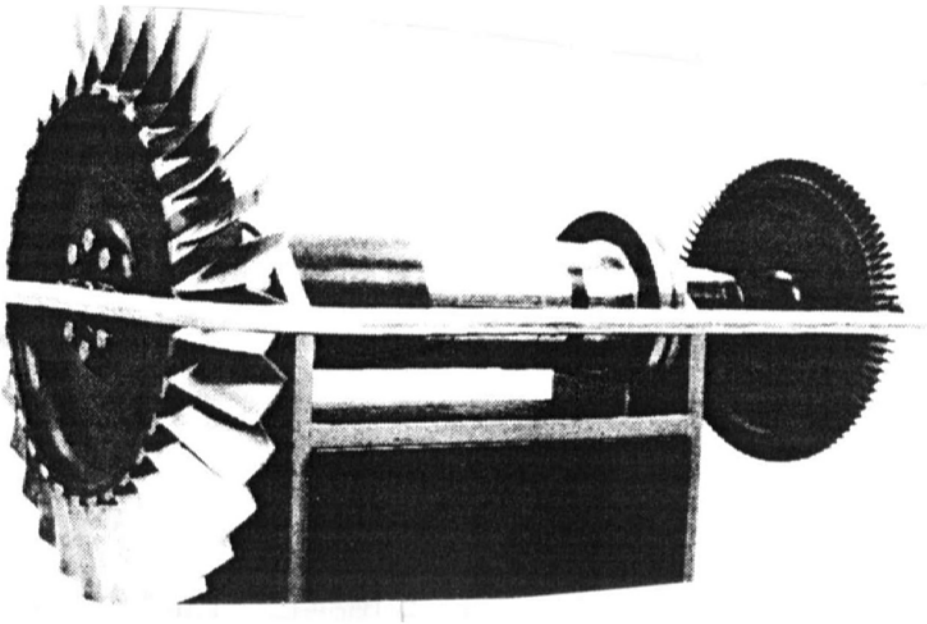


Fig. 3.16: Fort St. Vrain circulators, section through the component



a)

b)

Fig. 3.17: Helium circulators of Fort St. Vrain
a) view of the axial flow compressor
b) view of the whole component

3.6. HTR 10

The helium circulator of the HTR 10 circulates the main flow through the primary system, as indicated in Fig. 3.18. It has no safety function because it is only installed for normal operational function and to start and shut down the reactor. Together with the steam generator, it forms the normal cooling system of this reactor. The final cooling concept in this reactor uses the well known concept of self acting decay heat removal.

The circulator is a single shaft centrifugal machine built in vertical arrangement at the top of the steam generator. The drive is an electrical motor, which is totally integrated into the primary helium circuit (Fig. 3.19).

On the suction side of the circulator there is a valve between the steam generator outlet and the circulator inlet to control the flow.

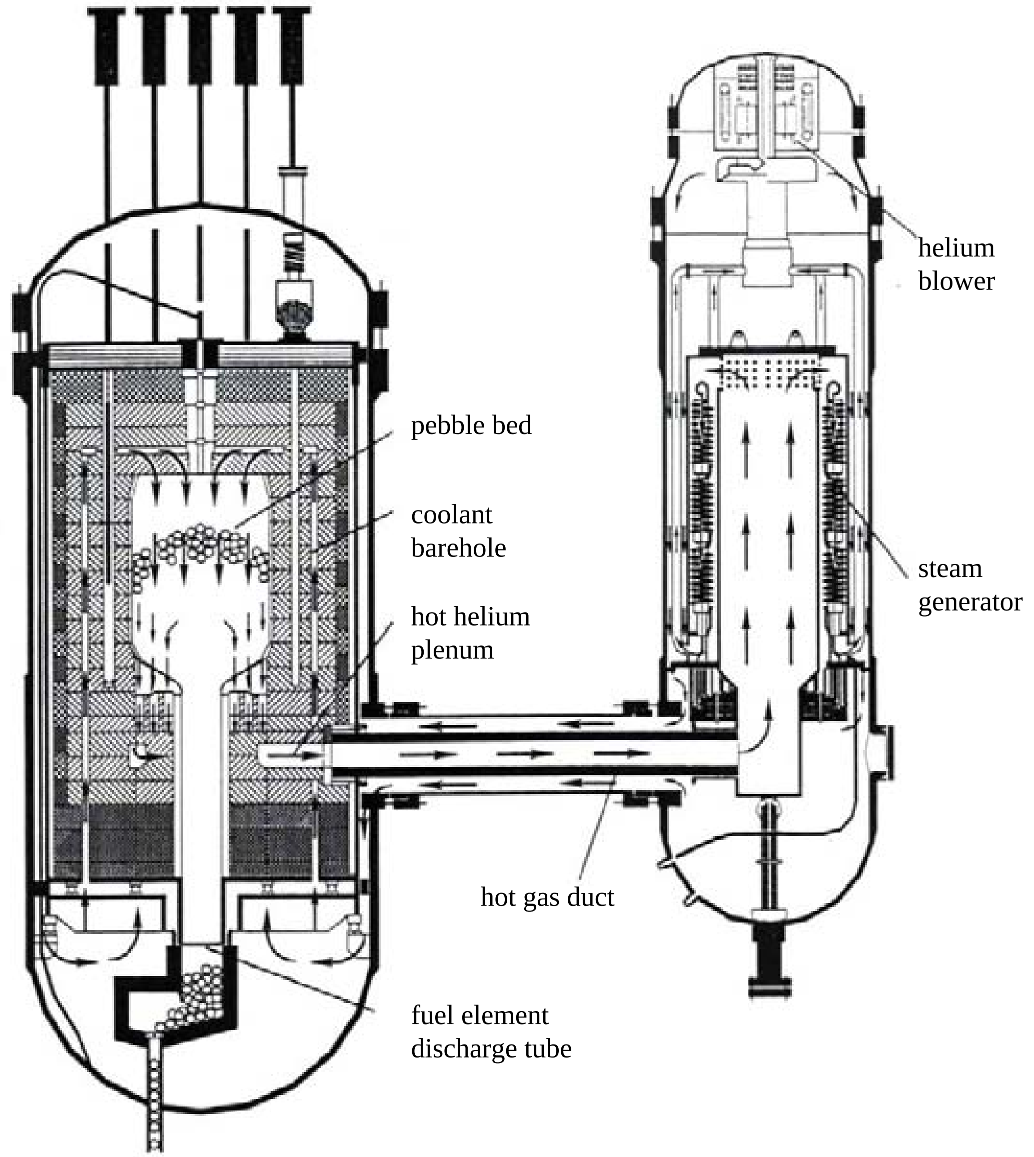


Fig. 3.18: Flow sheet of primary circuit of HTR10 and arrangement of helium circulator

Both the circulator and the steam generator are located in the steam generator pressure vessel. Flanges connect two parts of the pressure vessel with an end cap on the top of the circulator's part of the pressure vessel. An intermediate flange is used to connect the circulator to the pressure vessel. The cavity above the flange is for the motor, the one below for the circulator. Both cavities contain primary circuit's helium, but a labyrinth of the intermediate flange's shaft perforation prevents the two parts from direct gas flow.

The circulator bearings must withstand the operational requirement. The upper bearing is a journal-thrust combination, and the lower one is a single journal.

The drive motor is cooled by an auxiliary impeller to drive the helium. The cooling water of the gas cooler then removes the heat from the circulator pressure vessel. Cooling water also passes through the oil cooler of the bearing oil boxes in order to remove heat.

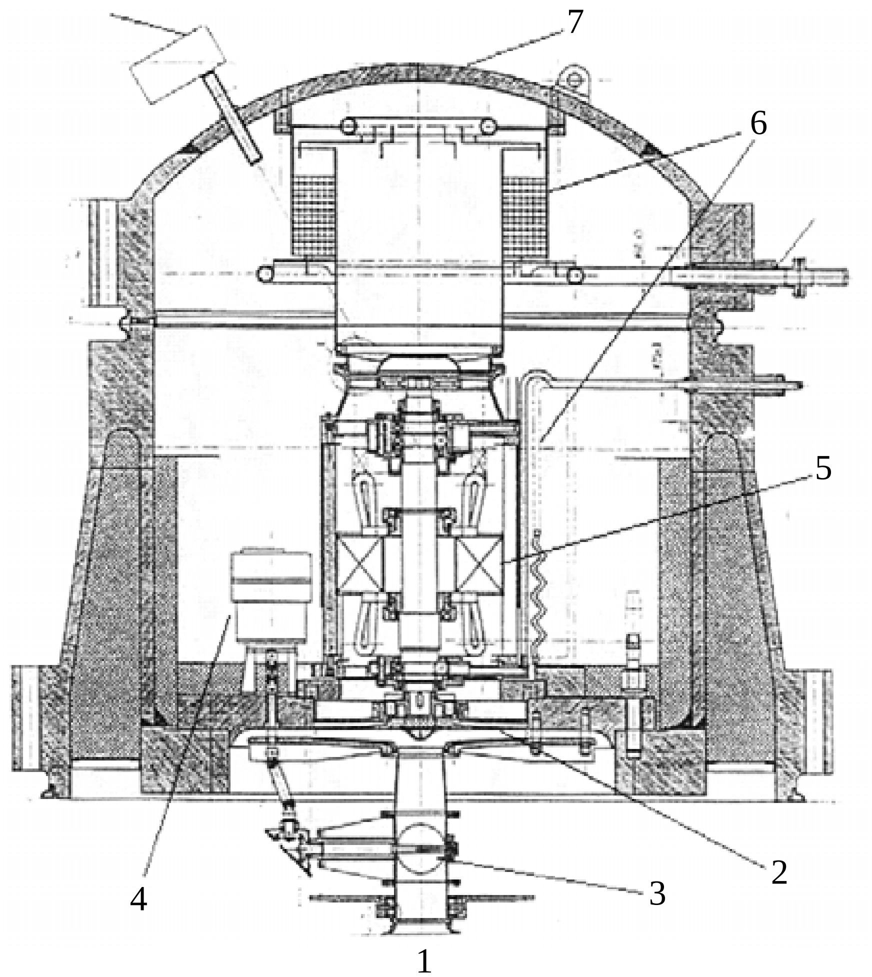


Fig. 3.19: Helium circulator of HTR 10
(1: Helium inlet, 2: wheel, 3: flap, 4: drive for flap, 5: electrical motor, 6: cooling system, 7: pressure vessel)

3.7. HTTR

The HTTR uses the common technology of helium circulators. Fig. 3.20 contains a flow sheet of the primary system, and Fig. 3.21 shows the arrangement of the main components of the helium circuit inside the reactor building.

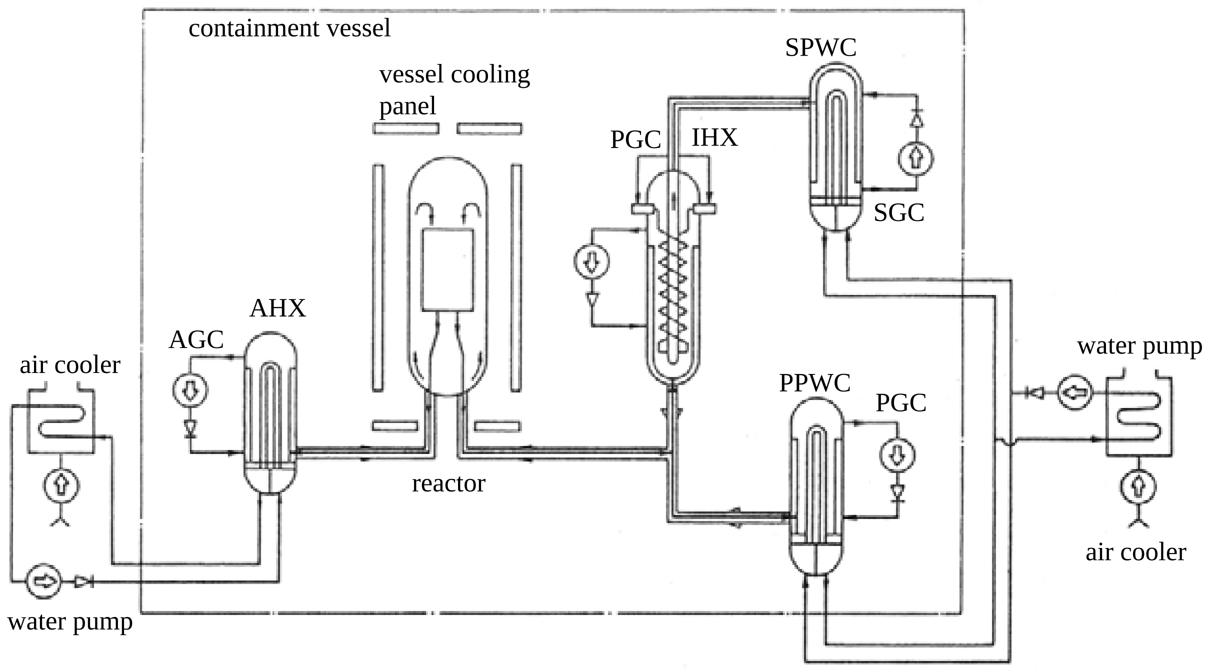


Fig. 3.20: Flow sheet of the primary system of HTTR

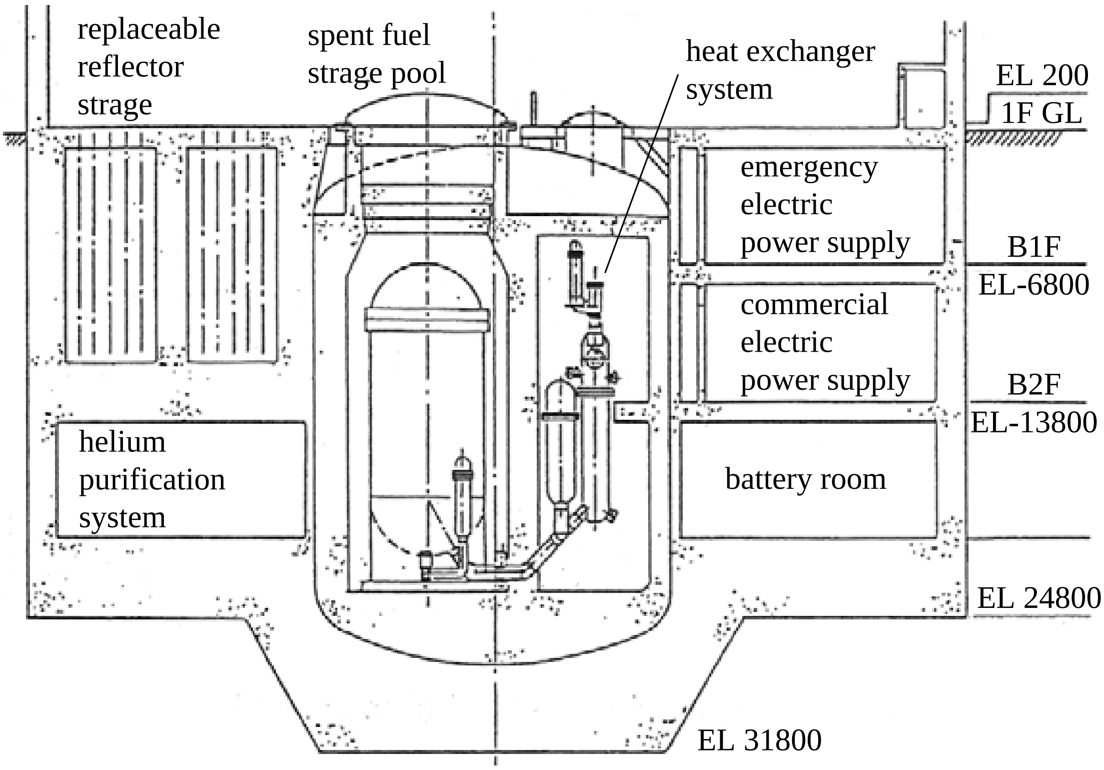


Fig. 3.21: Arrangement of components of primary system of HTTR

The reactor is connected to the heat exchanger system via a coaxial pipe. There is an intermediate heat exchanger (IHX)-loop and a loop containing a pressurized water cooler (PWC). Each loop contains a single stage radial circulator and an electrical motor as drive. Fig. 3.22 explains the design of this very special coaxial hot gas ducting system.

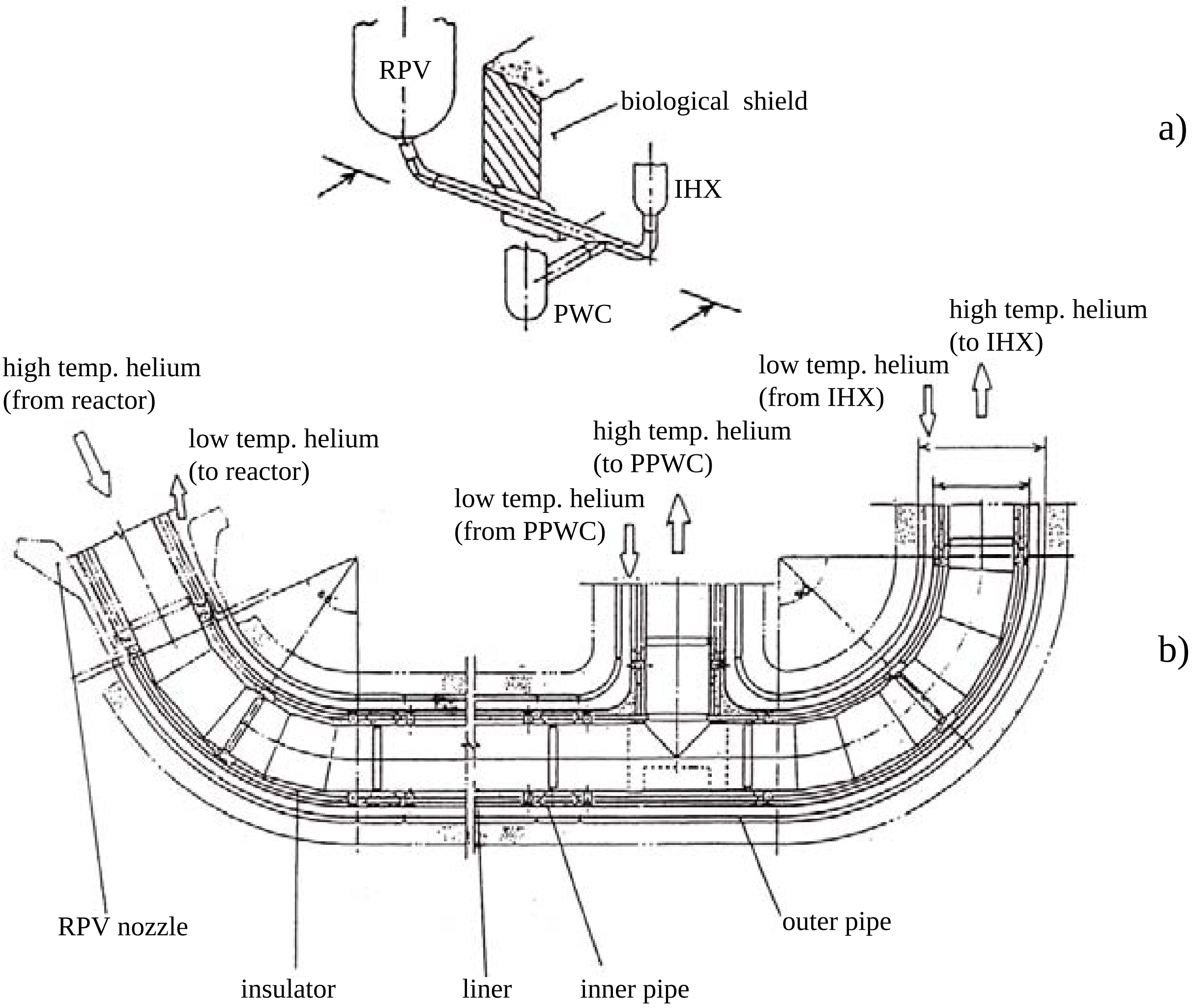


Fig. 3.22: Hot gas duct system of HTTR
a) arrangement of components (PWC = pressurized water cooler, IHX = Intermediate heat exchanger)
b) detail of hot gas duct design

The arrangements of the helium circulators of both components – IHX and PWR - are shown in fig. 3.23. The circulators are radial compressors with electrical motor drive and are arranged side by side with the heat exchanger components.

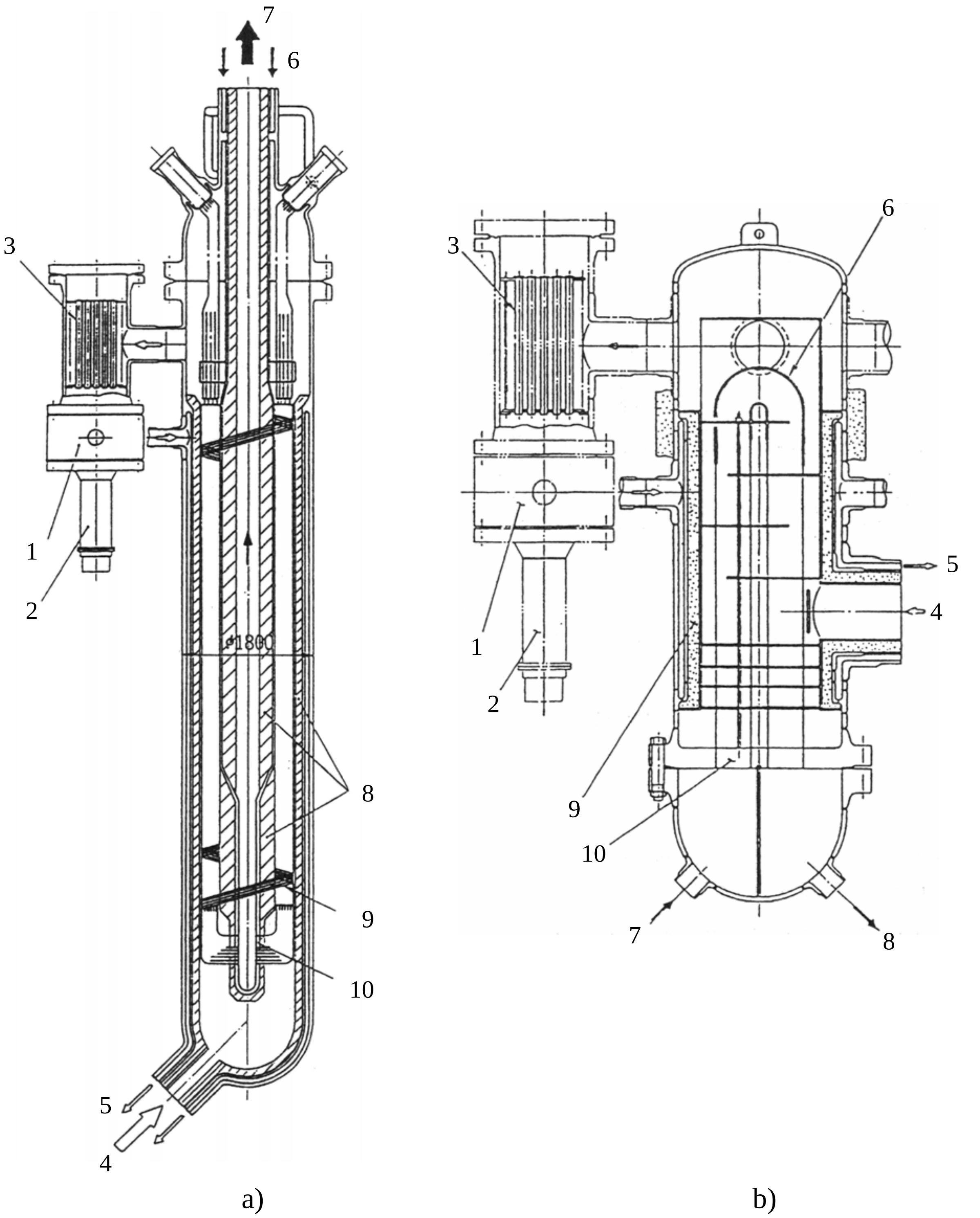


Fig. 3.23: Heat exchanger systems of HTTR

a) IHX (1: *He* circulator, 2; electrical motor, 3: filter, 4: primary *He* inlet, 5: primary *He* outlet, 6: secondary *He* inlet, 7: secondary *He* outlet, 8: insulation, 9: heat exchanger tubes, 10: tube sheet).

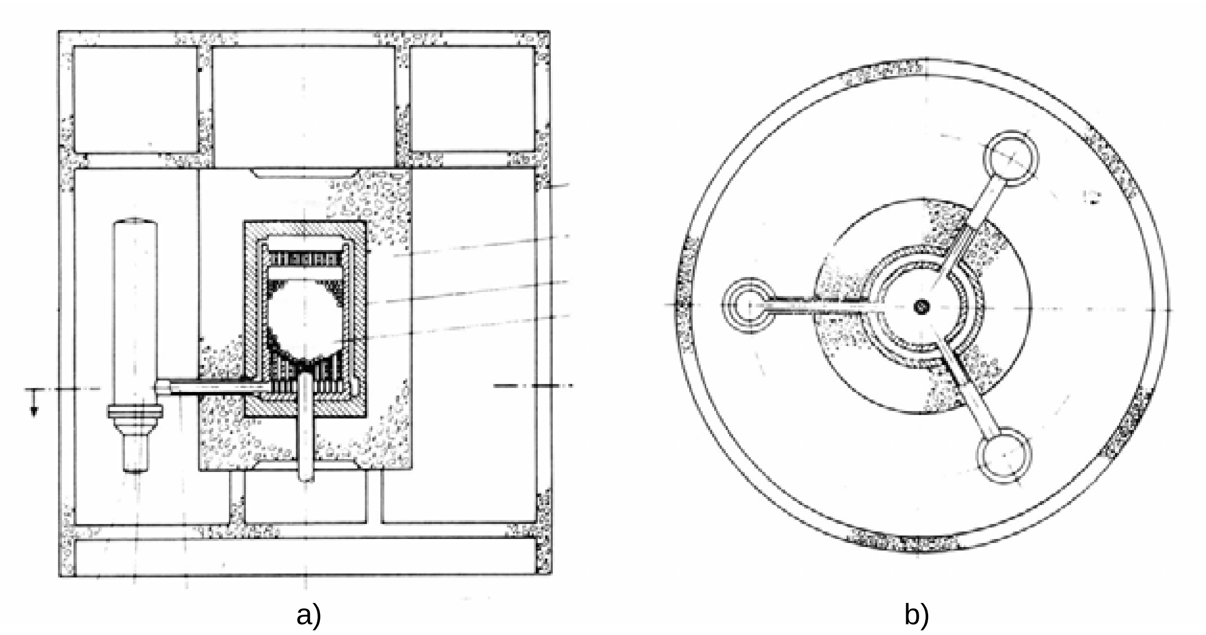
b) PWC (water cooler) (1: circulator, 2: drive, 3: filter, 4: *He* inlet, 5: *He* outlet, 6: tube, 7: water inlet, 8: water outlet, 9: insulation, 10: support plate)

4. Detailed Explanation of Helium Circulators in Planned Reactors [4.1 to 4.8]

4.1. PR 500

The PR 500 was based on the pebble bed principle and was planned for cogeneration of heat and electricity. It is laid out to generate a thermal power of 500 MW_{th} using the OTTO-principle of fuel element management in pebble bed reactors.

The reactor was planned to contain a concrete prestressed reactor pressure vessel with three loops, each containing a steam generator and a helium circulator (Fig. 4.1). The reactor was planned for underground siting to realise high safety standards against strong impacts from the outside.



a) b)

Fig. 4.1: Concept of the PR 500 pebble bed reactor (500 MW_{th} for cogeneration)
a) vertical section
b) horizontal section

The helium circulators are arranged in vertical position. They are one stage radial circulators with an overhung wheel driven by an electrical motor, very similar to the THTR circulators. The planning company for this component was Brown Boveri Sulzer Turbomachines (BST) as well, which had already fabricated the THTR-circulators. The circulator is regulated via a diffuser. Fig. 4.2 shows the component in detail.

The motors are cooled with water, the bearings are lubricated with oil, and a labyrinth system with helium gas acts as a sealant. The circulator is directly connected to the steam generator vessel. The steam generator-circulator units were proposed to act as active decay heat removal systems. In this reactor the principle of self acting decay heat removal was foreseen with a maximal fuel temperature of 2000°C. The concept was the starting point for modular HTR-concepts.

The diameter of the wheel should be 1.35 *m* and the diameter of the flange 2.86 *m*. The total length of the circulator and drive are 4.12 *m*. Fig. 4.3 contains an operation diagram of the machine. The pressure drop dependency is indicated on the ordinate of the figure.

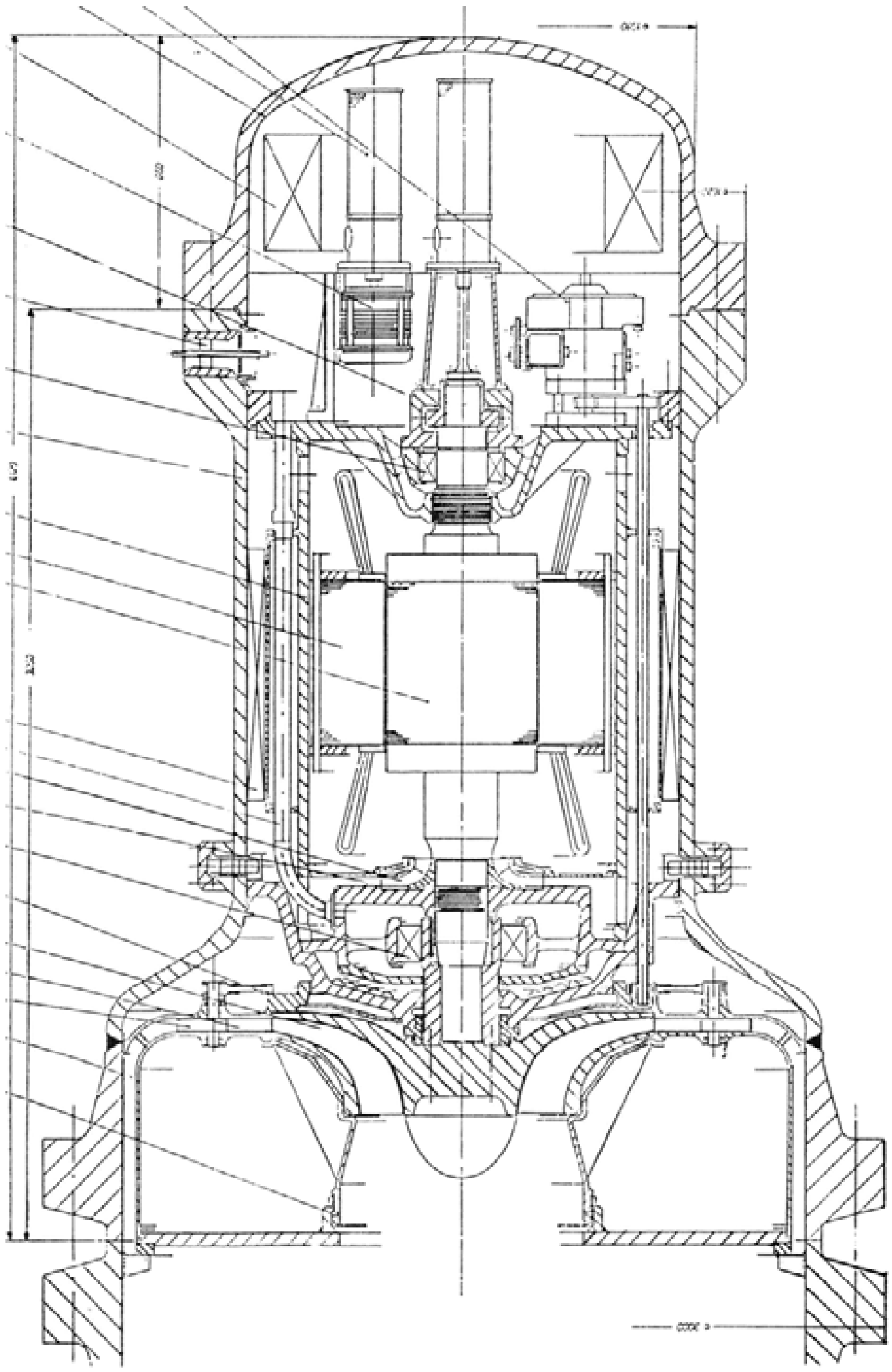


Fig. 4.2: PR 500 Helium Circulator

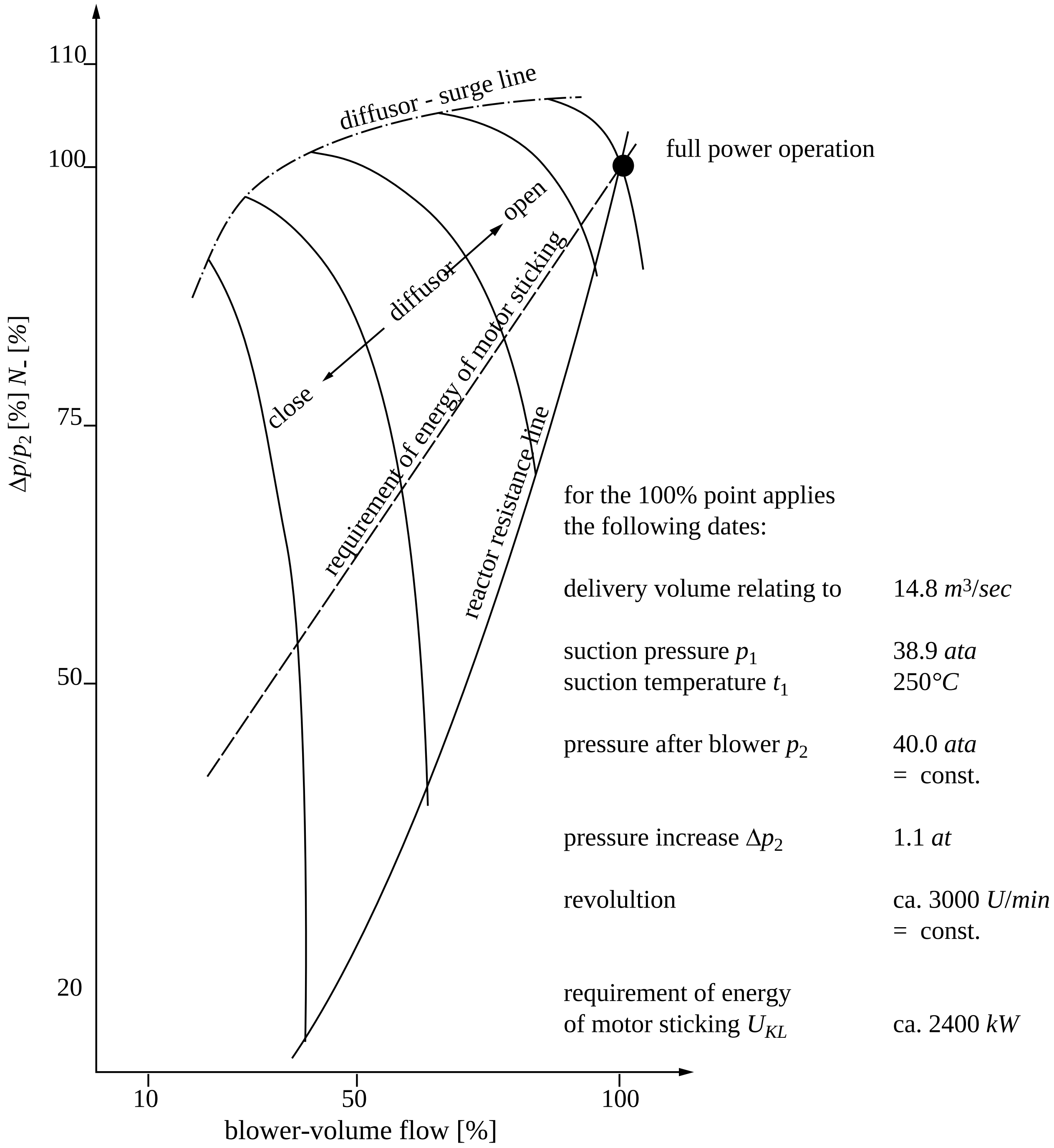


Fig. 4.3: PR 500 Helium Circulator Operation Diagram

It was foreseen to stop the flow through one single loop by o flap similar to the solution used in THTR. The access to this component for inspection, maintenance and repair was easy.

4.2. HTR-Modul

The HTR-Module was designed as a 200 MW_{th} modular reactor unit mainly for cogeneration. Firstly, production of electricity and process steam were considered, later the concept was proposed to be connected to steam reformer / steam generator loops as well as an IHX. Several modular units working together to feed one turbine would form the heat source for a large plant for electricity production using conventional steam parameters (530°*C*/180 *bar* today, 600°*C*/250 *bar* in future).

The total primary system was already shown in Fig. 1.2. The reactor and the steam generator loop are situated in a side-by-side arrangement. These components were designed to be connected via a coaxial duct in a separate connecting vessel.

The helium circulator was arranged at the top of the steam generator (

Fig. 4.4). The component is connected by a flange, and the electrical drive motor is practically integrated into the primary vessel system.

The total mass flow of the cold helium is used to cool all the components of the primary vessel system to below 250°*C* and there for is ducted around all the internals of the core and the steam generator and in the outer annuals of the coaxial duct.

Fig. 4.5 shows the helium circulator together with the electrical motor. Both components are integrated into a separate primary enclosure, which is flanged to the vessel of the steam generator. Therefore, relatively easy access to the components allows for the repair and/or the replacement of the unit.

The design of this component is very similar to that of the PR 500. It is a one stage radial compressor with a wheel in overhang position. The concept of bearing and sealing corresponds to that mentioned before, i.e. oil lubrication of bearings and helium for the sealing system.

At the inlet, the circulator possesses a flap that can stop the helium mass flow. The flap is operated by an auxiliary electrical motor. An auxiliary wheel connected to the main electrical motor provides for an intense movement of internal gas coolant.

Some future data may characterise this component: length:3.8 *m*, diameter of vessel: 1.9 *m*, total weight of component: 11.5 *t*, weight of the rotating masses: 1.4 *t*.

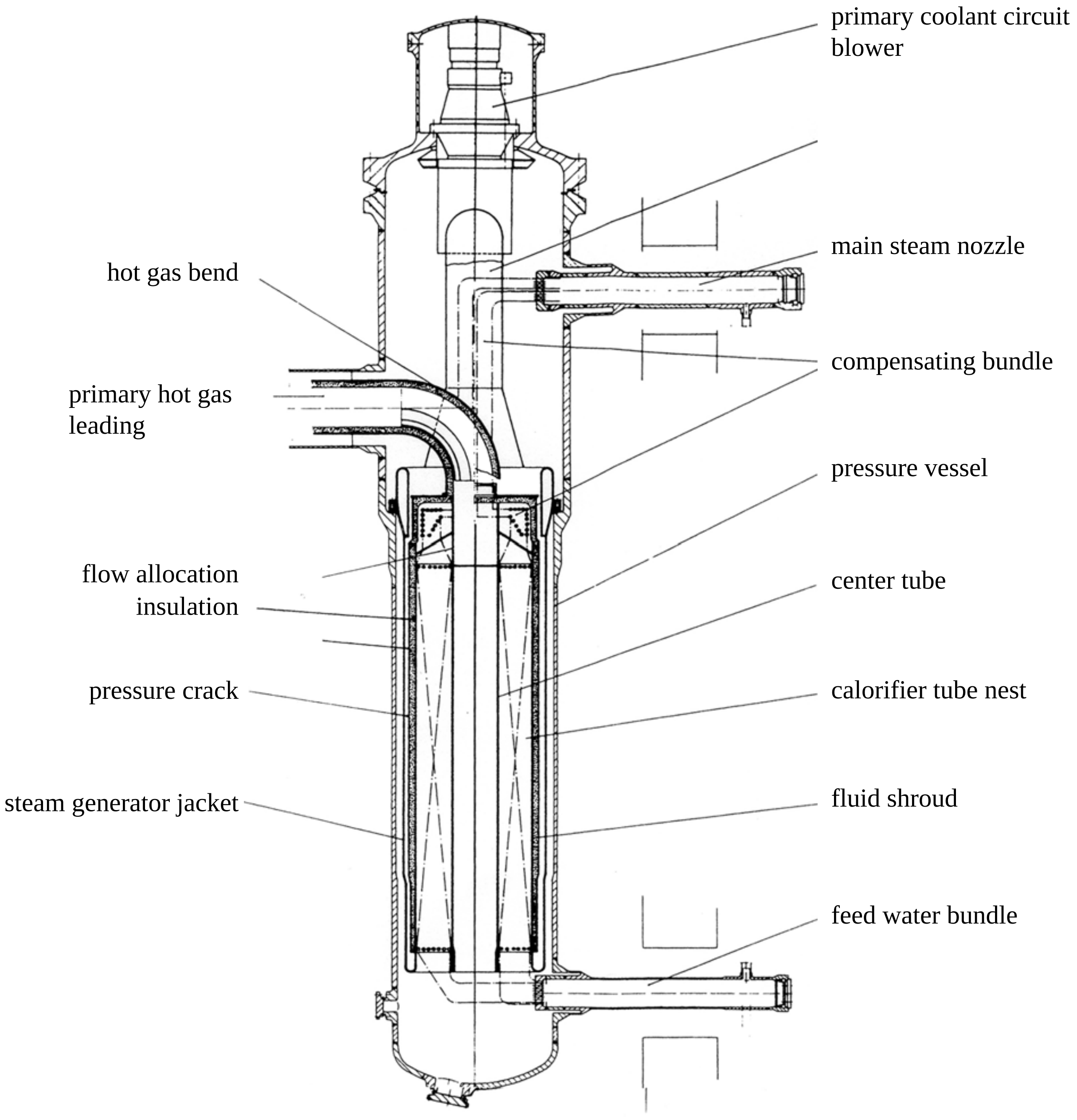


Fig. 4.4: Arrangement of the HTR-module helium circulator on top of the steam generator

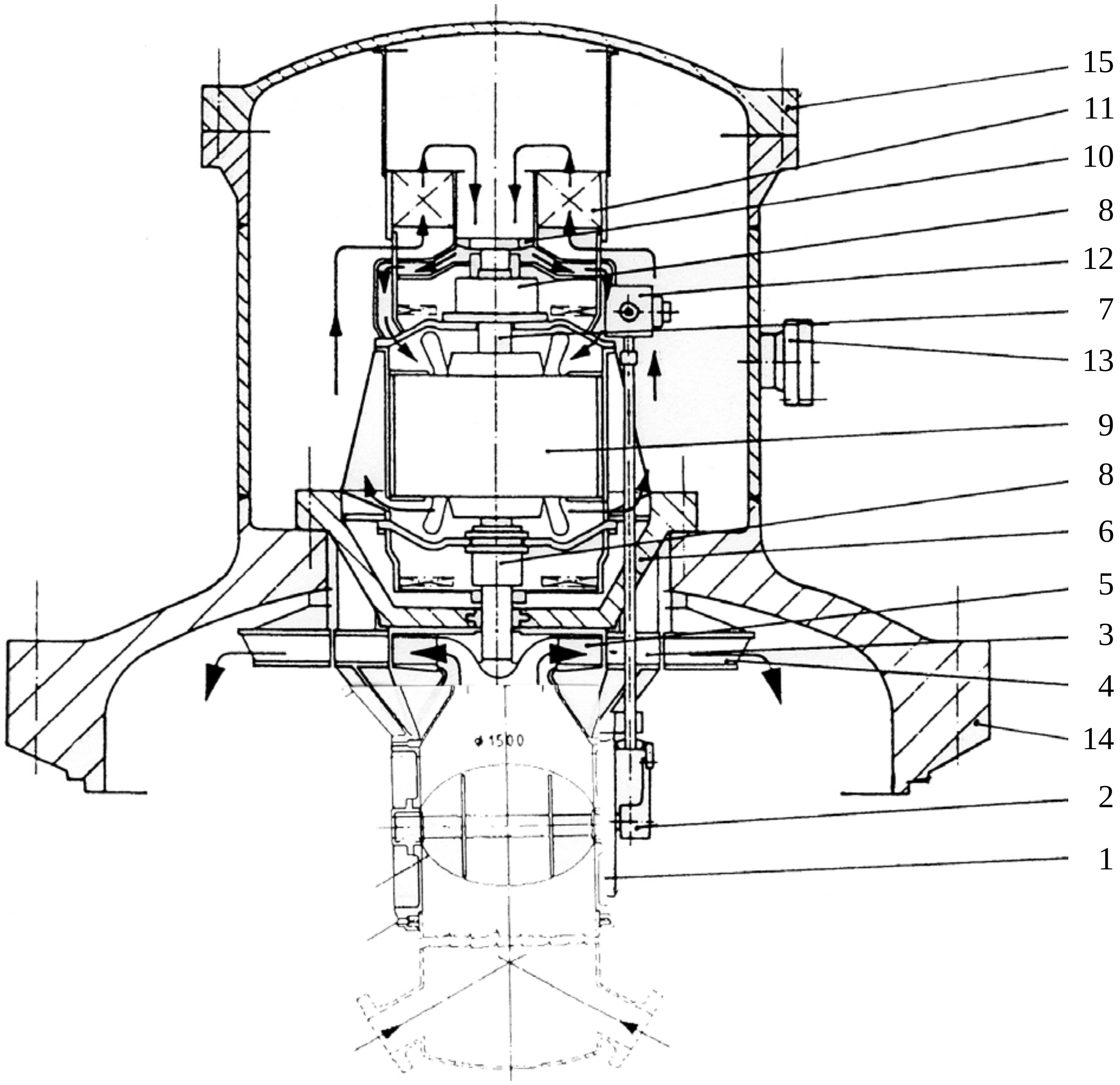


Fig. 4.5: HTR-Module Helium Circulator
1: suction, 2: flap, 3: inner diffuser, 4: outer diffuser, 5: wheel, 6: intermediate flange, 7: shaft, 8: oil bearing, 9: motor, 10: auxiliary wheel, 11: gas cooler, 12: drive of flap, 13: glass penetration, 14: flange, 15: closure

4.3. HTR 1160

In the 70's, the HTR-concept of HTR 1160 has been planned in detail by Gulf General Atomic in the USA. The 3000 MW_{th} prismatic block core is arranged in a prestressed concrete reactor vessel of the pod-boiler-type, and 6 loops containing a steam generator and a helium circulator are arranged inside the pods. Fig. 4.6 shows the design of the primary system.

The circulators are positioned vertically at the top of the vessel and are integrated into the pod-positions. The design is based on the Fort St. Vrain circulators. Again, steam turbines are used in place of electrical motors to drive the circulators. Each unit contains a one stage axial compressor and a one stage steam turbine (Fig. 4.7). In normal operation, cold steam leaving the high pressure turbine is used to operate the units. The steam for the steam turbine driving the helium circulator is ducted to the machine via a concentric annular space between two pipes, which are arranged at the closure of the circulator. Before entering the turbine part, the steam is accelerated and bend by 180°. After expansion, the steam leaves the turbine system via the inner part of the concentric pipe.

The reactor power is controlled by changing the mass flow of the helium coolant. The rotational frequency of the circulator is controlled by the help of throttle- and bypass valves at the inlet of the steam turbine. The driving turbines can also be operated with saturated steam with a maximum humidity of 1%, which can be taken from the starting expansion system or from other sources.

Each of the six helium circulators has a main closing valve that limits the flow of coolant gas through the circulator and the steam generator, if the particular loop is out of operation.

The valve that interrupts the gas flow is located on the diffuser and is operated by three drives.

The total system was designed to satisfy all requirements during the operation of these main helium circulators:

- a continuous supply of high pressure water to the circulator bearings
- a cooling system for the bearings
- a supply of helium in order to maintain a separation between the water circuit and the primary system
- a supply of high pressure helium to operate shaft breaks and sealing during standstill periods

The radial and pressure bearings of the circulator are lubricated with water. In standstill mode, the hydrostatic load of the bearings has to be provided. During operation, the pressure in the bearings is higher because of the hydrodynamics.

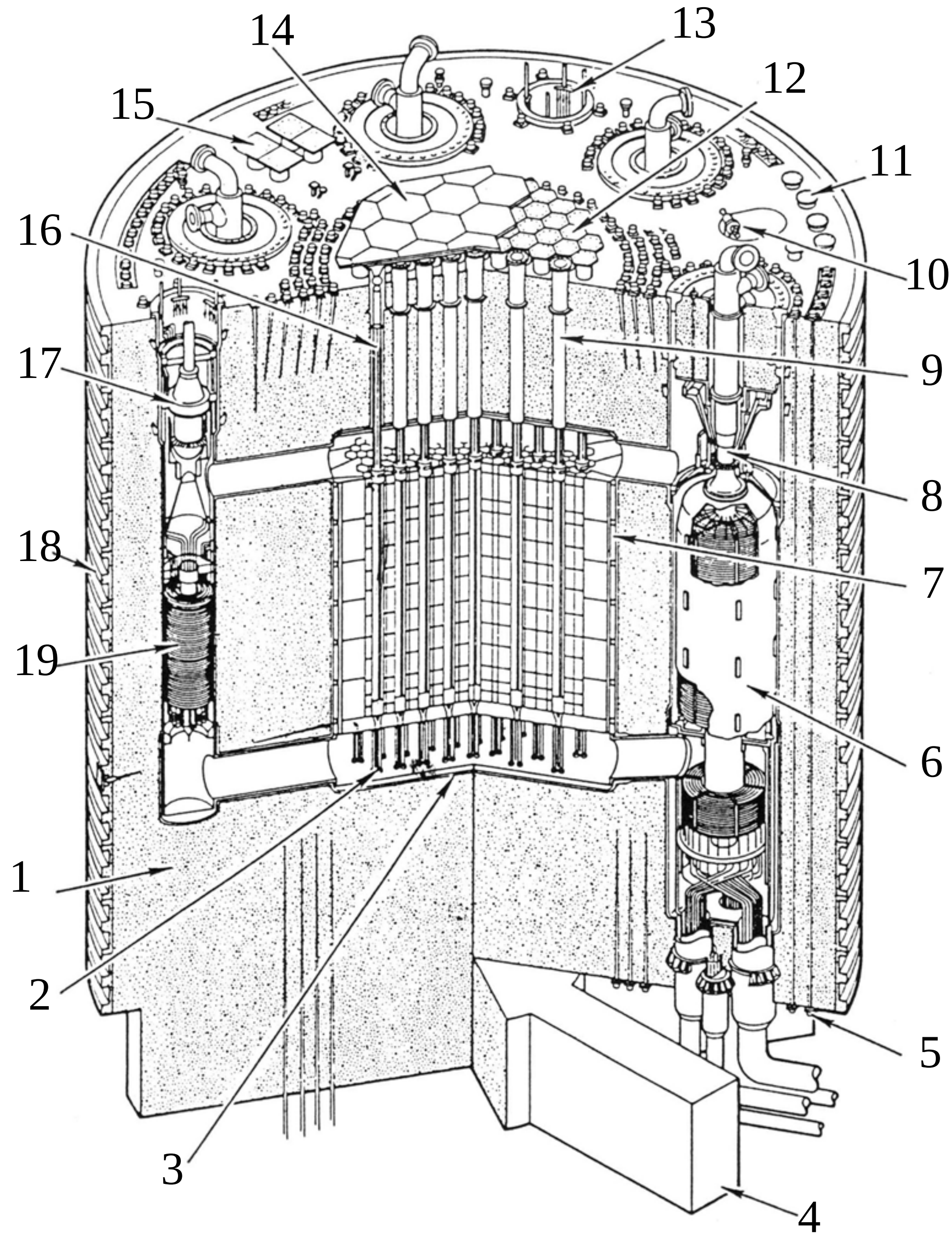


Fig. 4.6: Arrangement of the primary system of the HTR 1160
1: prestressed reactor pressure vessel, 2: core support structure, 3: liner with insulation and cooling, 4: support base, 5: axial prestressing of reactor pressure vessel, 6: steam generator, 7: reactor internals, 8: helium circulator, 9: penetration for loading, 10: safety valve for reactor pressure vessel, 11: connections to gas purification, 12: closures for penetrations of reactor pressure vessel, 13: circulators of auxiliary loops, 14: steel plates, 15: storage positions for control rods, 16: instrumentations, 17: circulators for auxiliary loops, 18: circumferential tendons, 19: auxiliary loop coolers

The penetration of the circulator wheel shaft has a double-labyrinth-sealing. The in-between space contains helium with a higher pressure than that of the primary circuit. The aforementioned design prevents primary helium from leaking into the circulator and water from the bearings from leaking into the primary system.

If the circulator is not operating a further sealing avoids the ingress of water from the water-circuit of the bearings into the primary helium circuit.

To avoid rotation in standstill mode, a rotor break-system is installed that is operated by helium. Each circulator should have its own water supply system for the bearings.

The deign described here was very complicated and this concept caused many problems in Fort St. Vrain operation. In later proposals for HTR-concepts GAC changed over to the concept of electrical drive and oil lubrication.

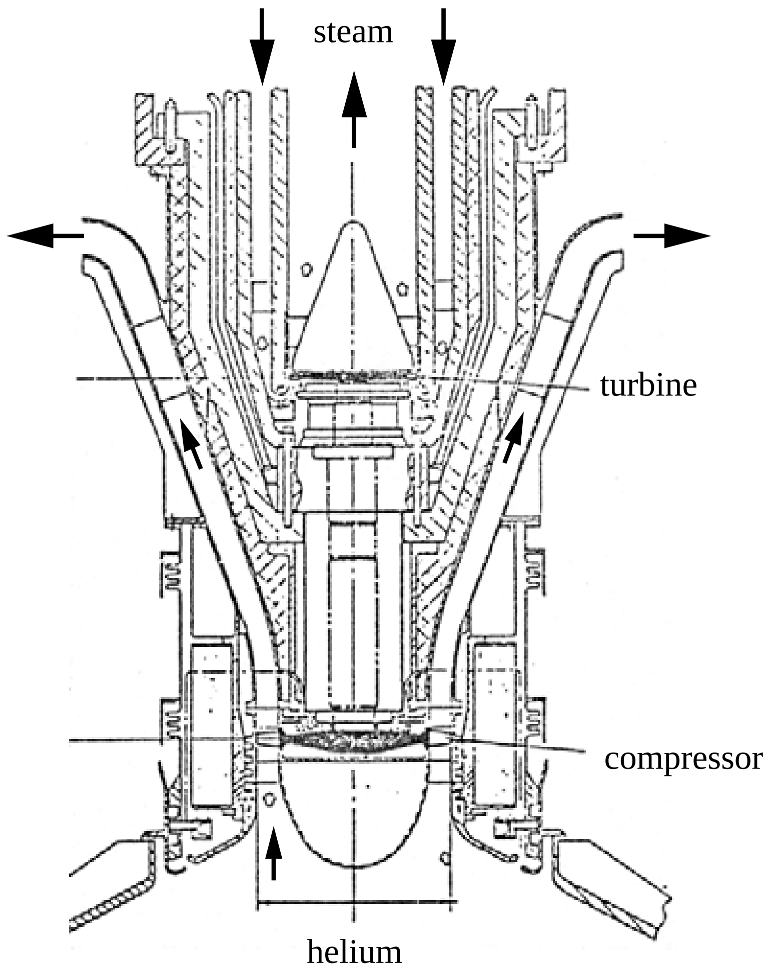


Fig. 4.7: Concept of the HTR 1160 helium circulator unit driven by a steam turbine

4.4. HTR-K

An helium circulator with a relatively large power has been designed for the HTR-K (3000 MW_{th}, 1200 MW_{el}) by BBC. 6 of these helium circulators were necessary to circulate the helium in the primary circuit of this reactor.

The circulators are arranged vertically in a pod-boiler vessel (Fig. 4.8). Each helium circulator is connected to a steam generator on the suction side. On the side of higher pressure, the circulators transport the helium to a header room surrounding the reactor core.

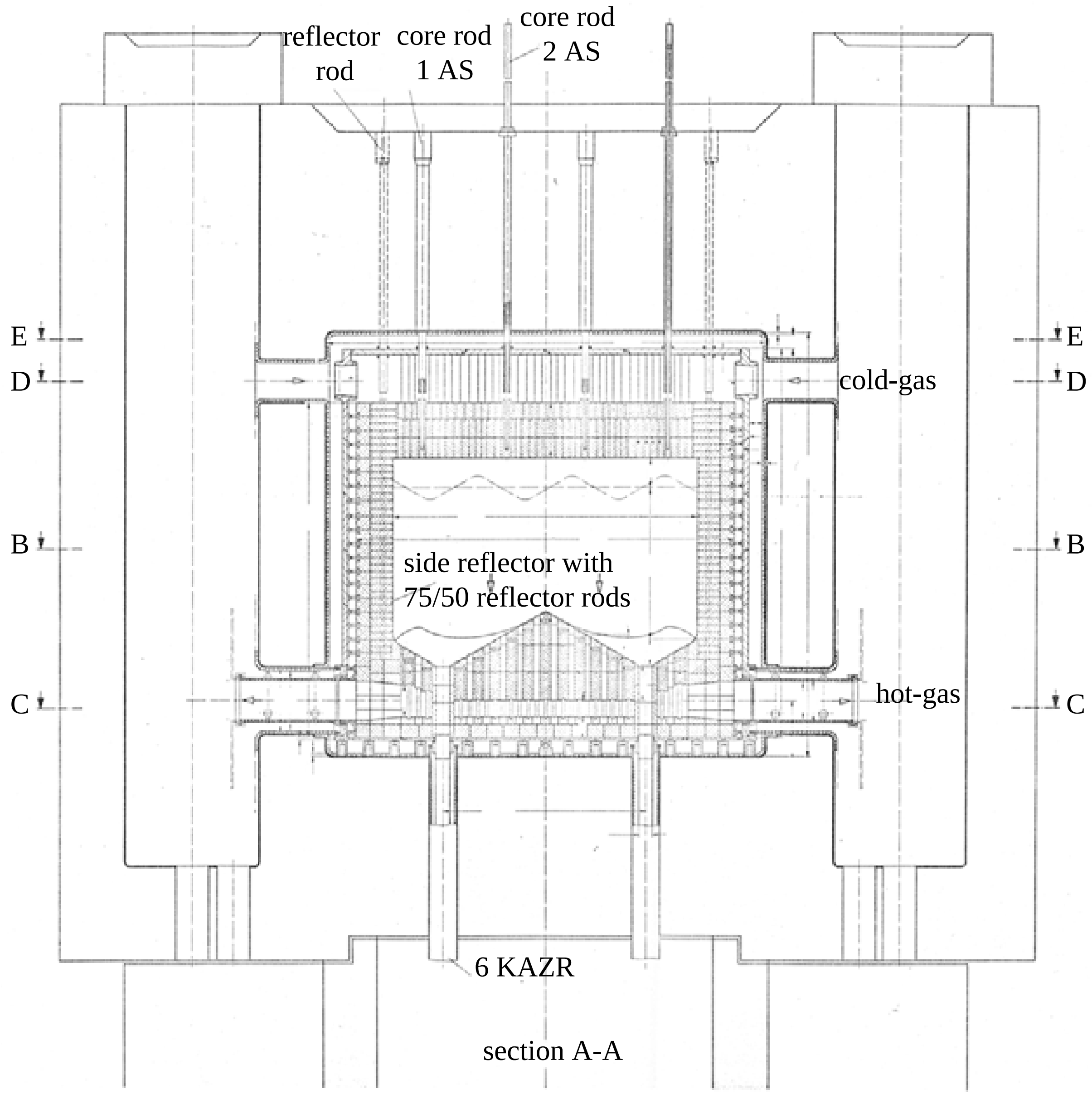


Fig. 4.8: Concept of the HTR-K design (3000 MW_{th}, 1200 MW_{el}, pebble bed core, steam cycle)

The power of one circulator was planned to be 9.2 *MW* The circulator is driven by a 3-phase synchronous-motor in a helium-atmosphere. The helium in the motor system is cooled by water cooling system. The bearings are lubricated with oil. The wheel is chosen to fit a radial compressor in overhung arrangement. The shaft penetration is closed by a sealing gas system to separate the primary helium from the oil inside the bearings. The circulator has a flap system to shut down the helium mass flow. The mass flow is controlled by the rotational frequency. Fig. 4.9 shows the main dimensions of the circulator-drive unit. Fig. 4.10 contains a more detailed view of the concept.

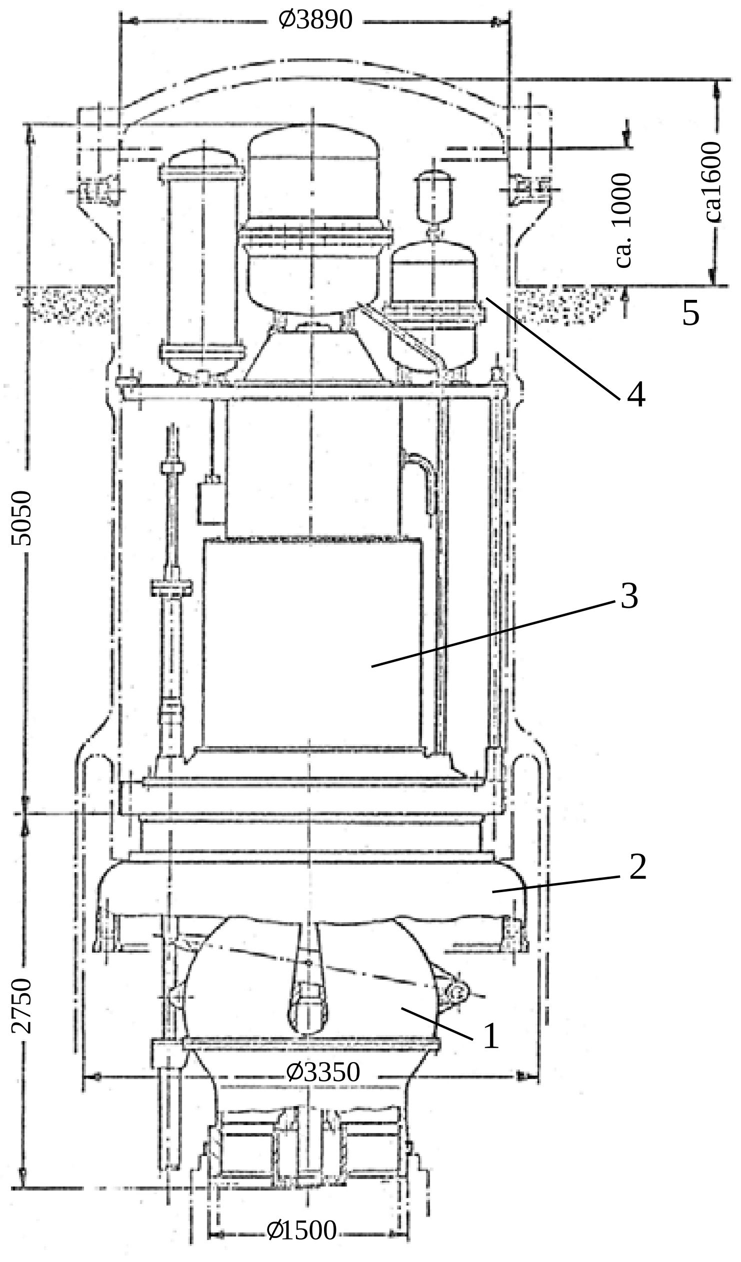


Fig. 4.9: Arrangement of the HTR-K helium circulator unit in the reactor pressure vessel and main dimensions (1: flap-system, 2: helium circulator, 3: electrical motor, 4: supply systems for oil lubrication, water cooling, 5: concrete wall of reactor pressure vessel)

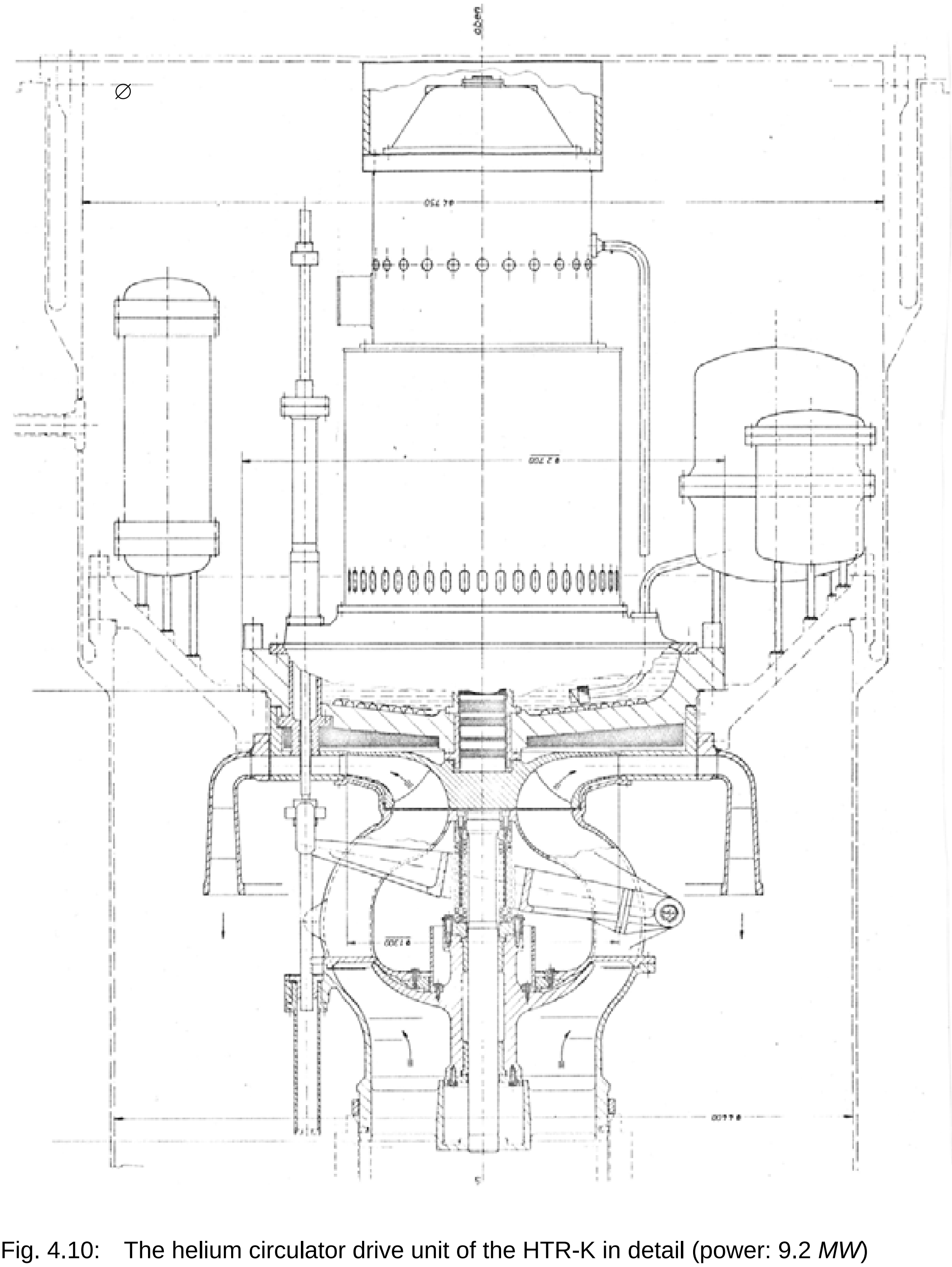


Fig. 4.10: The helium circulator drive unit of the HTR-K in detail (power: 9.2 *MW*)

4.5. MHTGR

GAC has planned the MHTGR with a thermal power of 350 *MW* as a modular HTR with steam generator. The nuclear steam supply system is shown in Fig. 4.11. It contains one loop consisting of a steam generator and a helium circulator.

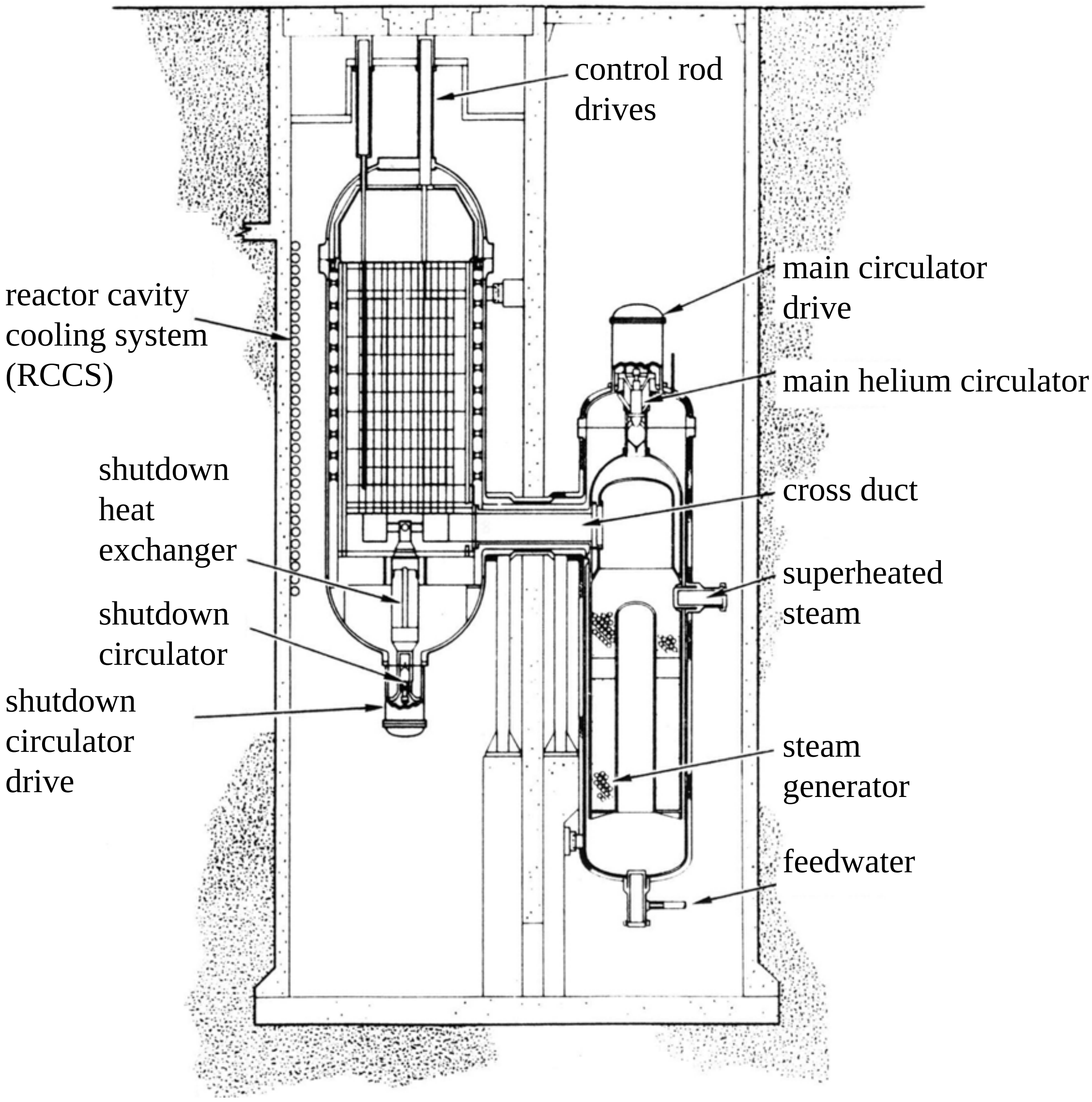


Fig. 4.11: View of the nuclear steam supply of the MHGR

The helium circulator was planned as a variable speed, electrical motor driven, axial-flow compressor. It was planned to arrange it above the steam generator.

Additionally the plant design contains a reactor shutdown cooling system, consisting of a small heat exchanger and a circulator, both located in the lower position of the reactor pressure vessel.

Fig. 4.12 shows details of the design of the circulator-drive unit.

The electrical motor is integrated into the system and forms an integral part of the compressor rotor (Fig. 4.13). The rotating assembly is fully suspended by a set of active magnetic bearings, supported by a set of antifriction catcher bearings.

The helium circulator is installed with the compressor impeller section extending into the steam generator vessel.

The cold helium coming from the steam generator enters the circulator via a cylindrical opening.

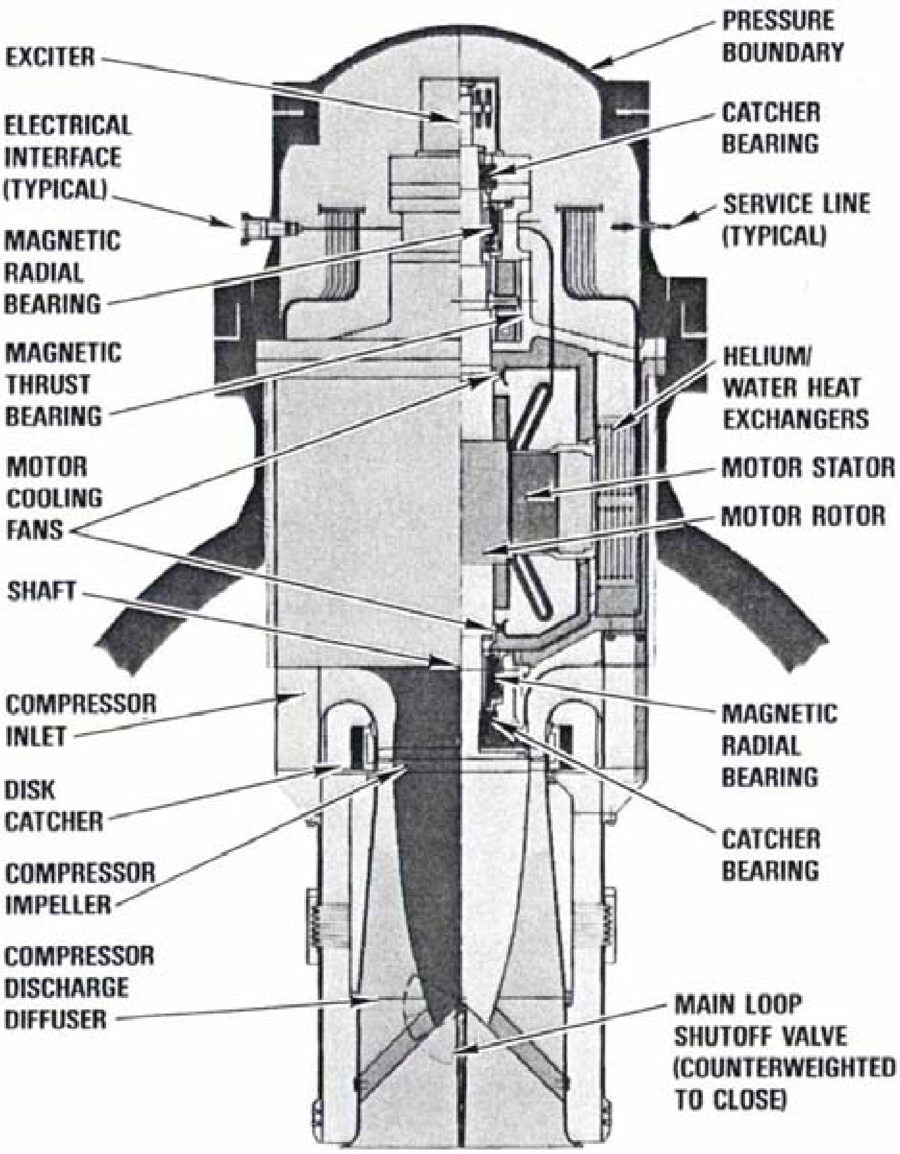


Fig. 4.12: Helium circulator and electric motor drive unit of MHTGR

After compression the gas exits from the diffuser section and sweeps the upper portion of the vessel prior to entering the outer annuals of the cross duct, which connects the reactor pressure vessel and the steam generator vessel.

The total circulator assembly consists of the following components:

- Electric motor/compressor rotor assembly.
- Compressor stator and diffuser assembly.
- Electric motor stator and internal structural supports.
- Helium-to-water heat exchanger for cooling the motor.
- Two radial and one double-acting axial, active magnetic bearings.
- Two angular contact (radial-axial) catcher bearings.
- Hermetically sealed connectors for electric power, cooling water, helium buffer, magnetic bearing controls and instrumentation.

The circulator/motor cavity is filled with purified helium at a pressure slightly higher than that of the reactor system. The small resultant flow through the labyrinth system prevents the primary coolant from entering the electric motor cavity and contaminating the motor. The motor and the magnetic bearings are cooled by the helium-to-water heat exchanger surrounding the motor stator. When the machine is in operation, two cooling fans (integrally mounted on the shaft) cause a helium flow through the motor, around the magnetic bearings and through the heat exchanger, where the heat from electrical and rotor windage losses is dissipated. The pressure of the helium is higher than that of the cooling water. This alleviates the potential for water ingress in the unlikely event of a tube leak.

The primary flow is controlled by a variable speed motor. The circulator is required to operate over the range of 310 *rpm* (5% of nominal speed) to a maximum of 6820 *rpm* (110%). The maximum rotational speed is considerably less than the first critical speed.

Upstream of the compressor impeller, a flow actuated check valve is incorporated into the cylindrical duct. This valve isolates the heat transport system from the reactor vessel when the circulator is not operational and prevents the natural circulation flow of hot gas from entering the steam generator. The valve consists of two semi-elliptical plates that are held open by the circulator's dynamic head. The closure is caused by gravity. A helium jet mechanism used to assist in closing the valve (as a back-up) is included in the design.

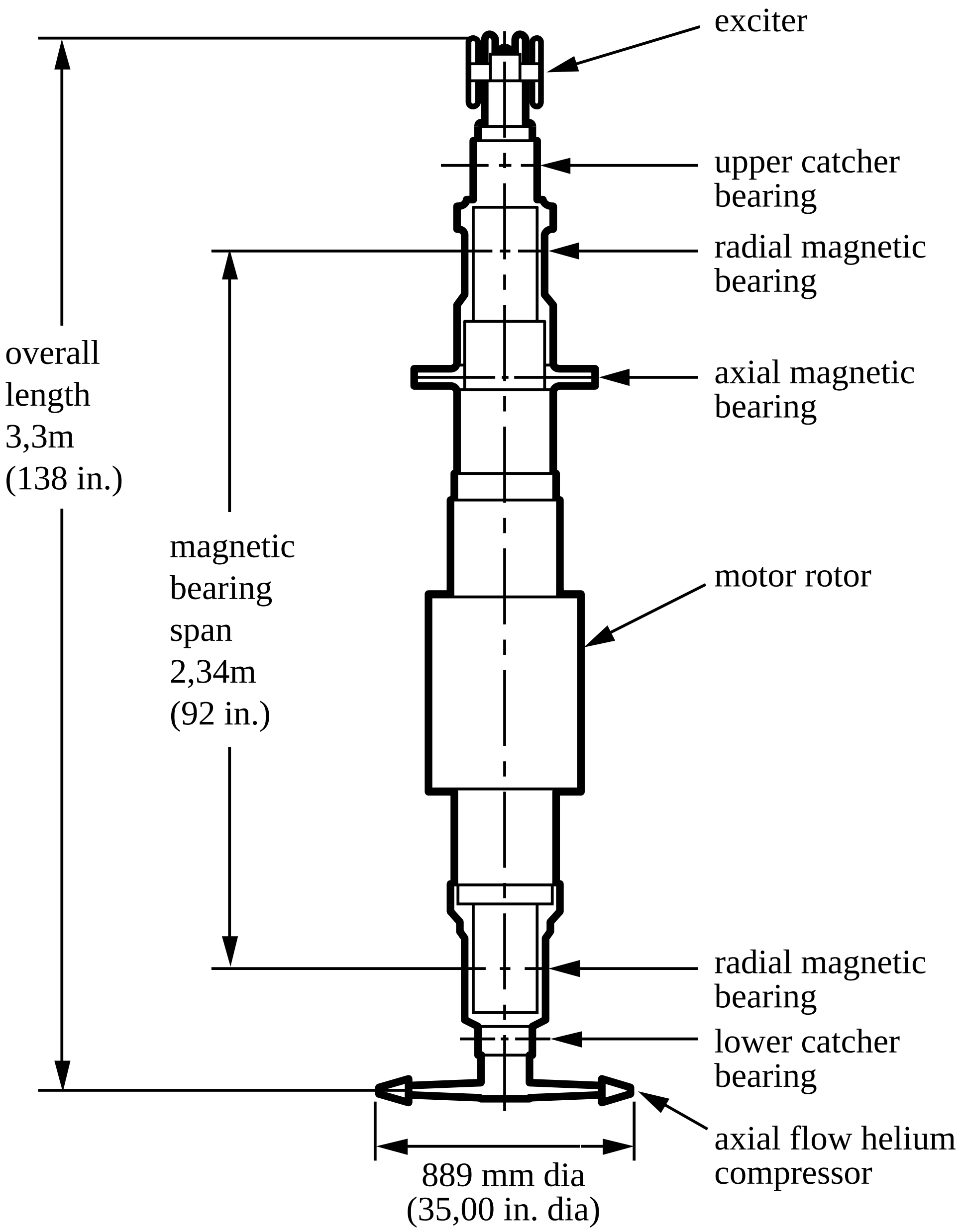


Fig. 4.13: Circulator assembly

Some additional data for this component relevant for plant design considerations are: diameter of assembly: 2.5 *m*, length of assembly: 6 *m*, weight of the component: 30 *t*.

4.6. HTR 100

The HTR 100 was designed with a thermal power of 250 *MW* per modular unit for cogeneration purposes. As indicated in Fig. 4.14, the primary system contains one steam generator arranged above the core corresponding to the design of the AVR-reactor. On top of the steam generator two helium circulators are installed to compensate for the pressure drops in the whole primary circuit (Fig. 4.15).

The coolant gas circulators are single stage radial blowers driven by a speed-controlled asynchronous motor. The circulator shaft is held in place by active magnetic bearings so that there is no mechanical contact between the rotating and the static parts. The bearings require no lubricants like oil or water.

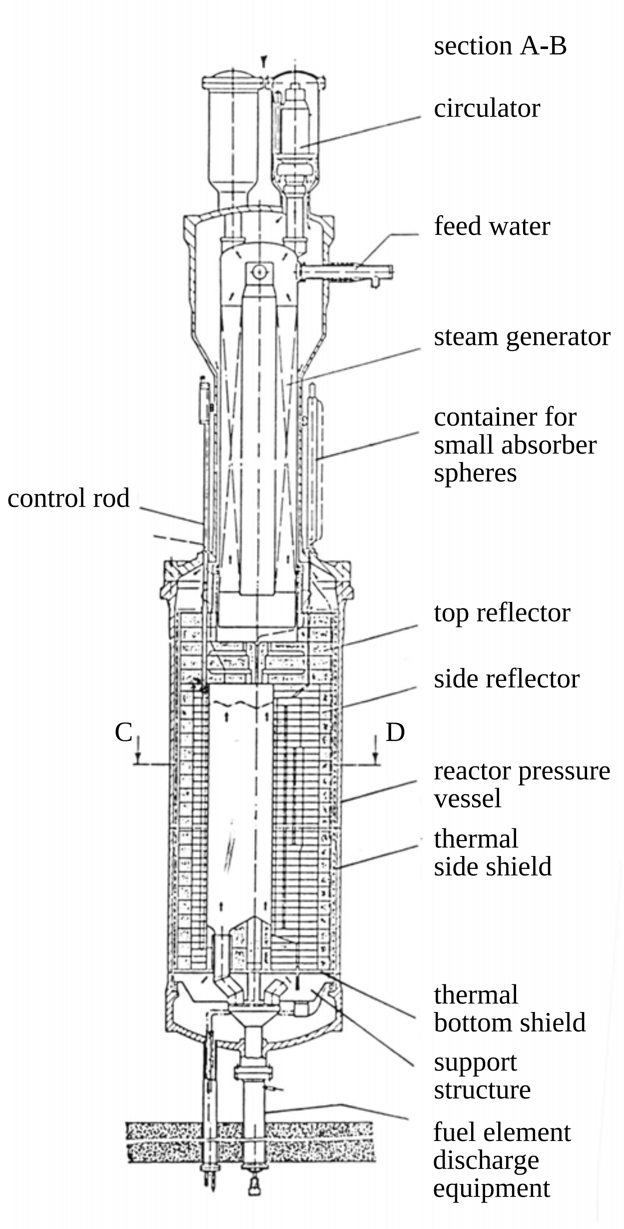


Fig. 4.14: Cross-sectional diagram of the primary system of HTR 100 (250 MW_{th})

The coolant gas circulators are single stage radial blowers driven by a speed-controlled asynchronous motor. The circulator shaft is held in place by active magnetic bearings so that there is no mechanical contact between the rotating and the static parts. The bearing require no lubricants like oil or water.

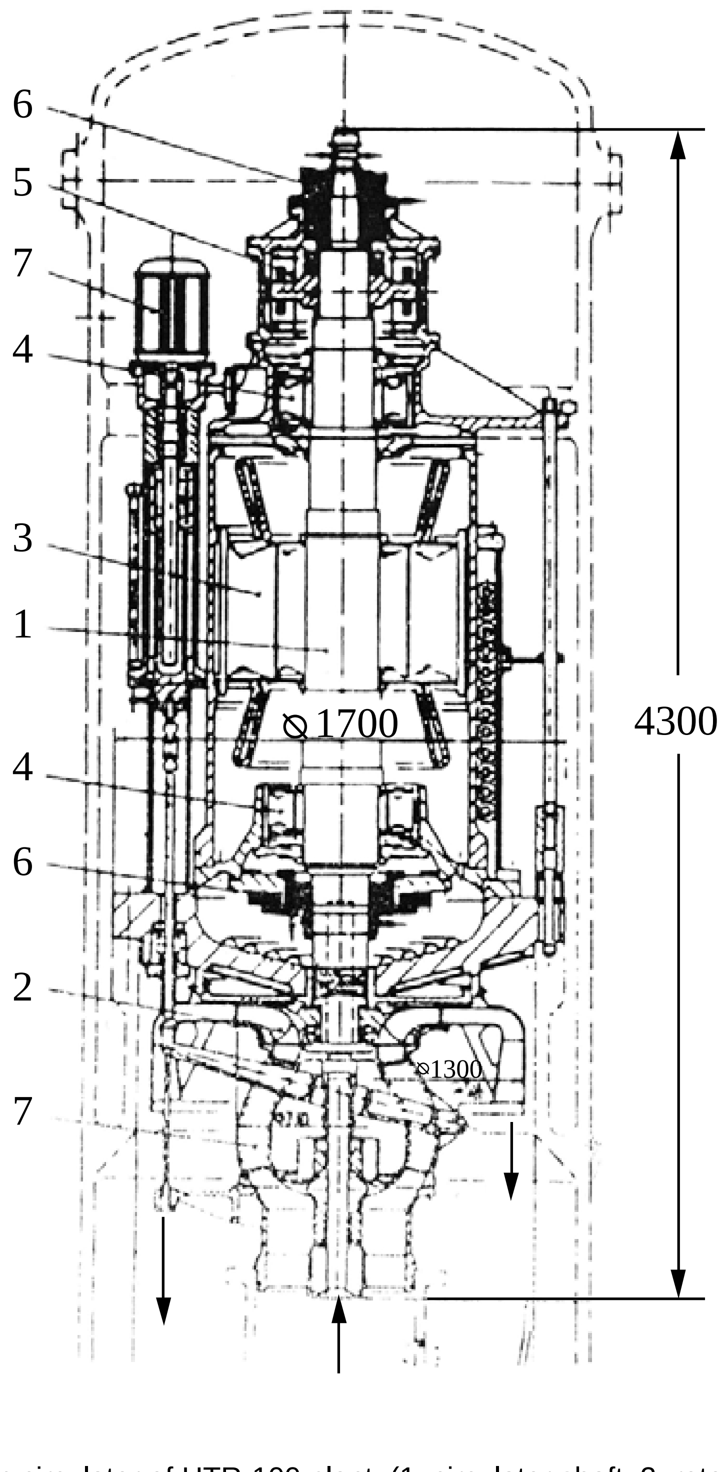


Fig. 4.15: Helium circulator of HTR-100 plant: (1: circulator shaft, 2: rotor, 3: motor, 4: radial magnetic bearing, 5: axial magnetic bearing, 6: catcher bearing, 7: shut-off valve with actuator)

5. Circulators in helium cooled test facilities [5.1 to 5.12]

5.1. Circulators of the KVK Plant

The KVK facility was build and operated to test all high temperature components necessary for process heat applications.

The KVK test facility used two helium circulators. Fig. 5.1 contains a diagram of the KVK test facility. Fig. 5.2 gives an overview on the helium ducting system in this plant. The 1P1 circulator was connected to the cold gas loop to allow the execution of trial operations at certain time intervals prior to commissioning the KVK double loop operation. Then, both circulators were operated during the testing of the intermediate heat exchangers. The data of the two circulators are contained in table 5.1. The most important differences are the disparity between the pressure increases and that between the rotational frequencies.

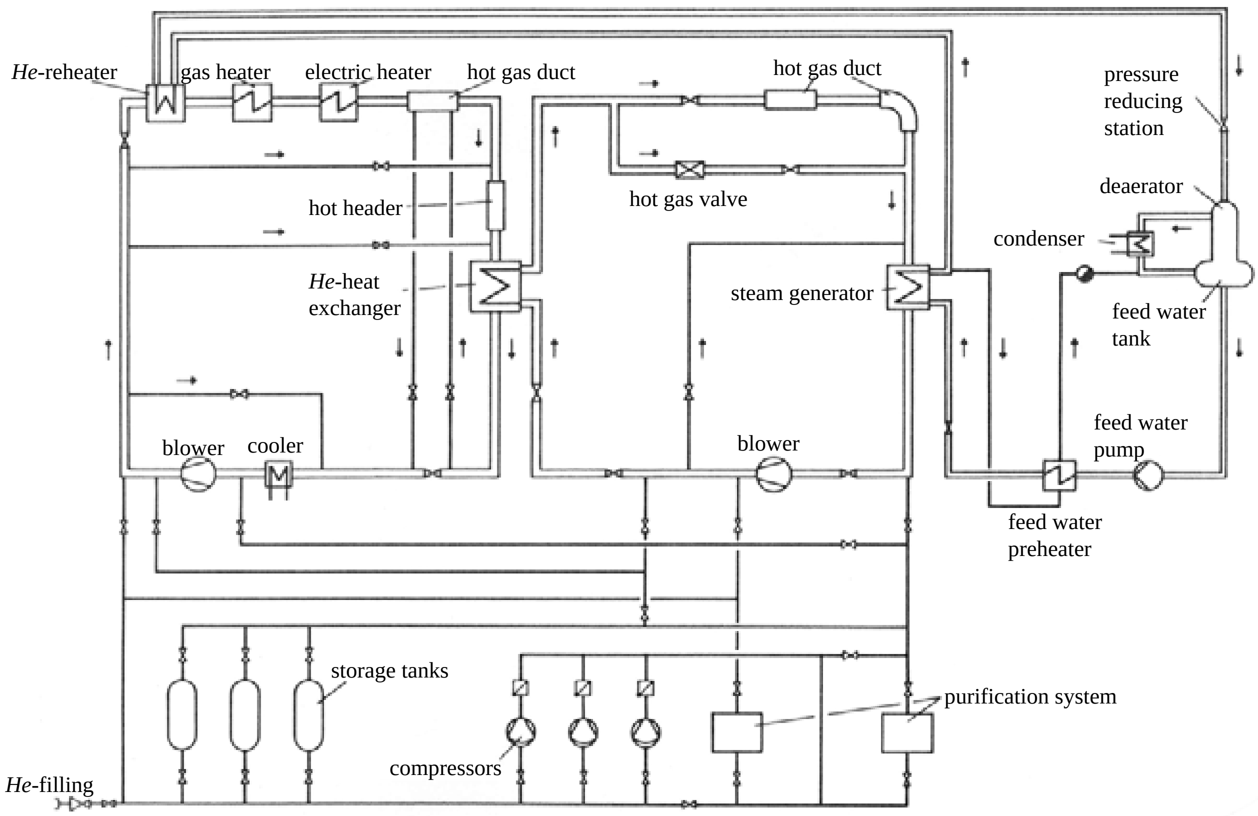


Fig. 5.1: Flow sheet of the KVK test facility (arrangement for test of *He*/*He*-heat exchanger)

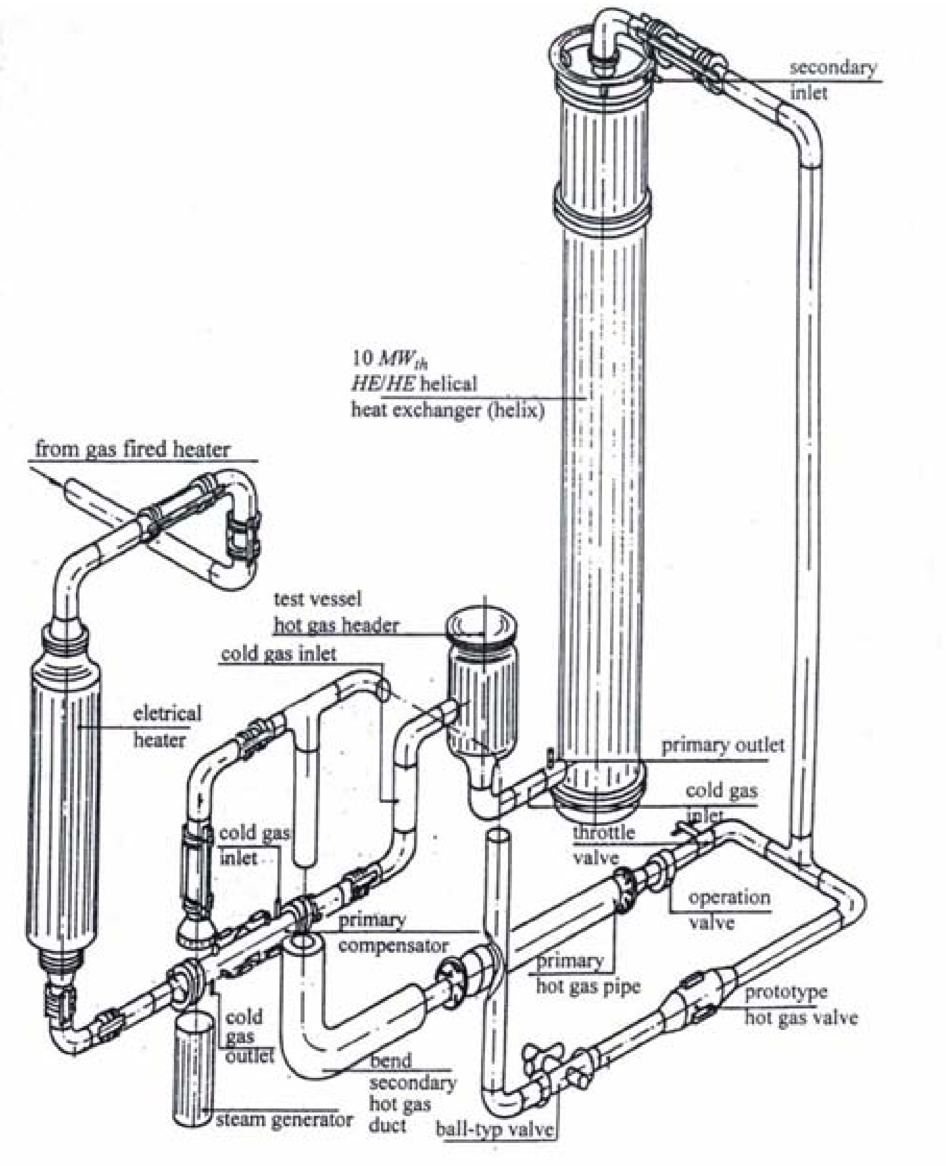


Fig. 5.2: Arrangement of the 10 *MW-He*/*He*-heat exchanger and other test components in the KVK-plant

The circulators are radial machines in horizontal arrangement. The 1P1 circulator is a three-stage and the 1P2 is a four-stage compressor. The oil systems are integrated into the machines. A gear connects the circulator to the drive, which is provided by an electrical motor whose frequency is controlled. The inner casing of the circulator has a horizontal discontinuous joint.
The shaft with the wheels has oil-lubricated bearings outside the compressor space. The shaft penetration is sealed by labyrinth systems, sliding sealing and standstill sealing.

The oil has to be kept separate from the helium, cooling and lubrication of the sealing systems are necessary. Fig. 5.3 shows a schematic arrangement of a circulator with the relevant auxiliary installations. A separate, partly closed helium circuit consisting of an auxiliary circulator, a cooler, and an oil separator is needed for the sealing system additionally.

This circuit is connected to the main circuit by labyrinth sealings and additional pressure equalization spaces. Each circulator is equipped with a device that measures the vibrations it experiences.

The operational behaviour of the circulators in this test facility was very good for nearly 10 000 hours.

Fig. 5.5 additionally contains some of the characteristics of both circulators and the pressure dependency on the mass flow with the rotational frequency as a parameter.

Table 5.1: Design data of the KVK helium circulators

Data	**Dimension**	**Circulator 1P1**	**Circulator 1P2**
Mass flow	*kg/s*	3	3
Suction pressure	*bar*	39	39
Suction temperature	*°C*	230	230
Pressure increase	*bar*	3.3	4.25
Power	*MW*	0.466	0,502
Speed	1/*min*	8660	15500
Control range	%	20...100	20...100
Design pressure	*bar*	46	46
Design temperature	*°C*	350	350
Design lifetime	*h*	$3 \cdot 10^4$	$3 \cdot 10^4$

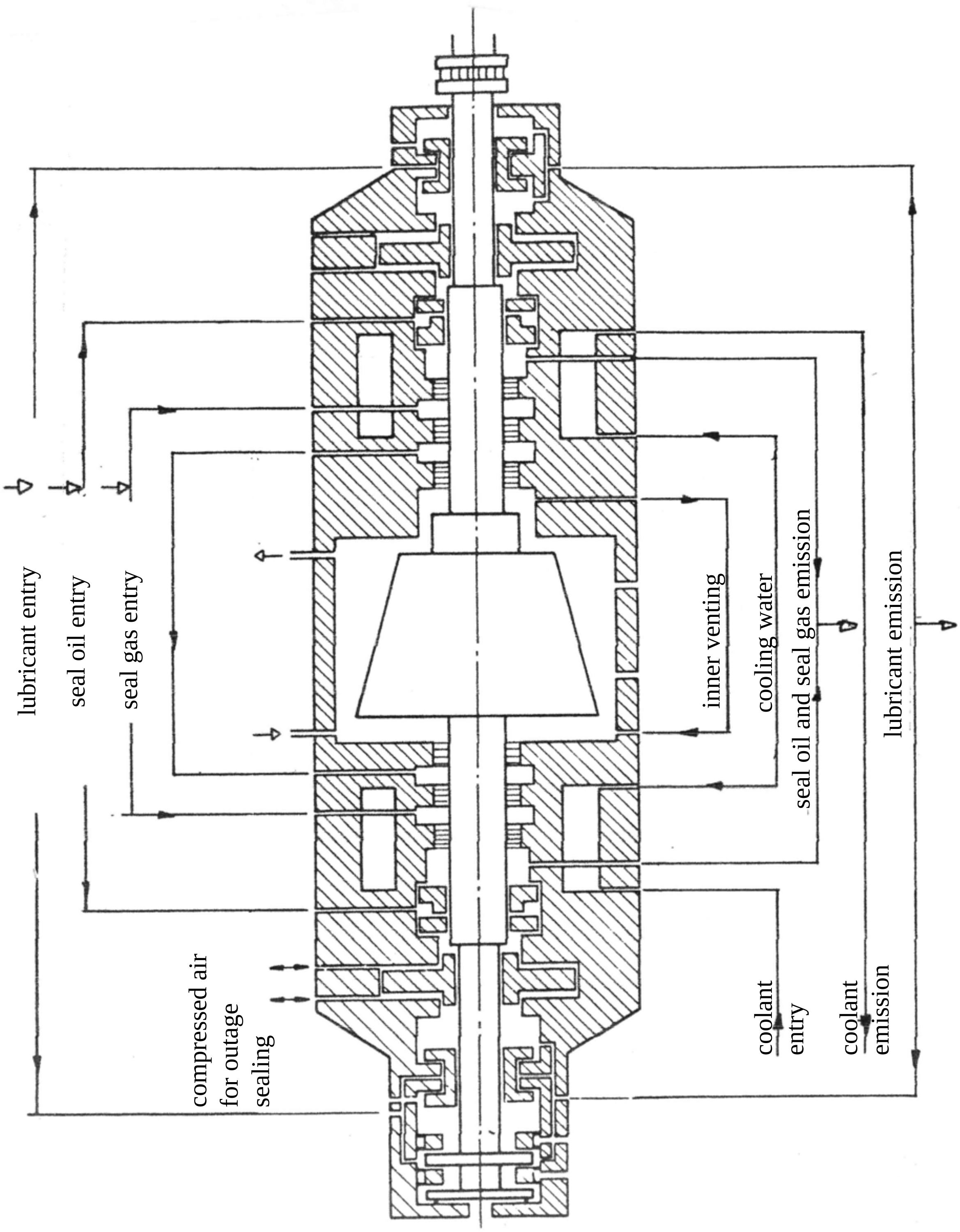


Fig. 5.3: Principle concept of the KVK helium circulators

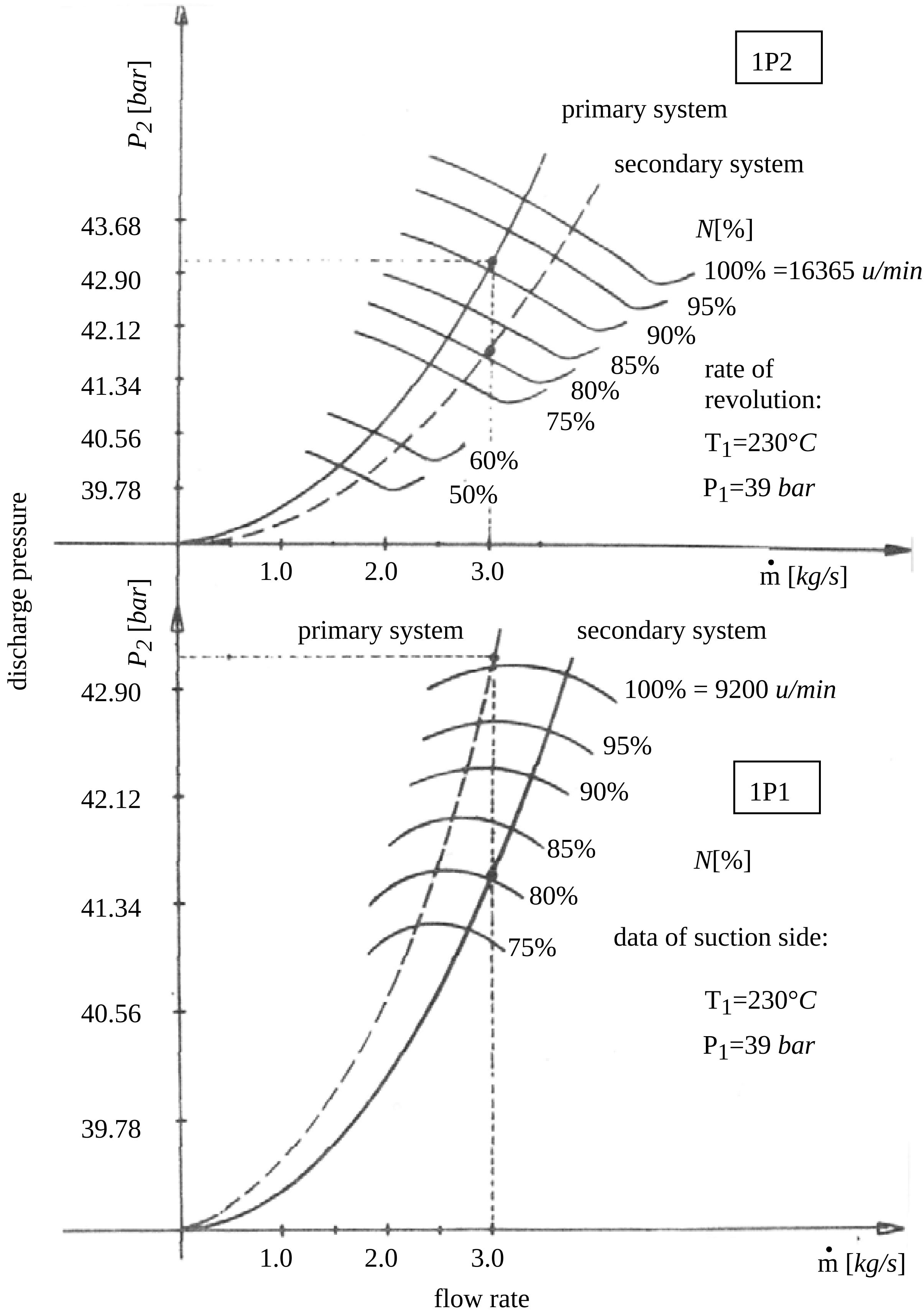


Fig. 5.4: Characteristics of the two helium circulators of the KVK

5.2. Helium compressors in the EVO power plant

As part of the German helium turbine project in Oberhausen, a closed helium turbine plant has been built and long-term operated. It contains two helium compressors, as the flow sheet in Fig. 5.5 indicates. The thermal power of the plant is 150 *MW* and the plant operates with a gas-fired heat source.

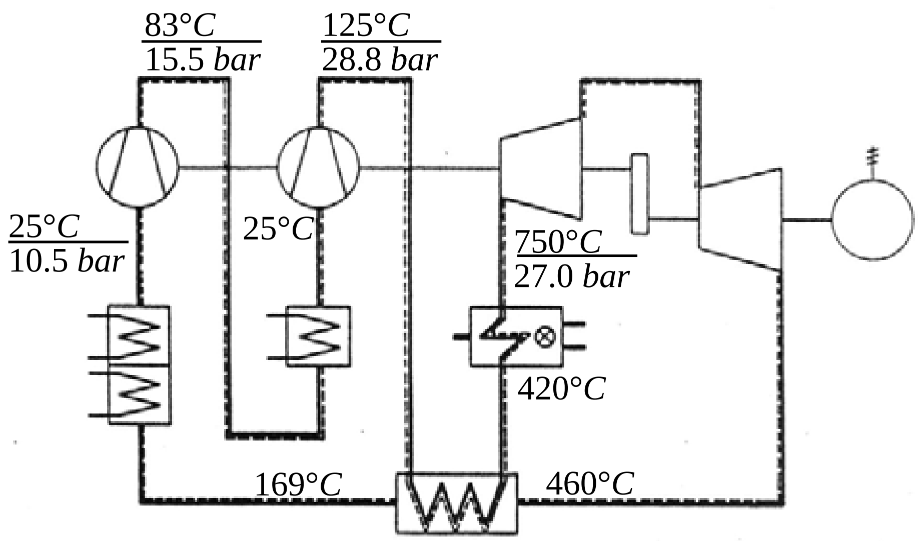


Fig. 5.5: Flow sheet of the EVO Plant

The helium was at a maximum temperature of 750°*C* and a pressure of 27 bar. The plant delivered 50 MW_{el} and around 170 MW_{th} district heat. The plant operated via a two-stage compression and a helium recuperator.

Fig. 5.6 shows the arrangement of all the components of the helium cycle. The main space is needed for the fossil fuel fired heater. This is that large because the heating process occurred at normal pressure.

The inlet temperature of the helium turbine was 750°*C*. A double shaft design of the turbo machinery was used. The high pressure turbine powers the compressors connected to the first shaft, and the low pressure turbine powers the generator using the other shaft. Both rotor shafts are connected by a gear.

Some operating data included in Fig. 5.5. The HP-compressor and the HP-turbine are shown in Fig. 5.7 and Fig. 5.8. The speed is 5500 1/*min*. Both machines are arranged in seperate casings. The high pressure compressor is arranged in a common casing with the high pressure turbine. The HP-compressor´s blades are made of forged, semifinished parts, which specifically were precisely machined. The blades for the HP-turbine were made by precision forging.

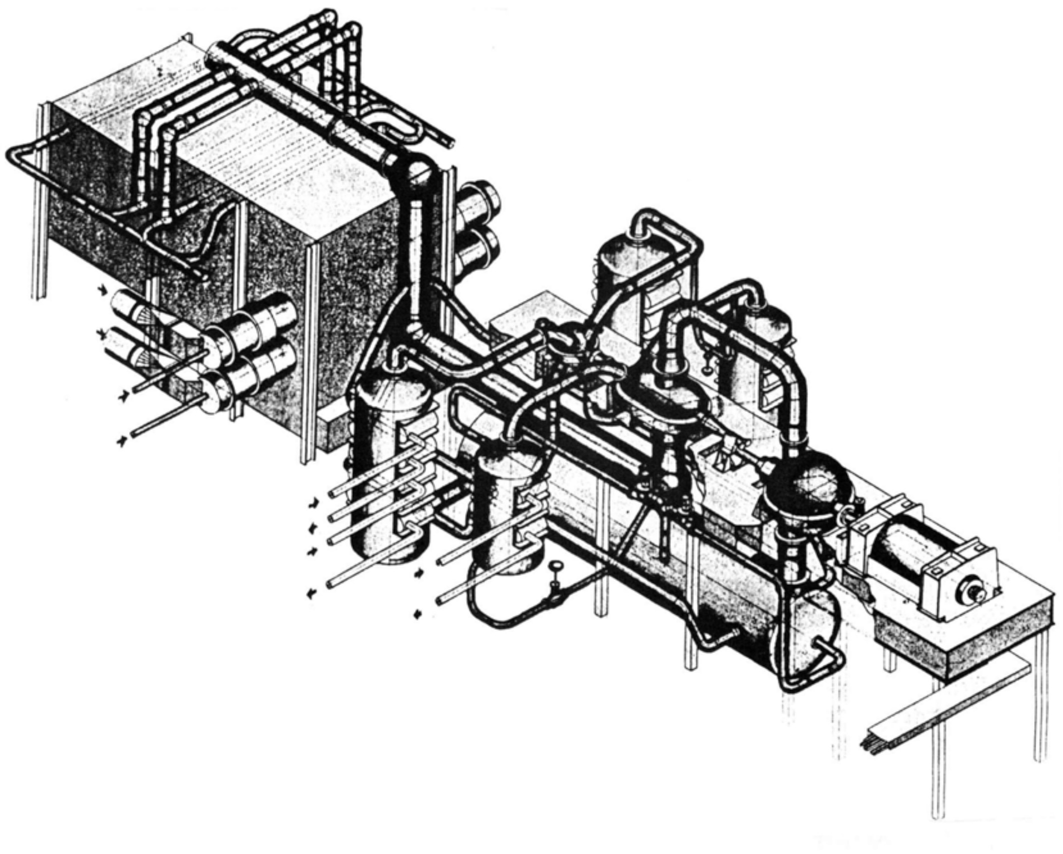


Fig. 5.6: Component arrangement of the EVO plant.

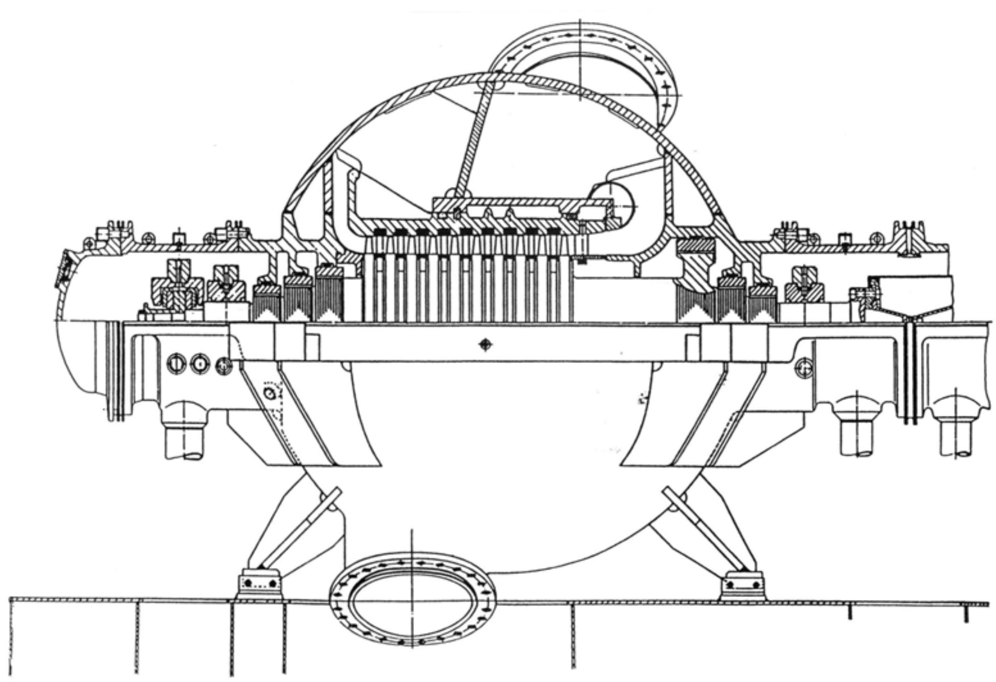


Fig. 5.7: Low pressure compressor of the EVO plant

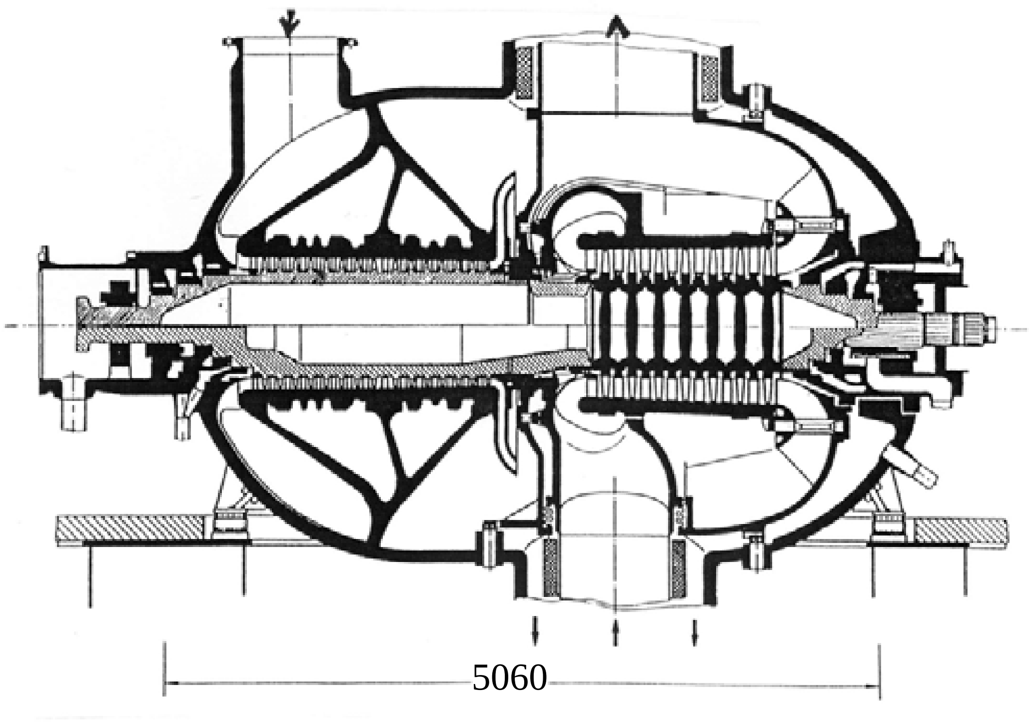


Fig. 5.8: EVO high pressure compressor and high pressure turbine on one shaft

The bearings of all three turbo-machines can be removed separately without opening the horizontal flanges of the main casings. The flanges were sealed with welded lip seals. In order to cool the turbo-machine casings, a multiple casing system is used wherein a part of the total mass flow provides the cooling.

The low pressure compressor had 10 stages and the high pressure machine was operated with 15 stages.

When the high pressure turbine is operated at nominal capacity, it creates just enough power to drive both compressors on the shaft.

The gear between the high pressure section and the low pressure turbine connected to the generator transfers only a small amount of power.

The sealing between the bearings and the helium circuit contains three labyrinth seals. The helium in the sealings is mixed with the oil drained from the bearing and is subsequently regained in an oil-helium separation process.

5.3. The helium compressor in the HHV Plant

The HHV facility was built and operated to demonstrate the feasibility of a large helium circuit at high temperatures and high pressures and to test specific components for gas turbine applications, specifically turbo machines.

Fig. 5.9 shows the general flow sheet containing the compressor used to heat up the helium to 850°*C* and 60 *bar*, the test section, the expansion turbine, and the connecting gas ducts.

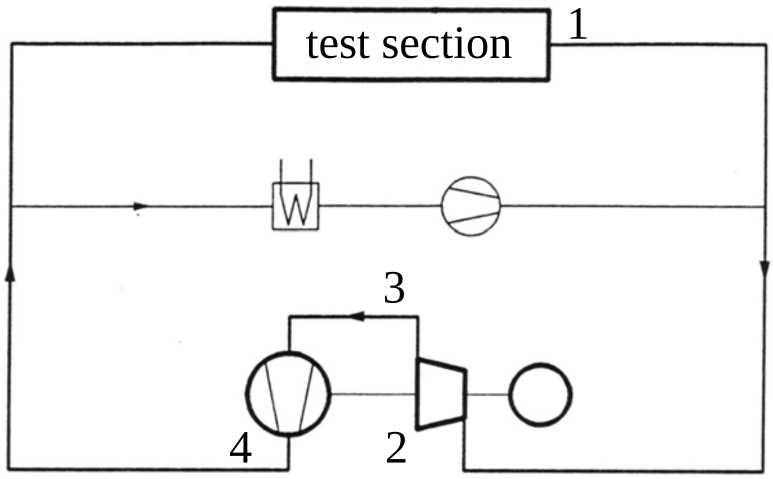


Fig. 5.9 Principal flow sheet of the HHV plant: (1: test section, 2: helium turbine, 3: connection to the compressor, 4: compressor (used as heater))

A more detailed flow sheet is given below in Fig. 5.10, which includes the position of the valves in the gas ducts as well as other important auxiliary helium systems.

The compressor had a power of 90 *MW* and heats a mass flow of 212 *kg/s* to a temperature of 850°*C* and 60 *bar*. The turbine generates 45 MW of the compressor power and the difference of 45 *MW* is delivered by an electrical motor, which is supplied by the grid. It is a very unusual method to heat up helium. But it was one intention of the experiment to test turbo machines under different conditions.

The main goal of the HHV plant was to test HHT components of relatively large size. Fig. 5.11 shows the turbo machine. The compressor is driven by an electrical motor and heats the helium. The helium is expanded in the turbine, where 50% of the compression energy can be regained. The difference must be delivered from the grid. The compressor and the turbine are placed on one shaft. The dimensions of the turbine correspond to the hot part of a 300 MW_{el} machine. Helium is circulated in the loop with a high mass flow and therefore different tests can be carried out simultaneously. Tests were conducted on the hot gas ducts, the flaps and valves, the heat exchangers, and different important systems of the HTR such as the gas purification system.

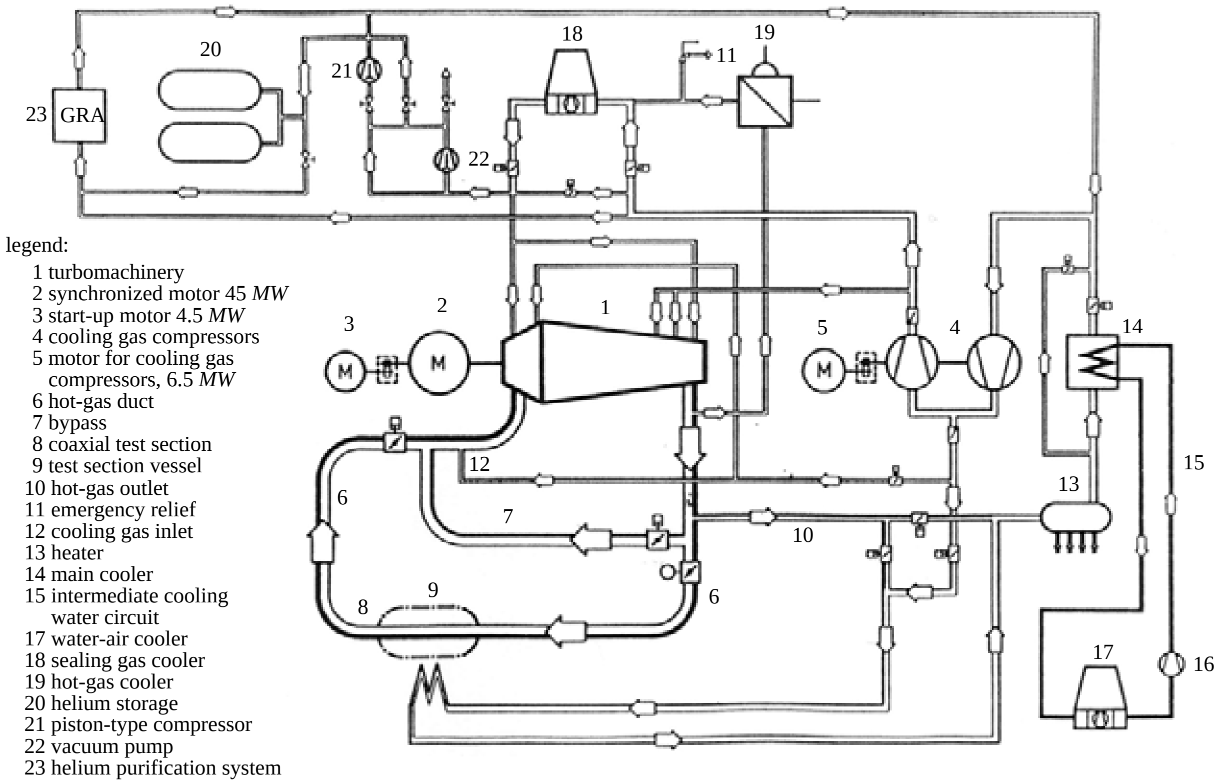


Fig. 5.10: Overall flow sheet of the HHV plant

The turbo machine has a compressor with eight stages while the turbine has just two stages. The turbo machine rotor had a weight of 60 *t*, a bearing distance of 5.7 *m*, and a total length of 8 *m*. The blade channel had an inner diameter of 1.6 *m*,an outer diameter of 1.8 *m*, and an overall length of 2.3 *m*. The blades were made from Nimocast 713 LC, all blade feet were provided with a helium cooling. The rotor was supported by two segmental shoe bearings with forced oil lubrication.

The power and temperature of the test plants were regulated at constant revolutions of the turbo machinery. The temperature and the pressure were regulated by adjusting the helium flow rate. Fig. 5.12 gives a detailed diagram of the flow of the coolant and sealing gas in the turbo machinery.

The HHV experienced some start-up problems that were soon corrected. The research and development program at this facility is considered to be successful and fully demonstrative of the feasibility of using high temperature helium as a Brayton cycle working fluid for direct power conversion from a helium cooled nuclear reactor.

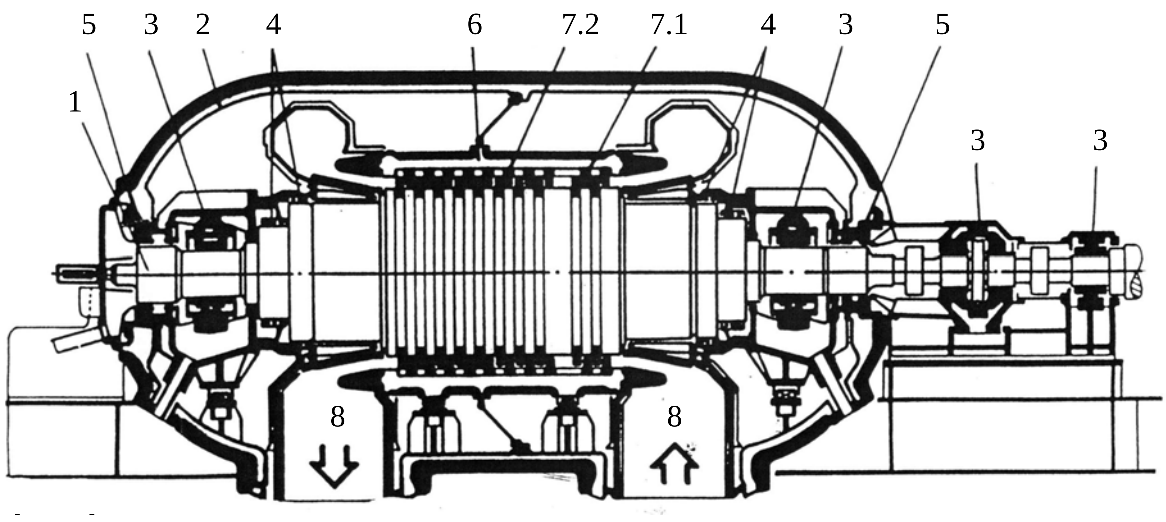
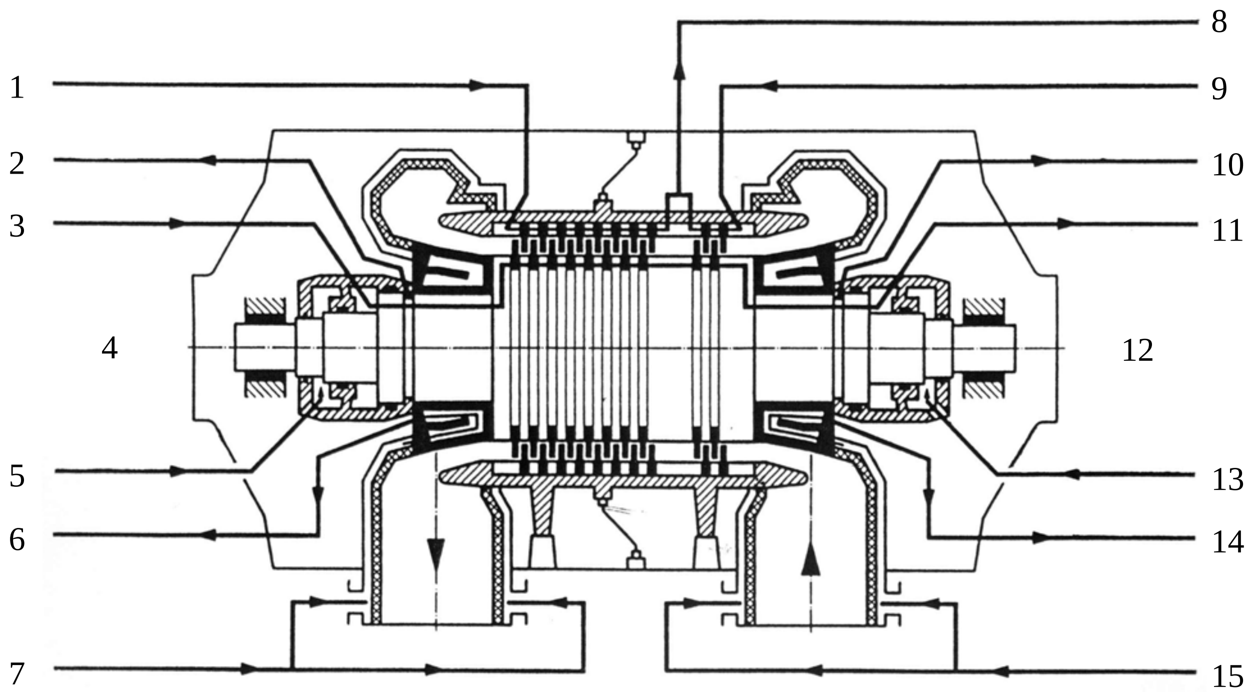


Fig. 5.11: Longitudinal section of the HHV turbo machine: (1: rotor, 2: outer casing, 3: bearings, 4: labyrinth seals, 5: shaft seals, 6: stationary blade carrier, 7: blades, 7.1: turbine section, 7.2: compressor section, 8: connecting nozzles to and from hot gas ducts)



legend :

1 inlet at stator compressor section	5 sealing gas inlet	9 inlet at turbine section
2 sealing gas outlet	6 gas outlet nozzle	10 sealing gas outlet
3 inlet into rotor	7 gas inlet nozzle	11 outlet from rotor
4 low pressure side	8 outlet at stator	12 drive-motor side

Fig. 5.12: Cooling and sealing gas flow in the turbo machinery of the HHV

6. Circulators in CO_2 cooled reactors [6.1 to 6.11]

6.1. Overview on Magnox- and AGR-reactors

CO_2 cooled reactors have been built and operated successful as Magnox- and AGR-plants. Many different circulator designs have been used in the CO_2-cooling loops, and these designs from the technological basis for circulators in helium cooled reactors as well. The availability of these reactors is very high to some extent, and many years of successful operation demonstrate that the circulator designs are based on proven technology. Table 6.1 contains some data of Magnox reactors, where as table 6.2 provides some information on AGR plants.

Table 6.1: Some data of Magnox-reactors

Plant	Electrical power (*MW*)	Core power density (*MW/m³*)	Coolant pressure (*bar*)	Reactor pressure vessel	Net efficiency (%)	operations time (start up)
Calder Hall	4 x 46	0.55	8	steel cylinder	19	1956 ... 1958
Chapelcross	4 x 46	0.6	17.6	steel cylinder	19	1958 ... 1960
Berkeley	2 x 166	0.55	9.6	steel cylinder	24.6	1962
Bradwell	2 x 169	0.56	10.1	steel	28.2	1962
Latina	210	0.71	13.6	steel	28.4	1963
Hunterston A	2 x 160	0.6	10.4	steel	28.0	1964
Hinkley Point A	2 x 270	0.73	13.8	steel	25.7	1965
Trawsfynydd	2 x 235	0.74	17.6	steel	29.0	1965
Dungeness A	2 x 212	0.76	19.5	steel	32.8	1965
Tokai Mura	166	0.51	14.4	steel	26.8	1966
Sizewell A	2 x 250	0.8	19.2	PCRN	30.5	1966
Oldbury A	2 x 225	0.82	24.1	PCRN	33.6	1967
Wylfa	2 x 495	0.9	27.6	PCRN	31.4	1971
Marcoule, G1-G3	3 x 28	0.08	1	PCRN	--	1958 ... 1960
Chinon 1	68	0.6	28.4	PCRN	23.3	1963
Chinon 2	198	0.95	24.5	PCRN	25	1965
Chinon 3	476	1.1	26	PCRN	30.8	1966
St. Laurent 1	487	1.16	26.5	PCRN	29.3	1969
St. Laurent 2	515	1.16	26.5	PCRN	30.5	1971
Bugey 1	555	1.85	42.3	PCRN	27	1972
Vandellos	500	1.22	28.4	PCRN	28.0	1972

Table 6.2: Some data of AGR-plants

Plant	**electrical power (*MW*)**	**power-density in core (*MW/m³*)**	**pressure of coolant (*bar*)**	**reactor-pressure vessel**	**net efficiency (%)**	**start-up**
Windscale* AGR	34			steel		1963
Hunterston B	2 x 660			PCRV		1976 1977
Hinkley Point B	2 x 660	2.77	42	PCRV	41	1976 1978
Dungeness B-1	508			PCRV	41	1983
Dungeness B-2	660			PCRV	41	1985
Hartlepool	2 x 660			PCRV	41	1983 1985
Heysham I	2 x 660			PCRV	41	1983 1985
Heysham II	2 x 660			PCRV	41	1988
Torness	2 x 701			PCRV	41	1989 1989

6.2. CO_2 circulators in Magnox plants

Table 6.3 contains some information on circulators in Magnox plants. Partly the power of these machines had to be very large, caused by the use of CO_2 as reactor coolant.

Type of compressors, design of impellers, type ofl lubrication, and type of sealing system using gas flow are necessary specifications for CO_2 circulators as well as for helium circulators.

It was easy to design helium circulators on the basis of proven technology of machines for CO_2-cooled reactors. All the technical aspects, which are today important for the realisation of helium circulators as radial compressors, over-hang arrangement of the impeller, oil lubrication, sealing system using gas flow, where already realised in these machines.

An example of these designs is given in the next figure. Fig. 6.1 show the CO_2 circulator in the Tokai Mura plant (Japan). It is a radial machine. A different design for a CO_2-circulator is explained on behalf of the machines used in the plant in Oldbury. The circulators are installed in the walls of the prestressed concrete reactor pressure vessel. The separation between the both sides of the circulator is formed by the boiler shield wall in this application.

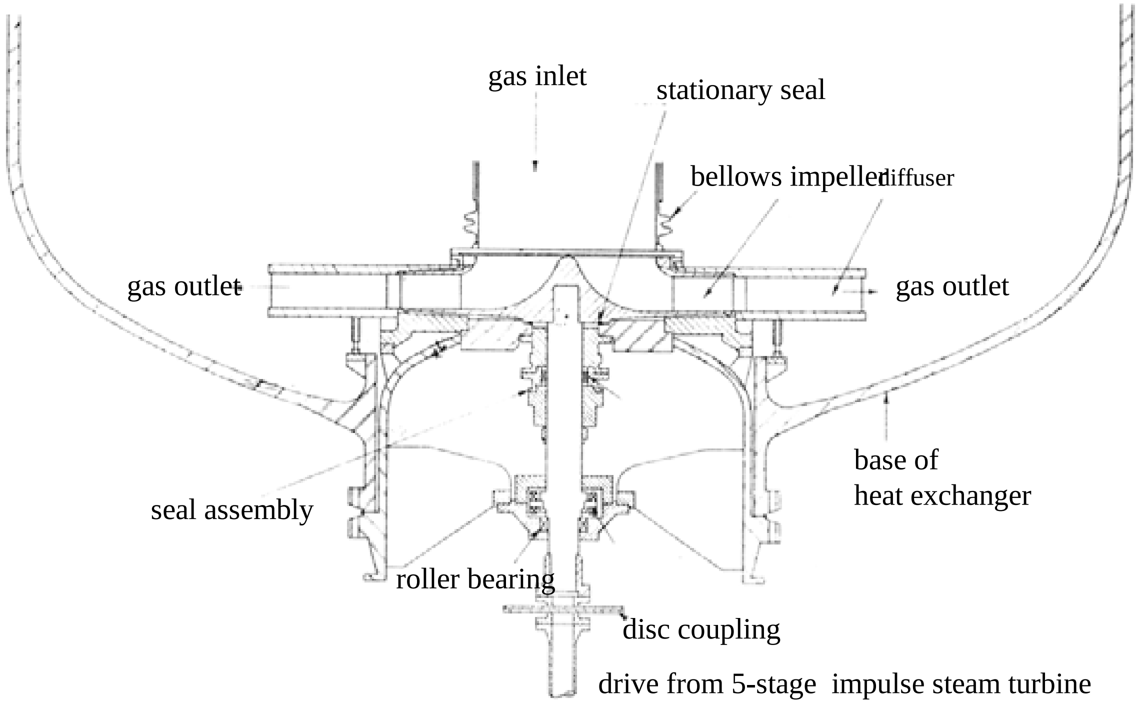


Fig. 6.1: Cross-sectional through the Tokai Mura circulator (centrifugal compressor, arranged at a steam generator vessel)

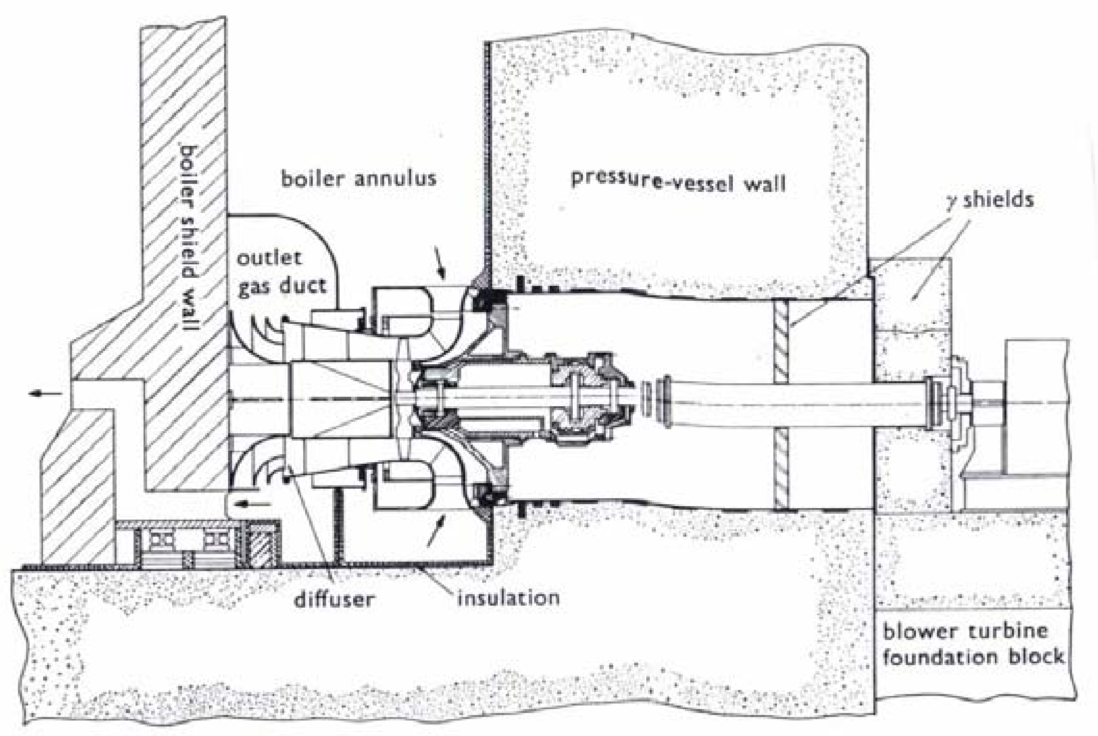


Fig. 6.2: Circulator of the Oldbury plants (arrangements on the walls of prestressed reactor pressure vessel)

Table 6.3: Data of CO_2-circulators in Magnox reactors

Plant	Calder Hall	Bradwell	Berkely	Huterston	Hinkley Point	Latina	Trawsfynydd
Station manufacturer	--	N.P.P:C	A.E.I./J.T.	G.E.C/S.C.	A.P.P.	N.P.P.C.	A.P.C.
Circulator manufacturer	Parsons	Parsons	A.E.I.	G.E.C.	E.E.C	Parsons	R.W.
Power output (per reactor) [*MW*]	40	150	138	160	250	200	250
Number of circulators per reactor	4	6	8	8	6	6	6
Coolant	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2
Type of circulator	C.F.	Axial	Axial	C.F.	Axial	Axial	Axial
Shaft layout	Horizontal	Horizontal	Horizontal	Verical	Horizontal	Horizontal	Horizontal
Sub-type (blading arrangement)		S.R.	RS(S)		SRS	S.R.	SRS
Drive motor	d.c.	a.c.	Mains a.c.	d.c.	a.c.	a.c.	Mains a.c.
Flow variation controller	Ward Leonard	Auxiliary turbine	Hydraulic coupling	Transformer and mercury arc rectifier	Auxiliary turbine	Auxiliary turbine	Control valves
Circulator performance							
Power, hp	1500/200	3225/4325	3800	2130/2350	7100	4115/4760	6200/7000
Mass flow, [*lb./sec*]	500/550	903/993	805	756	1736	1162/1220	1500/1550
Inlet temperature, [°*C*],	140	175	155	200	180 (250 max.)	175	196
[°*F*]	284	347	311	392	356	347	385
Inlet Pressure [*psia*]	110	140	132.45	158	192	187	241
Pressure rise [*psi*]	5.5/6.7	7.6/9.2	7.25	6.8/7.6	8.0	10.1/11.1	14.0
Pressure ratio	1.05/1.06	1.055/1.066	1.055	1.043/1.048	1.045	1.054/1.059	1.058
Speed [*rpm*]	850/940	3000/3300	2725/2903	1000/1040	2550/2950	2250/2363	2950/3000

6.3. CO_2-Circulators in the Windscale AGR

The Windscale AGR was the prototype of the AGR reactor. It had a thermal power of 200 *MW* and was in successful operation for more than 10 years. It used four loops containing steam generators and CO_2 circulators as shown in Fig. 6.3. The steam generators were connected to the reactor pressure vessel via coaxial duct systems. The CO_2-circulators were situated at the bottom of the steam generator vessels.

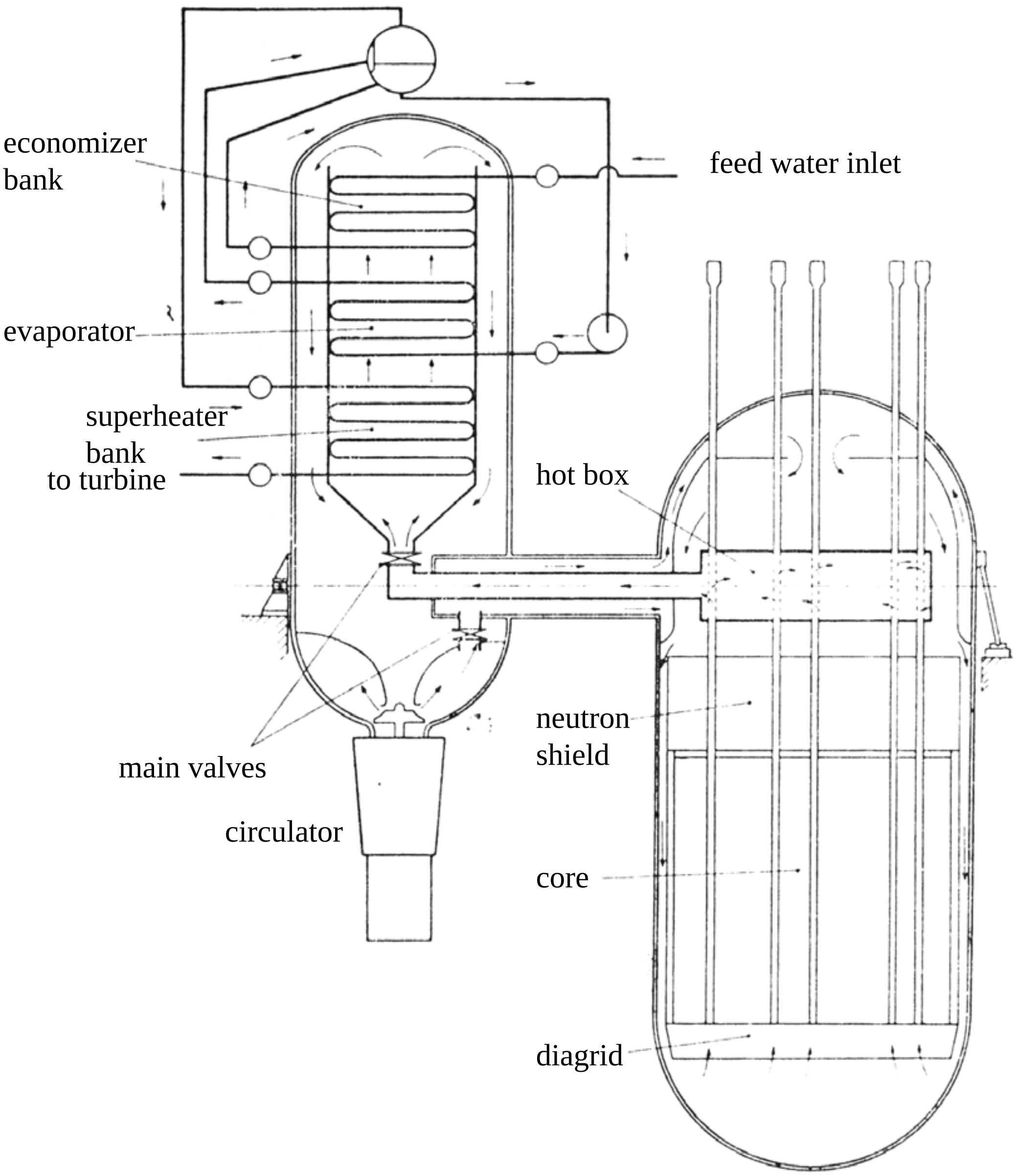


Fig. 6.3: Arrangement of the primary components of the Windscale AGR plant

The circulator shown in Fig. 6.4 is a one-stage radial compressor with the wheel in the overhang position. An electrical motor contained in the pressure circuit provides the drive.

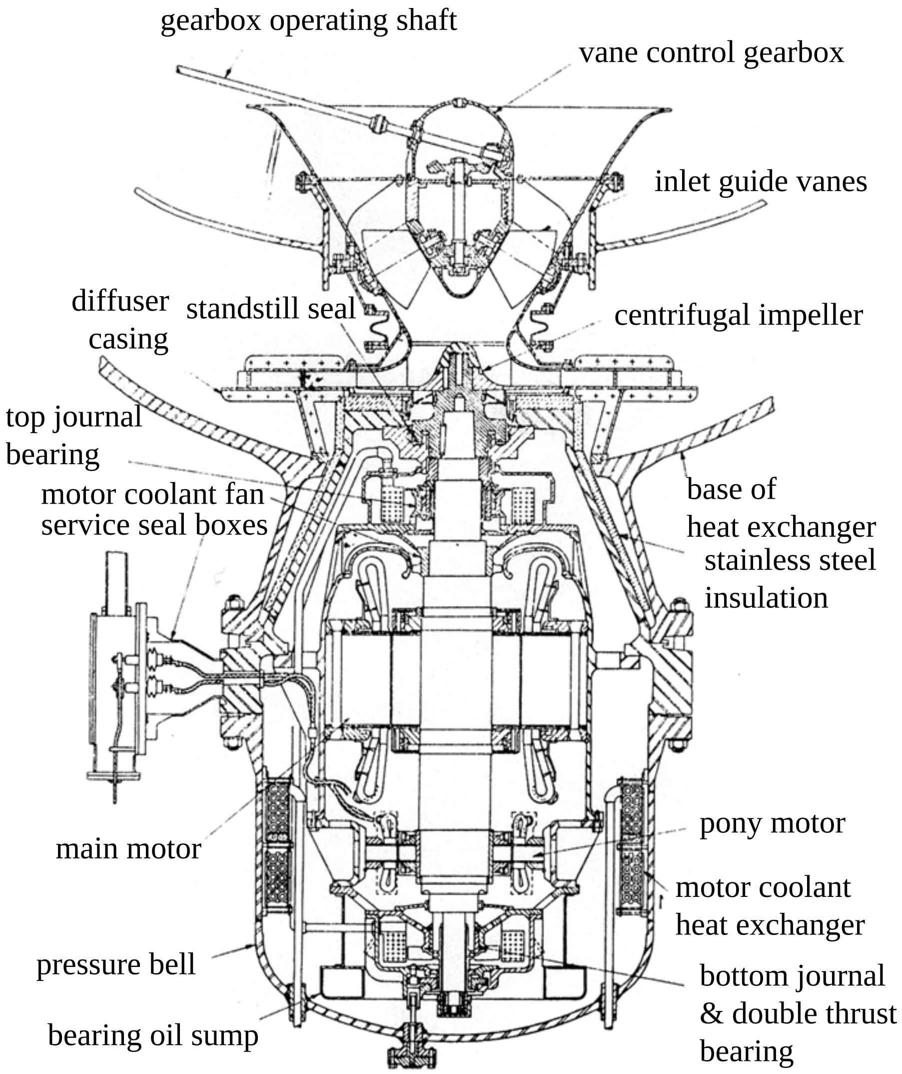


Fig. 6.4: Diagram of the CO_2 circulator in the Windscale AGR plant

6.4. CO_2 circulators in large AGR plants (arrangement of steam generators in the core cavity)

Some large AGR plants use a pre-stressed concrete reactor pressure vessel with a large cavity containing the reactor core and steam generators. The helium circulators are placed in the cylindrical wall of the reactor pressure vessel (Fig. 6.5). In a 660 MW_{el} plant, 8 CO_2 circulators are installed to compensate for the pressure losses in the cycle.

The compressor unit is shown in Fig. 6.6. It is a radial one stage circulator. The impeller is placed in overhang position at the end of the shaft, therefore allowing the motor and the circulator to be designed in a compact manner.

All of the aggregate is housed in an armoured steel pipe which is arranged inside the walls of the pre-stressed concrete vessel.

There is a flange ring seal between the impeller and the motor. The pressure difference on either side of the seal is negligible in normal operation.

The circulator can be controlled over a wide working range, and it must be possible to start blowers with the other machines already running.

The blowers are operated at a constant speed of revolution by means of adjustable initial vortex vanes. A bypass device at the impeller outlet makes it possible to achieve a slow increase of the delivery flow from almost zero to full mass flow.

The vanes are operated by an electric servo motor.

The backward rotation of the blower in the event of outage is prevented by a pawl stop at the end of the shaft. The electrical drive motor is a very compact squirrel cage a.a. motor. The motor cooler is also housed in the armour pipe.

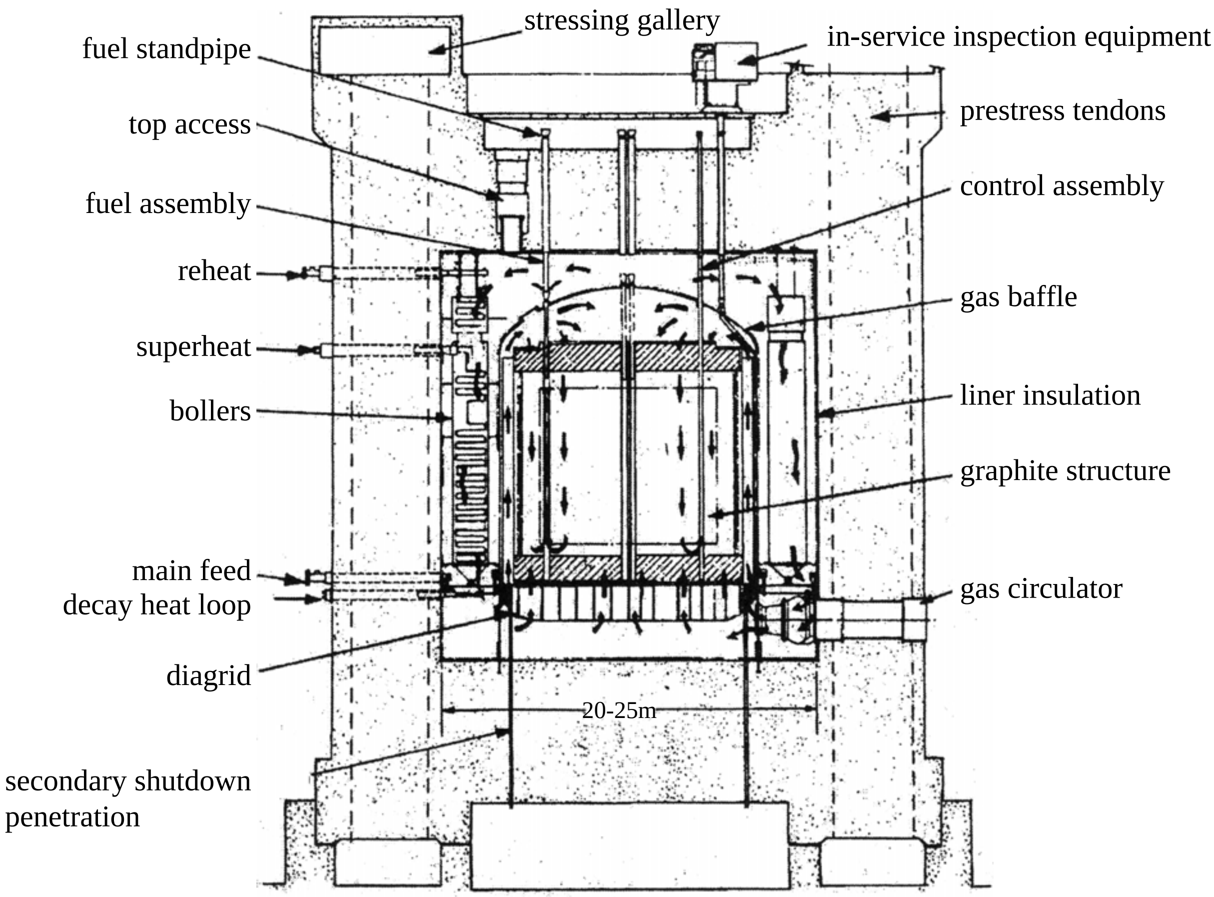


Fig. 6.5: Primary system of a large AGR plant (Heysham 2, steam generators in core cavity)

The motor is cooled by a small blower on the motor shaft.

The impeller shaft runs in sliding bearings lubricated with oil under pressure. The oil supply unit is housed in a separate pressure vessel that contains the oil pumps, the valves, the regulation devices, and the oil supply tank.

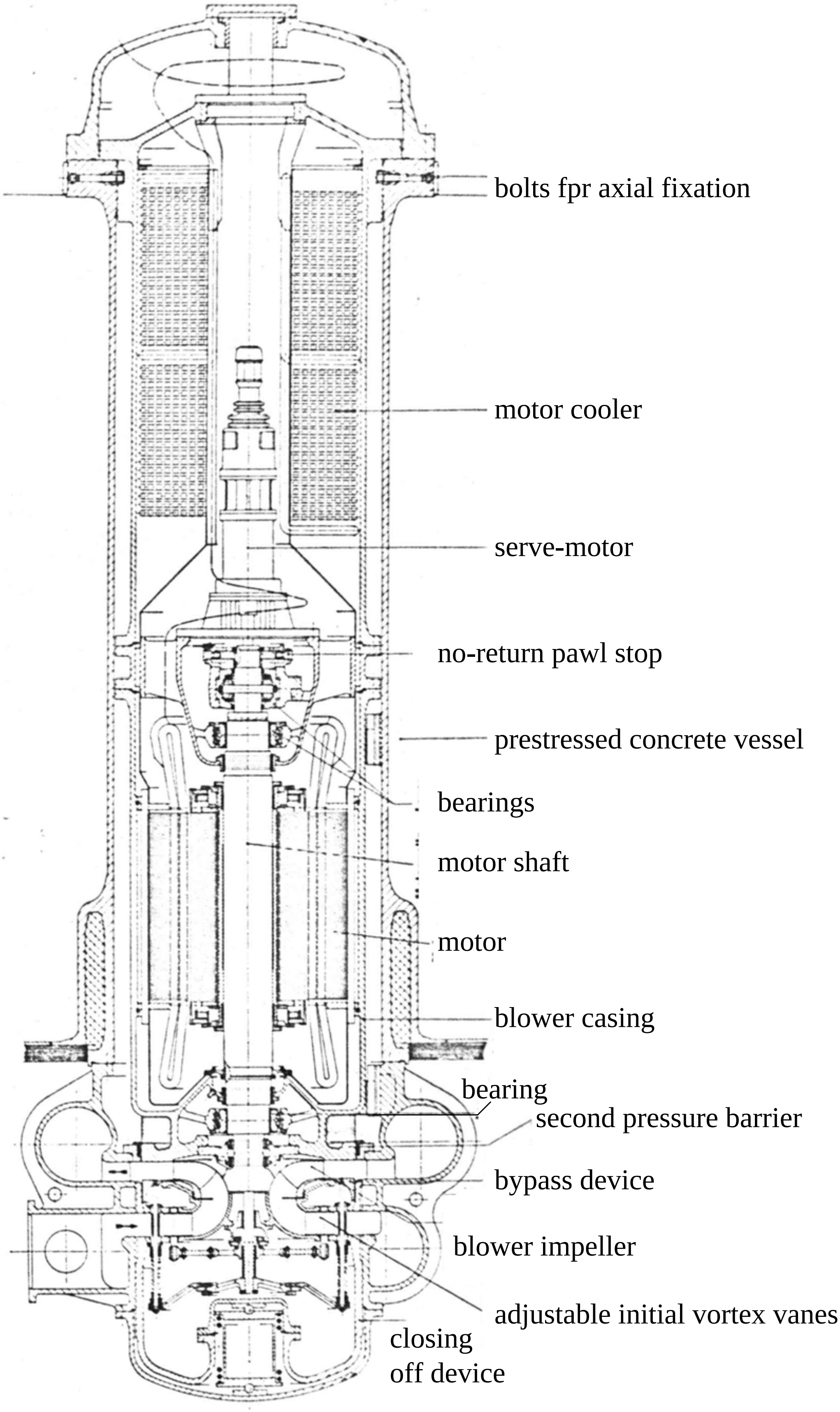


Fig. 6.6: CO_2 circulator in an AGR plant (Heysham 2)

6.5. CO_2-circulators in large AGR-plants (pod boiler arrangement of steam generators)

The AGR-plants that have been built in the last phase of the AGR development, were pod boiler systems (Fig. 6.7). Eight steam generator/CO_2-circulator units are arranged in the wall of the reactor's prestressed concrete pressure vessel. These so-called pods are connected with the core cavity by gas ducts as shown in Fig. 6.7. The circulators are arranged in vertical position at the bottom of the vessel. They are completely enclosed with an electrical motor and control gear in a penetration at the vessel bottom.

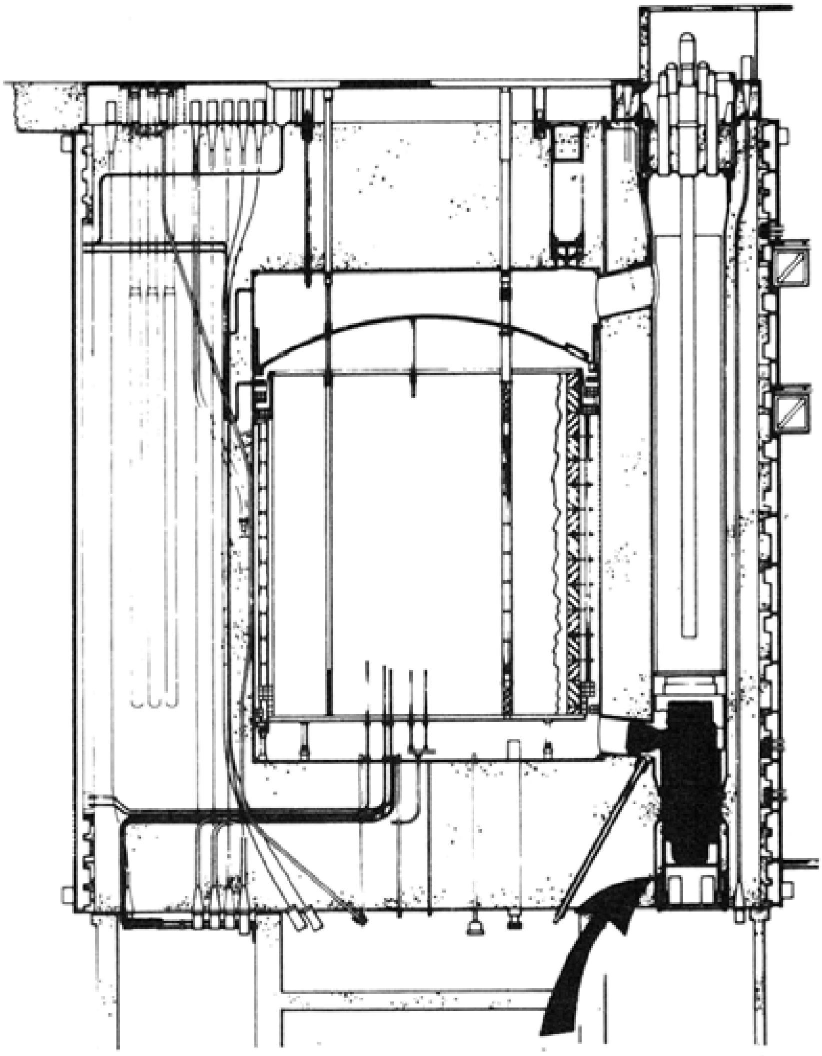


Fig. 6.7: Arrangement of primary circuit of an AGR pod boiler plant

The circulator units (Fig. 6.8) are centrifugal compressors driven by induction motors.

The CO_2-inlet is at the top of the component, the outlet on the side. The normal operating speed of the machine is 3000 1/*min*, a variable frequency supply of the motor via a separate circuit-breaker enables the operation at lower speeds. Typically the circulator speed can drop under trip conditions to around 450 1/*min*. The gas flow is varied by inlet guide vanes, which also control the reverse gas flow, when the machine is operating in a stationary mode. The guide vanes, links, drive shafts and associated spur gears are located within the pressure vessel penetration, which houses each circulator unit. The drive motor gear box and the equipment for position indication is arranged outside the penetration. The machine has shaft bearing seals and a shaft labyrinth system to control the gas flow between the reactor gas circuit and the motor compartment and to prevent the ingress of oil into the reactor gas circuit.

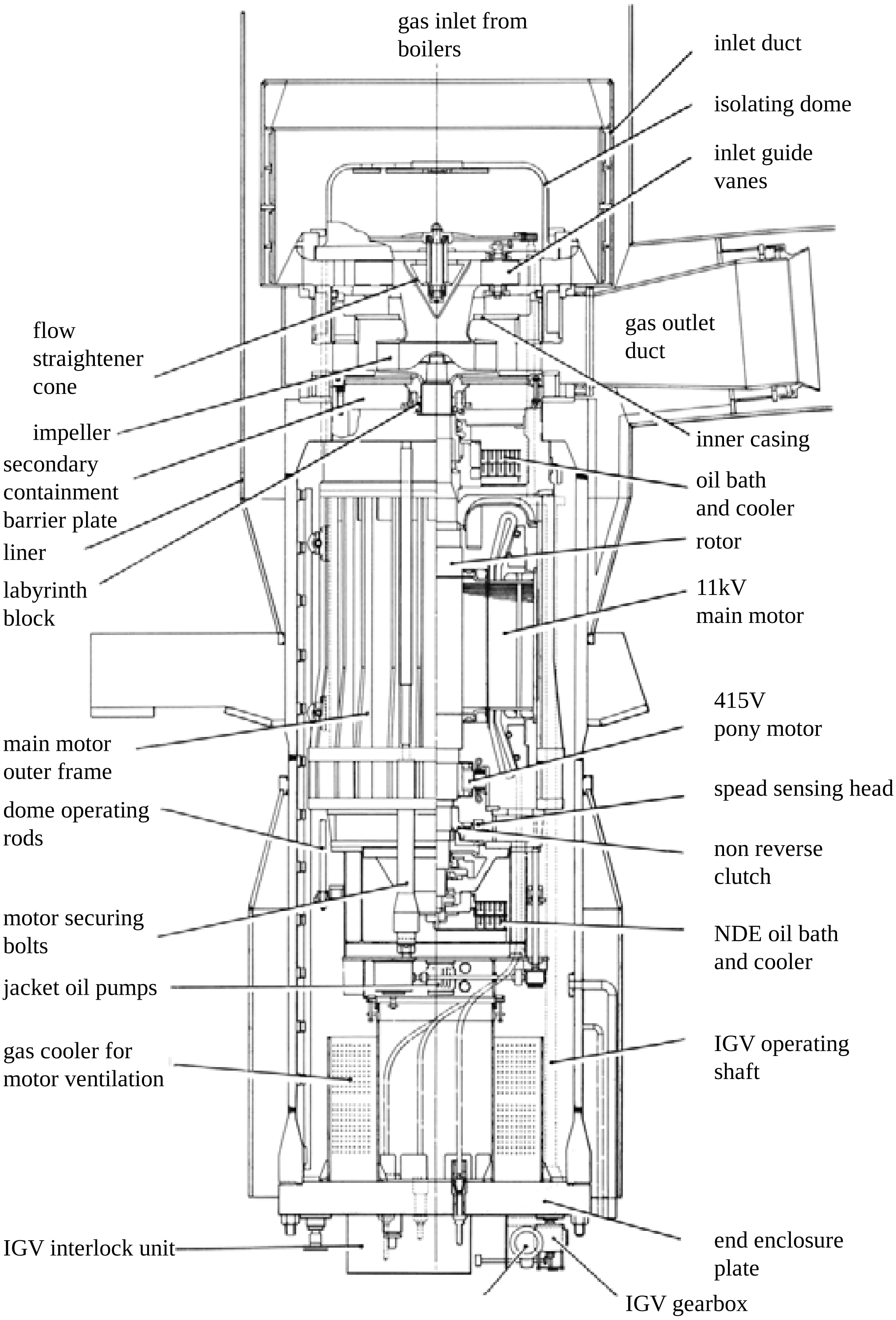


Fig. 6.8: CO_2-circulator of a large AGR-plant

The circulator inlet guide vanes and their castings are attached to the penetration and located below the steam generators and within the boiler annulus.

The outlet gas leaving the impeller is discharged via the diffuser into a nozzle, which is arranged in the gas baffle cylinder.

Any thermal movement between the outlet nozzle and the circulator casing is accommodated by the seal.

Overall it can be stated, that the circulators of CO_2-cooled reactors are very good proven technology today and that they form a very good basis for the technology of circulators of helium cooled reactors.

7. Some technical aspects relevant for helium circulators

The intention in this section is not to discuss aero dynamical aspects of helium circulators, but to give some information which have impact on the design of the component in a nuclear power plant.

There are some mayor requirements, which have to be fulfilled:

- continuous operation of the reactor, high availability of the plant
- long periods between the overhand of the component including the drive
- easy maintenance and inspection
- large region of load of operation, easy control of mass flow and speed
- high efficiency of the machine and the drive
- high safety factors for the design of sensitive parts of components
- good part load behaviour
- proven design
- lifetime of the whole plant

The combination helium circulator and drive includes a large number of items, which have to be considered to find an adequate design:

- convenience of integration into the primary system of the reactor corresponding to the power of Loops
- housing of circulator, drive an auxiliary systems
- supply with necessary media (electricity, oil, coolant)
- foundation of the component, weight, handling inside the reactor building
- shielding against radiation from the reactor core
- deposition of solid fission products on the wheel and diffuser
- methods of control
- all associated equipment
- reliability of the component

- inspection, maintenance and repair
- investment costs of the component
- operation costs
- companies ready to deliver components
- importance of helium circulators and drives in the nuclear licensing process

All these aspects influence the choice of type of circulator units including drive. As already shown in an overview in Fig. 2.1 many different design options exist for the modular HTR.

Many combinations are possible and have been considered and partly planned in detail. Just some concepts stayed over and have been used successful.

Some technical aspects, which always cause discussions on this component are:

- type of bearings
- method to get tightness
- concept of drive
- materials

Related to bearings the status today is as follows. Bearings with oil are fully developed and state of technology. Magnetic bearing would be advantageous for future gas cooled reactor plants, because the supply with operational fluids would be much easier and the ingress of external fluids getting from this component into the primary circuit would be avoided. Today however this type of bearing is just available for machines with small power.

Bearings using gas have some advantages: no impurities from oil lubrication can enter the primary circuit; these type of bearings can be operated at relatively high temperatures, too; there is no influence by radiation; sealing systems and bearing system use the same gas.

The Dragon reactor used this concept very successful for many years. Fig. 7.1 shows the concept of lubrication by oil and by gas.

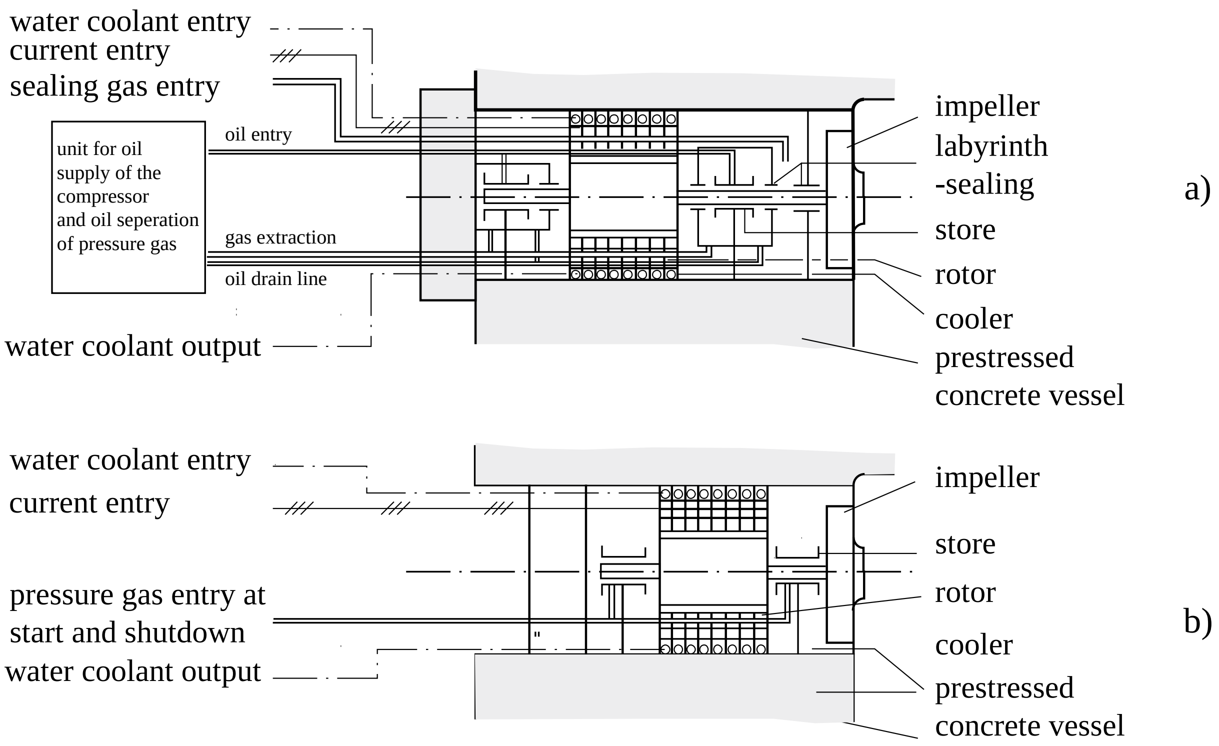


Fig. 7.1 Principle of lubrification of circulators in helium cooled reactors:
a) oil lubrification,
b) gas lubrification

In case of oil lubrication effective sealing system have to be installed to prevent the ingress of oil effective sealing systems have to be installed to prevent the ingress of oil into the primary system. Oil would cause the forming of impurities like H_2, CO, CO_2 or CH_4. They could cause corrosion on graphite structures, if their content became too high.

A further interesting option for the future are magnetic bearings instead of oil lubrificated bearings this system could reduce the maintenance expenses significantly. Figure 7.2 shows the principle of such a magnetic bearing. A stationary electromagnetic field for the stator and rotating iron material for the rotor are used. The well is hold in the foreseen position under different loads by sensor-steering. For smaller units this concept of bearing is already state of technology. Larger bearings corresponding to the power of circulators of some MW are under development and will be available in the future.

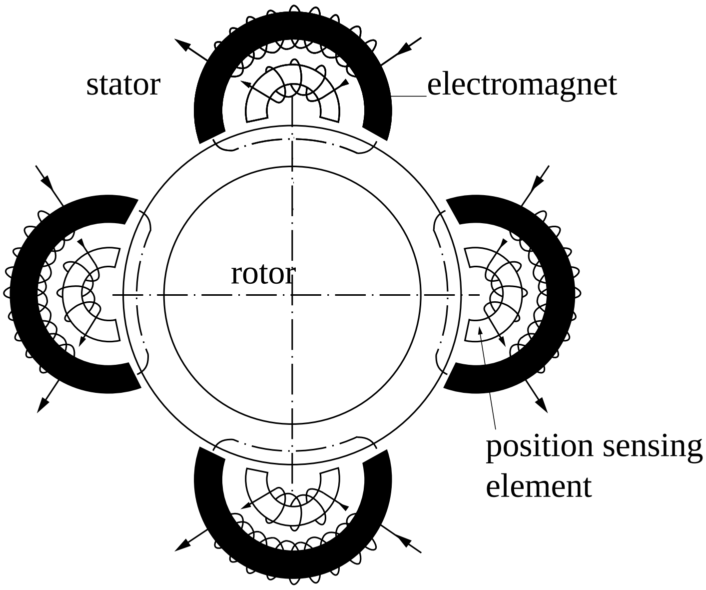


Fig. 7.2 Magnetic bearing for circulators in helium cooled reactors

The drive of the circulator either can be a steam turbine or an electrical motor. Fig. 7.3 shows both principles.

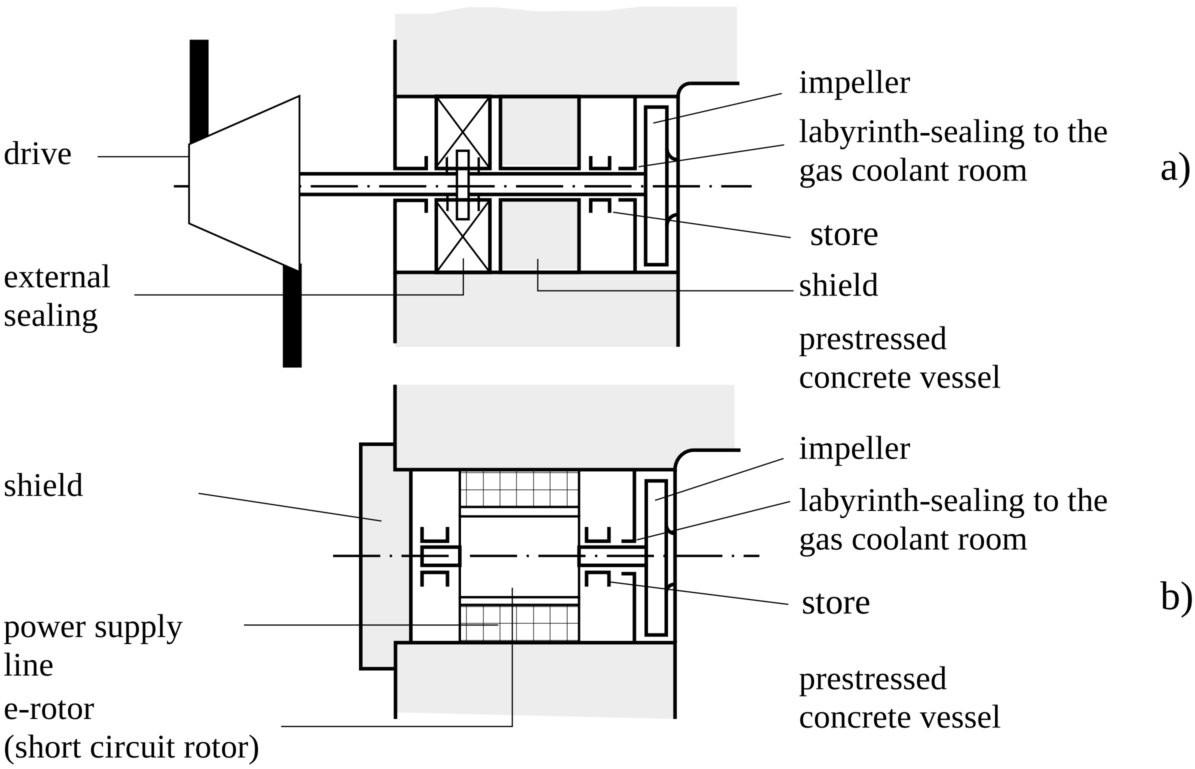


Fig. 7.3 Technical solutions of tightness problems for the circulator unit:
a) steam turbine,
b) electro motor drive

The materials used in helium circulators are oriented at an inlet temperature of values between 250 und 350°C. For the THTR 300 with an inlet temperature of 250°C as example the following materials were foreseen:

wheel	GS17 MoV5´1
shaft	24 Ni 8
bearing	Lg Sn 80
bypass and closure system	GS17 CrMo55
housing	15 MO 3
suction system	22 Cr Mo44
housing of motor, closure	H1

These are normal materials known from power technology. Irradiation effects are avoided by a suited design of shielding in case of THTR and by arrangement of circulator far away from core with additional concrete shielding in modular HTR.

Steam turbines promise some advantage so far as total efficiency of the drive units considered. However especially the sealing plays a mayor role. The experience with steam turbine drives at Fort St. Vrain was not good as expected. Sometimes leakages of steam into the primary system happened and caused shut down of the plant. Sealing system with helium worked very well in all HTR-plants and can be valuated as state of technology today.

The circulator drives are switched on and off automatically or hand operated. When the oil supply is disturbed or limiting temperatures in the motor are exceeded, an automatically shut-off is carried out. Measurements of oil temperatures, bearing temperatures, numbers of revolution, power input, oscillations, flow throughput for oil are carried out for the surveillance of the component.

Due to the successful operation of circulators in gas cooled reactors (AVR, Dragon, Peach Bottom, Magnox and AGR) for decades, it may be stated, that this component is well proved today. Important technical aspects are the tightness against the primary helium circuit and the concept of lubrication.

Especially the circulators of AVR have worked for more than 20 years with very high availability and without any serious problems. Even after a large ingress of water into the primary system the circulator was able to continue operation after drying the component.

Further developments in the field of helium circulators are carried out in order to use circulator units positioned as hanging or in a standing position.

For the wheel of the circulators standard materials have been applied, because the temperature normally was limited to 250 to 350°C.

8. Appendix: Data of Helium [7.1 to 7.2]

The following equations and correlations are valid in the temperature range from 273 to 1500 *K* and pressure range from 10^5 to 10^7 *Pa*. Where relevant, an estimate is given on the error bounds for the particular quantity in question. The uncertainty values represent the estimated error bounds except for the viscosity and thermal conductivity, for which the standard deviations are given. Values in parentheses are estimated for the extended temperature range from 90 to 3000 K. Where only one value is given, it may be used for the complete temperature range.

Gas Constant — Uncertainty

$$R = 2077.22 \frac{J}{kg \cdot K} \qquad < 0.05\%$$

Equation of State:

$$P \cdot V = R \cdot T + P \cdot B(T),$$

where

$$B(T) = C_1 + \frac{C_2}{1\text{-}C_3 \cdot T} + \frac{C_4}{1 + C_5 \cdot T}$$

$$C_1 = 9.489433 \cdot 10^{-4} \left(\frac{m^3}{kg}\right)$$

$$C_2 = 9.528079 \cdot 10^{-4} \left(\frac{m^3}{kg}\right)$$

$$C_3 = 3.420680 \cdot 10^{-2} \left(K^{-1}\right)$$

$$C_4 = 2.739470 \cdot 10^{-3} \left(\frac{m^3}{kg}\right)$$

$$C_5 = 9.409120 \cdot 10^{-4} \left(K^{-1}\right)$$

Compressibility:

$$Z = 1 + \frac{P}{R \cdot T} \cdot B(T) \qquad < 1\%$$

Density:

$$\rho = \frac{P}{R \cdot T + P \cdot B(T)} \qquad < 0.5\% \; (< 5\%)$$

Specific heat:

$$C_p = 5193 \frac{J}{kg \cdot K} \qquad < 0.5\% \; (< 4\%)$$

$$C_v = 3116 \frac{J}{kg \cdot K} \qquad < 0.5\% \; (< 4\%)$$

and

$$\gamma = \frac{C_p}{C_v} = 1.666$$

Enthalpy: Uncertainty

$$H - H_0 = C_p \cdot T + \left[B(T) - T \frac{d}{dT} B(T) \right] \cdot \mathrm{P}$$ <1%

Entropy:

$$S - S_0 = C_p \cdot \ln\left(\frac{T}{T_0}\right) - R \cdot \ln\left(\frac{P}{P_0}\right) - P \frac{d}{dT} B(T)$$ <1%

Sonic velocity:

$$c = Z\sqrt{\gamma \cdot R \cdot T}$$ <1%

Viscositv:

$$\mu = 3.953 \cdot 10^{-7} \cdot \mathrm{T}^{0.681} \frac{N \cdot s}{m^2}$$ $\sigma_\mu = 1.5\%$

Thermal conductivity:

$$k = 2.77a \cdot 10^{-3} \cdot T^{0.701} \frac{W}{m \cdot K}$$ $\sigma_k = 2.4\%$

Prandtl number:

$$\mathrm{Pr} = \frac{\mu \cdot \mathrm{C_p}}{\mathrm{k}} = 0.740 \cdot T^{-0.014};\ T \text{ in } K$$ $< 3\% \ (< 5\%)$

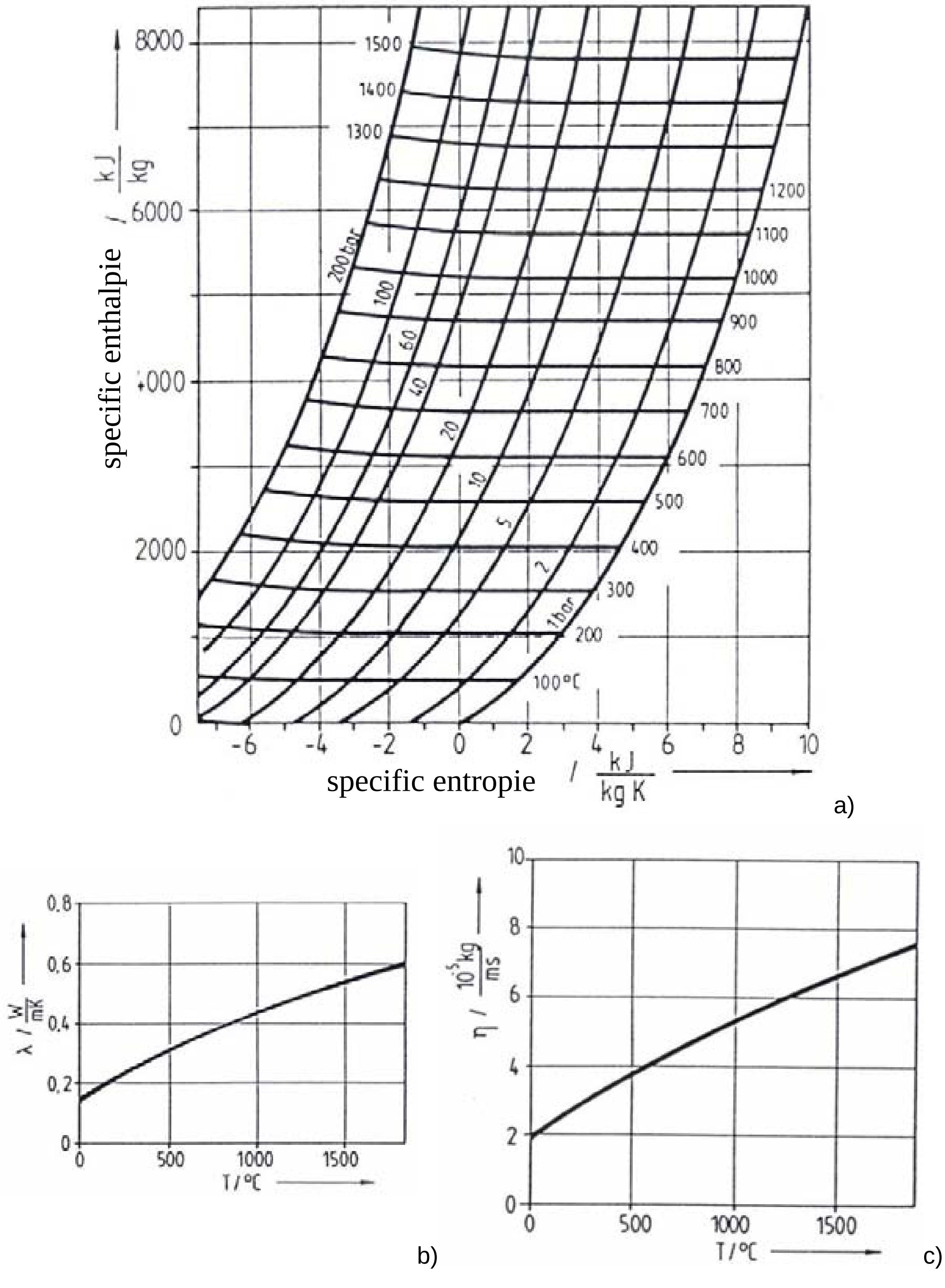


Fig. 8.1: Some useful data of helium
a) *h*-*s*-diagram, b) $\lambda(T)$, c) $\eta(T)$

9. Table of figures

10. Table of tables

11. Literature

Chapter 1

[1.1] R. Katz:
Thermal design aspects of gas cooled reactor cores
GA7941, 1967

[1.2] G. Melese, R. Katz:
Thermal ad Flow Design of Helium Cooled Reactors
American Nuclear Society,
La Grange, Illinois, USA, 1984

[1.3] I. Kosmowski, G. Schramm, G. Sörgel:
Turbomaschinen
VEB Verlag Technik, Berlin 1987

[1.4] K. Kugeler, R. Schulten:
Hochtemperaturreaktortechnik
Springer Verlag, Berlin, Heidelberg, New York, London, Paris, Tokyo, Hongkong, 1989

[1.5] G. Melese - d'Hospital:
Simplified Analysis of Coolant flow and outlet temperature in gas cooled Nuclear reactor cores
Nucl. Science Engin. 35, 165, 1969

Chapter 2

[2.1] C.A. Rennie
High temperature Gas Cooled reactors
Trans. Am. Nucl. Soc. 11, 1968

[2.2] R. Schulten, D. Trauger
Gas Cooled reactors
Trans. Am. Nucl. Soc. 24, 1976

[2.3] Britisch Electricity International
Modern power station practice
Vol. 7, Nuclear power generation
Pergamon press, 1990

[2.4] D.R. Poulter
The design of gas cooled graphite miderated reactors
London Oxford University Press, 1963

Chapter 3

[3.1] E. Ziermann, G. Ivens
Abschlußbericht über den Leistungsbetrieb des AVR-Versuchs-Kernkraftwerks
FZ Jülich / AVR, 3448, 1997

[3.2] AVR-Experimental High temperature Reactor - 21 years of Successful Operation for a future Energy Technology VDI- Verlag, 1990

[3.3] E. Houert, H. Knüfer:
Gesichtspunkte für Planung, Bau und Betrieb von Gebläsen für Dampferzeuger,
VGB-Fachtagung Dampfkessel und Dampfkesselbetrieb, 1970

[3.4] J. Engelhard:
Abschlußbericht über die Errichtung und den Anfahrbetrieb des AVR-Atomkraft-Werks, K72-23, 1972

[3.5] W.C. Birley:
Operating experience of the Peach Bottom atomic power station,
Proc. ANS Meeting on Gas Cooled Reactors: HTGR and GCFBR, Gatlinburg,
May 1974

[3.6] R.D. Duffield.
Development of the high temperature Gas cooled reactor and the Peach Bottom high Temperature Gas cooled reactor prototype,
J: Brit. Nucl. Energy Soc, 5, 1966

[3.7] B. Chapman:
Operation and maintenance experience with the Dragon reactor experiment:
Proc. ANS Meeting on Gas Cooled Reactors: HTR and GCFBR, Gatlinburg, May 1974

[3.8] D. Bedenig
Gasgekühlte Hochtemperaturreaktoren
Verlag Karl Thiemig, München, 1972

[3.9] Y. H. Dschen
Gasdynamische Lager
BBC Mitteilungen, 51, No. 12, 1964

[3.10] H. Baumann
Description and Performance of the primary circulators for the OECD
High temperature Project Dragon, England,
Proc. of Meetings on Rotating Machines for Gas Cooled Reactor Application
US Atomic Energy Commission, Wash. 1963, TIO-7690

[3.11] NN:
Das 300 MW Thorium-Hochtemperatur-Kemkraftwerk THTR,
Sonderdruck Atomwirtschaft 5, May 1971

[3.12] NN:
Projektinformationen: 300 MW-THTR-Kernkraftwerk Hamm-Uentrop;
Druckschriften von H RB Mannheim, 1975 bis 1986

[3.13] Referenzentsurf 300 MW_e|-Prototypanlage; THTR-Thorium-Hochtemperatur Assoziation, 1968

[3.14] H. Crameretal.:
Components of the THTR 300 Heat transfer System;
Proc. on Compon Design in high temp. Reactor using Helium as coolant,
Instit. of Mechan. Engineers, June 1972

[3.15] J. S. Yampolsky
Circulators for helium cooled reactors
Nuclear Engineering International Dec., 1971

[3.16] C. F. Mc Donald, M. K. Nichols:
Helium circulator design considerations for modular high temperature gas cooled reactor plant,
GA-A18566, Dec. 1986

[3.17] P. E. Davis, J.M. Krase
Nuclear Components of Fort St. Vrain,
Nuclear Engineering International, Dec. 1969

[3.18] W. M. Fräser:
A Review of submerged gas circulators as applied to advanced gas cooled reactors;
Nuclear Energy, Oct. 1985

[3.19] H.G. Olson, H.L. Brey, F. E. Swart:
Fort St. Vrain high temperature gas cooled reactor;
Nuclear Engin. and Design 72, 1982

[3.20] Xu Yuanhui, Qin Zhenya, Wu Zongxin:
Design of the 10 MW High temperature reactor,
IAEA, TCM, Petten, 1994

[3.21] Xu Yuanhui, Szn Yulian:
Der gasgekühlte 10 MW-Hochtemperaturreaktor in Peking,
VGB Kraftwerkstechnik, 11, 1999

[3.22] T. Tanaka, et al.:
Construction of the HTTR and its Testing Program,
3rd JAERI Symposium on HTGR Technologies, Oarai, 1996

[3.23] JAERI:
Present Status of the HTGR Research and Development, 1989

[3.24] The Chinese High Temperature Reactor HTR 10, The First Inherently Safe Generation IV Nuclear Power System, Topical Issue, Vol. 218, 2002, No.1-3

Chapter 4

[4.1] PR 500

[4.2] Siemens/Framatome
Hochtemperaturreaktor- Modul-Kraftwerksanlage, Referenzkonzept Bd. 1 und 2;
KWU Interatome, Januar 1984

[4.3] H. Reutler:
Plant Design and Safety concept of the HTR Modul: Small and Medium Sized Nuclear Reactors:
SMIRT. Lausanne, Aug. 1987

[4.4] K. Knizia, D. Schwarz:
Der HTR 500 als nächster Hochtemperturreaktor,
VGB Kraftwerk Kraftwerkstechnik, Heft 3, 1985

[4.5] HTR 1160-Prospect

[4.6] S. Brandes. W. Kohl:
HTR 100 Industrial Plant for Generation of Heat and Electricity;
International Atomic Energy Agency, Jülich, Oct. 1986

[4.7] R. F. Turner, O. M. Stansfield, R. E. Vollman:
Annular Core of Modular High Temperature Gas Cooled Reactor;
First International Seminar on Small and Medium Sized Nuclear Reactors, Aug. 1987

[4.8] J. E. Jones Jr, P. R. Kasten:
Overview of US MHTGR Base Technology Development Program;
IAEA Techn. Com. Meeting Jülich, Oct 1986

Chapter 5

[5.1] W. Jansing, H. Breitling, R. Candeli, H . Teubner
KVKK and Status of the High Temperature component development IAEA.Techn. Comm. Meeting on Gas Cooled Reactors and their Applications 13-TC-598, 1986

[5.2] HTR-Komponenten
Stand der Entwicklungen auf dem Gebiet der wärmefiihrenden und wärmetauschenden Komponenten
Schriftenreihe „Energiepolitik in Nordrhein-Westfalen", Bd. 16-1, 16-2, 1984

[5.3] W. Jansing, H. Teubner
Der Hochtemperatur -Heliumkreislauf KW - Erfahrungen aus 20000 h Versuchsbetrieb
Jahrestagung Kerntechnik, 1990

[5.4] P. Zenker
Die 50-MW-Helium-Turbinenanlage Oberhausen VGB-Kraftwerkstechnik, 55. Jg., Heft 11, 1975

[5.5] GHH Oberhausen
Heliumturbinen für Kernkraftwerke
GHH-Technical Reports 4/67, 1967

[5.6] P. Zenker
Einige Aspekte zum Bau der 50 MW-Heliumturbinenanlagell der Energieversorgung Oberhausen
Atomkernenergie 23, No. 2, 1974

[5.7] P. Zenker
10 Jahre Betriebserfahrung mit der Heliumturbinenanlage Oberhausen

[5.8] G. Hebel, H. Weiskopf, J. Terkessidis, W. Hofmann
HHV-Anlage; Erfahrungen bei Bau und Inbetriebnahme Atomwirtschaft/Atomtechnik, No. 5, 1982

[5.9] I. A. Weisbrodt
Summary Report on Technical experiences from high temperature helium turbo machinery testing in Germany. IAEA, TEC DOC 899, 1996

[5.10] HHT-Piräsentation beim BMFT
HHT, 24, HRB-Bericht BA 1485, 1977

[5.11] HHT-Projekt
Ergebnisse der Entwicklung und Planung des Hochtemperaturreaktors mit Helium-Turbine von 1969 bis 1982 HHT, 43, BA 4267, 1983

[5.12] G. Noack, H. Weiskopf
Die Hochtemperatur-Helium-Versuchsanlage (HHV) - Aufbau und Beschreibung der Anlage, JÜL1403, 1977

Chapter 6

[6.1] K. H. Dent
The Status of Gas Cooled Reactors Nucl. Energy, 1980, 19, No. 4

[6.2] British Electricity International Modern power Station practice Vol. 7, Nuclear power generation, Pergamon Press, 1990

[6.3] G. Brown
Coolant gas circuit in D. R. Poulter, The design of gas cooled graphite moderated reactors, London Oxford University Press, 1963

[6.4] M. Simon
Circulation blowers for gas cooled reactors, Kerntechnik, 11. Jahrg. No. 9/10, 1969

[6.5] Th. Bohn
Handbuchreihe Energie Bd. 10, Kernkraftwerke Technischer Verlag Resch, Verlag TÜV Rheinland, 1986

[6.6] TNPG
Exploitation of the Advanced Gas Cooled Reactor for Hinkley Point B, Prospect

[6.7] E. P. Duffy et al.
Dungeness, B. Advanced Gas Cooled Reactors Power Station Nuclear Engineering 12, 1967

[6.8] P. J. Cameron
$C0_2$-Cooled Reactors in the UK
9. Internat. Konferenz über den H TR, VGB-TB 112, 1987

[6.9] Dungeness B.
Nuclear Engineering, 12, No. 134, 1967

[6.10] Hunterston B
Nuclear Engineering 13, No. 139, 1967

[6.11] AGR
Nuclear Engineering 6, No. 59, 1961

chapter 7

[7.1] Hewig G.:
Das reale Gasverhalten von Helium als Kühlmittel für Hochtemperaturreaktoren
Brennst.-Wärme-Kraft 29, 1977, Nr. 5, Mai

[7.2] Banerjea, A., Hammeke, K., Hüpping, N., Kipke, H.E., Stoehr, A.:
Thermodynamische Stoffwerte von Helium im Bereich von 20 bis 1500°C und 1 bis 100 bar
Bericht der Kernforschungsanlge Jülich, Jül.-1562, Dez. 1978, ISSN 0366-0885

UK experience with circulators in gas-cooled reactors

B F Riley and S Panchoo

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SUMMARY

The development of the Circulator for the VHTR is recognised as a real challenge. As part of the investigations within RAPHAEL SP CT Work Package 2, past experiences within the UK and Germany on HTG Circulators is being reviewed and assembled in order to provide an information platform on which to take the development further. This report provides the results of the UK past experience, recovering specific knowledge on development, design and operation from the Magnox, AGR and Dragon programmes with the aim of providing a collated synthesis for design investigations and future tests. This work represents NNC's contribution to Raphael Deliverable D CT 2-2.

1.0 INTRODUCTION

VHTRs are gas cooled nuclear fission reactors for future co-generation plants, designed for the sustainable production of electric energy and heat for hydrogen production or other high temperature processes. To achieve high efficiencies of 70% or more, gas outlet temperatures close to 1000°C are required. Materials and designs for long-term structural applications in such plants must be explored to allow efficient safe and reliable operation of such advanced plants.

As part of the investigations within RAPHAEL SP CT Work Package 2, past experience within the UK and Germany on Gas Circulators is being reviewed and assembled in order to provide an information platform on which to take the development further.

Gas circulation in the VHTR is required for a number of purposes. For the direct cycle VHTR, circulators are needed for the turbo-compressors/turbo-generators of the helium gas turbine plants, the start-up blower system for the turbo compressor, operational coolant gas circulation for heat transfer to the heat exchangers, coolant gas blowers in intermediate helium circuits, etc. Turbo compressors and turbo generators generally attract most attention within R&D programs, however other applications for blowers and compressors are equally important for the functionality and availability of the complete reactor system.

For the indirect cycle VHTR, the design of the Gas Circulator impeller, electric motor and bearings (electromagnetic bearings + catcher bearings and/or permanent magnetic bearings) is important for normal operation and also when under external loads from the process transients. For the power rotor, benefit can be taken from the materials investigations on the turbine. For the VHTR of 600 MWth a blower power of 10 to 15 MW is required which is much higher than in former HTRs (maximum 4 MW).

2.0 OBJECTIVES

The purpose of this report is to provide a review of UK past experience on Circulators and hot gas valves used in gas cooled reactor systems, to recover specific knowledge from development, design and operation with the aim of providing a collated synthesis for design investigations and future tests on a mock-up. This work represents NNC's contribution to Raphael Deliverable D CT 2-2.

3.0 THE HINKLEY POINT MAGNOX GAS CIRCULATOR

3.1 Design

With each of the two Magnox reactors at Hinkley Point there were six circulators, each driven by a 5.2 MW induction motor. Each circulator operated in a pressure vessel of its own, approximately 4 m in diameter and 5 m long, separate from the reactor pressure vessel. The machine is shown in cross section in Figure 1. The circulator was a single stage fan designed for a maximum speed of 3000 rpm. Other design conditions were:

Mass flow	750 kg s^{-1}
Volume flow	58 m^3 s^{-1}
Inlet pressure	11 bar
Inlet temperature	175°C
Pressure rise	0.61 bar

There were 25 inlet guide vanes. The blades were set in a nominally axial position and they were cantilevered from the outer casing where they were held firmly. They were supported lightly at the inner diameter by means of a friction damper to limit the amplitude of vibration as the circulator accelerates past the resonant frequency of the blades. Each of the eleven rotor blades were fixed to the disc by two pins. The outlet guide vanes were cantilevered from the outer casing of the diffuser and attached to it in a similar way to the inlet guide vanes. The same arrangement was also used for the attachment at the inner diameter. The diffuser was located axially by a clamp at the downstream end attached to the pressure vessel and it was allowed to expand in an upstream direction. The centre ‘bullet’ was supported by six radial spokes upstream and six downstream.

3.1.1 Failures during commissioning

Several circulators failed during the hot CO_2 test run, carried out at a temperature of 230°C with a gas inlet pressure of 14 bar. Mechanical damage to the diffuser and blading was severe. A large section of the diffuser had broken away, as shown in Figure 2, and extensive fatigue cracking was found in the outer shell and in the bullet section of one of the diffusers. Several fatigue-damaged parts are shown in Figure 3 to Figure 5. A badly damaged inlet guide vane ring is shown in Figure 6.

Large pieces of the diffuser casing had entered the circulator causing extensive impact damage. Heavy bolts and other fixtures had loosened.

The failure itself, and the wide-ranging investigation that followed, showed clearly the extreme importance attaching to acoustic phenomena in the design of large high-powered fans and structures operating at high fluid density. It was realised that the knowledge of noise generation, pressure wave propagation, and the response and fatigue endurance of structures in powerful acoustic fields was inadequate.

The primary cause of circulator failure was determined to be fatigue arising from the acoustic excitation of various components. The high excitation experienced was largely due to the aerodynamic interaction between the inlet guide vanes and the rotating blades of the circulator. The removal of the inlet guide vanes resulted in the largest single improvement of the various measures taken and greatly reduced the powerful harmonics previously measured. Improvements in the inlet flow distribution further reduced the excitation which in this case was of a random and low frequency nature. The major components involved in the failure, such as diffuser and corner cascades, were replaced by new parts of modified design. The final arrangement of the modified circulator is shown in Figure 7.

4.0 AGR GAS CIRCULATORS

4.1 Windscale gas circulator

In the prototype AGR at Windscale, which operated at 20 bar pressure, the circulator drive motor was located inside the pressure envelope even though, at 20 bar, the drive could have been located outside the pressure vessel, and a balanced pressure seal used to take the drive shaft through the vessel wall to drive the impeller. This arrangement was employed so that experience would be gained with the submerged circulator concept, which would help in the design of the circulators for future commercial AGRs operating at higher pressure. A schematic diagram of the Windscale circulator is shown in Figure 8. It was a compact vertical shaft circulator, attached to the bottom end of each of four heat exchanger vessels. The machines proved to be very reliable and gave virtually trouble-free operation for 20 years up to 1981. The first design of commercial AGR station, Dungeness B, operating at 30 bar pressure, did not use submerged gas circulators but all subsequent stations have done so.

4.2 Dungeness B gas circulator

At Dungeness B, there are four circulators per reactor, in a similar arrangement to that adopted at the earlier Magnox stations. Each circulator has an external motor unit which drives the impellor by means of a shaft penetrating the reactor closure.

The penetration of this drive shaft is sealed by a high pressure rotary seal. Flow control is achieved by varying the impeller speed with a scoop controlled fluid coupling. To make it possible to carry out maintenance work on the circulator bearings or rotating shaft seal, a stand-still seal is provided on the drive side of the impeller. To bring this seal into operation on a stationary circulator the motor thrust block is withdrawn, bringing that portion of the stand-still seal on the impeller into contact with a mating face on the circulator casing.

In the alternative design employed on future AGR stations it was decided to use circulators contained within the reactor pressure circuit, with eight circulators per reactor. This form of circulator was selected to eliminate the rotary shaft seal and provide a more certain method of preventing gas leakage at the higher pressures (40 bar) and temperatures. In addition, use of the submerged design of circulator would reduce reactor down time by having spare units available so that when a machine became due for overhaul it could be removed for service while the reactor was back at power with a replacement circulator installed.

4.3 Hinkley Point B and Hunterston B gas circulator

4.3.1 Design

The Hinkley Point B and Hunterston B AGRs incorporated eight submerged circulators per reactor. A schematic diagram of the circulator is shown in Figure 9. More detail is shown in Figure 10. The complete driving motor (1) is contained within the concrete wall of the pressure vessel. The outer end of the penetration is closed by a flat plate closure (2) which contains the gas pressure of 40 bar. The motor is cooled by circulation of the high pressure gas which gives up its heat to a finned tube cooler (3), controlling the motor compartment gas temperature to around 50°C. The motor shaft is carried in two oil lubricated, pressure fed bearings and extends forward to carry the direct mounted circulator impeller. The non-driving end of the motor carries the vane control operating gear (5) with duplicate drive motors and Selsyn transmitters, and also the isolation dome mechanical operating gear.

A sub-assembly, as shown in Figure 11, consisting of variable inlet vane control and inlet cone, annular diffuser, shaft labyrinth seal and 165 mm thick steel barrier plate is bolted to the forward end of the motor to form an integrated unit that can readily be removed with the motor and impeller for inspection and maintenance. The unit is secured to a removable mounting flange at the inner end of the reactor wall penetration by long studs, (6) in Figure 10. For ease of removal and installation, the unit is fitted with three recirculating roller units, running on a central monorail. In the event of failure of the end closure plate (2), or sudden depressurisation of the motor compartment, the unit will remain in position, the full gas pressure being contained by the heavy barrier plate at the forward end. This double containment is an important safety feature of the submerged circulator design. The circulator casing, shown in Figure 12, which is permanently fixed within the reactor circuit, is of annular design, and embodies fixed diffuser vanes and fixed straightening vanes. A high pressure isolation dome, (7) in Figure 10, is also incorporated in the circulator. By remote operation, the dome can be drawn into contact with a sealing ring and the inner end of the penetration, forming a pressure-tight closure. The motor compartment can then be pressurised and the circulator removed without depressurising the reactor.

The adiabatic static efficiency of the complete circulator, as measured in air at full speed, is 87%. The 813 mm diameter impeller pumps 0.5 tonnes of CO_2 per second, against a pressure rise of 2.9 bar. Impeller power is 5 MW at design conditions. The impeller, shown in Figure 13, is fabricated from cast hollow aerofoil blades, butt welded to cast, fully machined backplate and sideplate shrouds.

The drive unit is a constant speed two pole induction motor, operating from an 11 kV, 3 phase, 50 Hz supply. Conflicting requirements for full density and atmospheric operation meant that special consideration had to be given to thermal design to ensure adequate cooling at low pressure without excessive coolant pumping power at high pressure. Windage losses were controlled by clean main rotor design and by minimising the pumping action of all rotating parts, since windage is a major component of motor losses when operating in CO_2 at 62 kg m^{-3}. The motor frame is of robust construction to carry the full barrier plate load in the event of a depressurisation accident.

The complete working unit, consisting of motor, barrier plate, labyrinth system, vane control, inner casing, impeller and diffuser can be removed by taking out the end closure, disconnecting services and unbolting. A replacement unit can be quickly inserted.

4.3.2 Issues arising during development

Inlet guide vane bearings

A special stainless steel roller bearing was developed for the Windscale circulator, on which it worked successfully. The same bearing was used on the prototype circulator for Hinkley Point B. After a few hundred hours operation, the inlet guide vane system became very stiff to operate. The problem was traced to dimensional instability in the bearing components resulting from materials changes during manufacture and was solved by modifying the manufacturing specification and applying stringent QA procedures.

Vibration

In considering the design of the test rig for the Hinkley Point B circulators, is was deemed impossible to model exactly the mounting stiffness of the prestressed concrete pressure vessel. The estimated natural frequency of the circulator 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. However, when the first machine was run at site, the natural frequency of the assembly was found to be 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. Unexpected freedom of movement of the forward end of the shutter tube resulted in the mounting stiffness being lower than had been estimated, resulting in a lowering of the pitching mode frequency to coincide with running speed. To circumvent the problem it was found possible to decouple a self-contained assembly at the rear of the machine, which carried the dome operating gear, inlet guide vanes operating gear and other components. By this means and arranging for the circulator to take its support drectly from the shutter tube wall it was possible to raise the natural frequency to the originally intended level. This procedure improved the vibration performance greatly and provided adequate protection for the inlet guide vanes and dome mechanism.

Considerable care was taken at the aerodynamic development stage to reduce noise levels to a minimum. Blade passing has been kept well under control, which is of particular importance because of the risk of acoustic damage to components in the reactor gas circuit. During the early stages of prototype testing at full gas density, excited by general broad band gas turbulence in the region of the impeller and inlet guide vanes, the shaft was found to oscillate unacceptably in the journal bearings under certain operating conditions. Oscillation of the shaft was about 25% higher than the frequency of shaft rotation and was in the form of rigid body oscillation of the rotating assembly within the bearing oil film. The bearings, which are of anti-whirl design, and all forms of rotating stall were eliminated as the cause of the oscillation. The problem was eventually solved by simple aerodynamic means. Over 2000 hours of prototype testing was carried out on several machines at various stages of development. The tests included simulated reactor depressurisation accidents and other fault conditions.

Oil ingress

Two major problems were found with the horizontal circulators used at Hinkley Point B and Hunterston B. First was the problem of controlling oil ingress and secondly that of measuring it. The development task was to control the intermixing of gas and oil mist in the presence of vigorous turbulence in the various seal and labyrinth interspaces. The measurement task was to identify ~1 g of oil in a high pressure test rig that could readily adsorb several litres of condensed oil on its water cooled surfaces. The ingress of oil had to be identified while oil was continuously decaying and evaporating from the surfaces of the circulator. Eventually, a standard of acceptance was put on the oil content of the gas, without knowing what exactly this meant in terms of oil ingress.

At pressures above 27 bar, leakage of oil from bearing seals becomes increasingly difficult to control and the circulator design is based on the assumption that some oil leakage will occur. A labyrinth system is used to prevent oil ingress to the reactor. The main impeller rise is used to maintain the motor compartment just below reactor circuit pressure so that a small flow of gas is induced along the circulator shaft where it passes through the barrier plate and also through any other leakage paths in the barrier plate such as the guide vane spindle penetrations.

4.4 Hartlepool and Heysham I gas circulator

4.4.1 Design

The pod boiler design employed at Hartlepool and Heysham 1 lends itself to the use of submerged circulators. An extension downwards of the boiler pod provides a natural location for each circulator. There are eight boiler pods per reactor, with one circulator for each pod. Oil bath lubricated bearings are used, with integral water cooling coils, in the style of the original Windscale circulators. This arrangement eliminates the complication of the forced lubrication system which is necessary for the horizontal machines. A drawing of the circulator unit, located within the concrete pressure vessel wall, is shown in Figure 14.

The main motor (5.3 MW, 2970 rpm) is built with a substantial frame and incorporates oil bath lubricated bearings, top and bottom. Primary containment is provided by the heavy flat end closure plate at the bottom end of the penetration. A heavy barrier plate is built into the top end of the machine. In the event of failure of a service penetration or of the primary containment closure, the motor, which is secured by long studs, remains in position. The barrier plate then provides gas containment to the required leakage standard.

Gas is pumped by a centrifugal impeller, within a volute casing which is double skinned and has a built-in sound absorber. Flow is controlled by adjustable inlet guide vanes. An isolation dome is incorporated to isolate the motor compartment at low pressure during removal and replacement of the circulator unit. Heat in the motor compartment is removed by two 100% water-gas coolers. The design also incorporates a pony motor for emergency low speed operations. A simple gas purged buffer seal near the top of the shaft is continuously supplied with filtered gas by a fan and filter system. The purge gas is drawn from the motor compartment and returns to it via the buffer seal.

4.4.2 Issues arising during development

When first tested under full density conditions, the circulators were found to have some lively components in the region of the inlet guide vanes. Some were excited acoustically and some aerodynamically. Bringing these components under control was relatively straightforward but it was deemed unlikely that the problems would have been identified without a full density test facility.

One of the problems was the vibration failure of stiffening struts spanning the inlet passage. As the inlet guide vanes close the struts are swept by a wide range of gas velocities and consequently a wide range of vortex shedding frequencies. At some point the shedding frequency tunes into the natural frequency of the strut leading to failure. The problem was solved by machining spiral strakes on the surface of the struts.

During early reactor engineering runs, jacking oil supply pipes began to fail by fatigue. It was found that the motor was being induced into a self-sustaining vertical oscillation which interrupted the jacking oil supply cyclically, inducing cyclic pressures of up to 50 MPa in the supply pipes. A large programme of instrumentation, testing and mathematical modelling was carried out, without entirely eliminating the phenomenon. However, the use of rigid pipes and changes in some of the system stiffness and damping parameters enabled the system to be engineered for safe operation. Despite the lively behaviour of the motor, no thrust bearing failures or damage occurred.

4.5 Heysham II and Torness gas circulator

4.5.1 Design

Superficially, the gas circulators used on the last two AGR stations, Heysham II and Torness, are duplicates of the Hinkley Point B and Hunterston B circulators. However, a number of improvements were included. The main features of the design are a 5.2 MW, 2970 rpm motor, with forced lubricated bearings, a centrifugal impeller discharging into an annular casing, variable inlet guide vanes with mechanical drive taken out through an end closure plate, a barrier plate for secondary containment, and a dome to isolate the circulator penetration for circulator removal and replacement. Oil is supplied to the bearings by a three pump system. A labyrinth seal at the front end of the circulator is continuously supplied with filtered gas by a fan and filter system, using gas drawn from the motor compartment. A diagram of the circulator is shown in Figure 15.

While the Hinkley Point B/Hunterston B was fabricated from cast components, the Heysham II/Torness impeller used forged components because of supply problems. The forged impellers were kept geometrically identical to the previous cast impellers. Vibration response/decay testing was carried out on both impellers to demonstrate that there were no significant differences in performance. All likely sources of fatigue failure were profile dressed and polished.

4.5.2 Issues arising during development

Impeller failure

The sudden and extensive failure of a gas circulator at Torness in 2002 was thought, from forensic evidence, to be linked to the development of an unexpected fatigue related crack in part of the impeller. Later in 2002, another gas circulator on the other Torness reactor showed signs of increasing vibration and was promptly shut down. On subsequent disassembly, a fully developed fatigue related crack was revealed, in a similar position to that of the first failure.

Following the initial failure, increased attention was given to circulator vibration monitoring in AGR reactors in general. With the discovery of a systematic and potentially frequent failure mechanism, safety concerns increased and a revised and extended safety case was drawn up to cover operations. This incorporated forewarning of failure by early and effective detection of changes in vibration patterns together with recognition of the need to shut down any affected circulators before major failure and consequential damage to the circulator casing occurs. The safety case is now based on the presumption that impeller failure is a comparatively frequent failure mechanism, but that the failure will be contained within the circulator.

All other gas circulator impellers in service at Torness were inspected and no evidence was found of developing defects. Some impellers were also inspected at Heysham II, but again no defects were found. In 2004, examination of a Heysham II circulator impeller revealed a small, surface-breaking fatigue crack in the root region of a blade. The impeller was replaced.

4.6 AGR gas circulator dynamics

Various types of vibration are found in AGR circulators. Type A is mechanically induced; Types B, C and D are gas flow induced; Types E and F are electromagnetically induced. Some evidence of these types of vibration can be found on the vibration signature, as shown in Figure 16, of a gas circulator of Hinkley Point B design. The types of vibration are shown below.

A. 1 × machine speed (49.5 Hz) vibration component caused by forces generated by a rotor imbalance or by a permanent bend in the rotor (Figure 10). These vibrations can cause fretting damage to the main journal bearing mounting surfaces, isolating dome operating rods and inlet guide vane bearings, and their control mechanisms. Severe vibrations can also be transmitted to ancillary equipment mounted on the free end of the main motor frame, including the inlet guide vane driving motors, the Selsyn unit and the dome operating platform. Another possibility is the exceeding of shaft running clearances, such as that at the labyrinth seal.

B. Gas pressure fluctuations generated by a rotating stall in the impeller, occurring at about 30 Hz. This has been found at low inlet guide vane setting (low flow rates) and can cause shaft vibrations which limit the operational range.

C. Gas pressure fluctuations generated by inlet guide vane/impeller/diffuser interaction. These occur at 13 × machine speed (there are 13 impeller blades) and harmonics, i.e. at 643.5 Hz etc. The vibrations are normally of very small amplitude but can cause fretting damage to inlet guide vane bearings and their control mechanism. Changes in these vibrations can be used to indicate inlet guide vane defects.

D. Gas pressure fluctuations near components causing resonance vibration. This can occur in components that are situated in severe turbulent flow regions like the inlet guide vane section of the circulator.

E. Inherent electromagnetic forces associated with the stator. These occur at 2 × mains frequency and harmonics. These are normally of small amplitude and no damage has been attributed to this phenomenon.

F. Rotor bars/stator windings electromagnetic interaction. These are normally of very small amplitude, and occur mainly at 52 × machine speed (there are 52 rotor bars), i.e. at 2574 Hz. Changes in these vibrations can be used to indicate rotor bar defects.

During the routine maintenance of a gas circulator on the Hinkley Point B AGR, a vibrational problem occurred that was attributed to imbalance caused by a permanent bend in the rotor drive end journal resulted in a throw at the impeller end of approximately 150 µm, peak-peak. Difficulty was experienced in balancing the rotor satisfactorily for reactor running despite having been balanced at both low and high speed. It was eventually balanced satisfactorily in an air test rig under normal running speed. Several conclusions were drawn from an investigation:

- The rotor runs near its second critical speed in the high speed balancing pit, while it runs near its first critical speed when it is mounted in its own bearings within the motor frame and the whole circulator is supported in the air test rig.

- Residual in-phase imbalance in the rotor produces higher vibration levels than anti-phase imbalance when the circulator is run in the air test rig.

- Imbalance near or on the impeller cannot be adequately corrected on balance planes within the rotor body but can best be corrected on a balance plane near or on the impeller.

- The effect of an impeller throw can be reduced by a balance weight placed on or near the impeller. A throw of 150 μm peak-peak is equivalent to approximately 0.1 Nm impeller imbalance.

A comprehensive balancing procedure was developed based on low speed balancing together with trim balancing at normal running speed when the circulators are tested in the air rig.

4.7 Vibration induced wear

During the examination, and proof testing under reactor conditions, of a gas circulator of Hartlepool/Heysham I design (Figure 14), wear damage was noticed on the upper surface of the isolating dome flange and its stop ring, and also on the sealing ring flange and its stop ring. The damage to the dome was characteristic of fretting and consisted of several discrete major scars and a few minor marks, each of several cm^2 area. In the uncleaned condition, the scars were overflowing with the brown oxide debris typical of fretting. Matching scars of similar dimensions could be seen on the stop. The scars on the inner sealing ring and its stop were more numerous but smaller in size. To alleviate the problem, a 150 μm layer of the Detonation-Gun coating LW5 (WC-NiCr) was applied to the mating faces of the dome and inner sealing ring, and their stops. A programme of work was initiated to quantify the effects of the modification. Instrumented runs on the circulator test facility provided the data on frequency and movements necessary to ensure representative tests. A difficulty with fretting experiments, though, is accelerating the wear process without changing the wear mechanism. A wear projection equation was developed during the investigation. The wear acceleration factor f is given by

$$f = \frac{(\sum_I P \sum_{\Delta f} Af)_{rig}}{(\sum_I P \sum_{\Delta f} Af)_{reactor}} \tag{1}$$

where I is the inlet guide vane angle, P is the fraction of duty at a given vane angle and A is the mean amplitude of response for a given frequency band width Df, with centre band frequency *f*. If some allowance is made for the observed reduction of wear with amplitude then the wear acceleration factor is given by

$$f = \frac{(\sum_{I} P \sum_{\Delta f} Ay(A) f)_{rig}}{(\sum_{I} P \sum_{\Delta f} Ay(A) f)_{reactor}} \quad (2)$$

where ψ(A) is the relative rate of damage at a given amplitude compared with the constant damage rate at high amplitude. A decision was taken to accelerate the wear process by increasing the frequency. In the longer term, further tests, closer to the operating conditions, would be carried out. An assessment of the wear results showed that the projected life of the dome closure components would be extended by 10 years to 30 years.

Some conclusions were drawn from the investigation:

A. The examination of wear scars can provide an early indication of the direction and severity of vibratory movement.

B. Laboratory scale tribology tests are often necessary to assess vibratory wear problems and remedial measures. Only by an adequate knowledge of component vibration characteristics can realistic tribology experiments be conducted.

C. To extrapolate wear rates from laboratory tests, the vibration conditions during experiment and service must be known.

D. Specific wear rates depend on the amplitude of motion in the vibratory wear regime.

5.0 THE DRAGON GAS CIRCULATOR

5.1 Design

The gas circulators on the Dragon reactor were totally enclosed blowers with hydrodynamic gas-lubricated bearings. There were six circulators in all, one attached to each heat exchanger, as shown in Figure 17. The circulators were designed to work over a wide range of conditions. Relevant design criteria were:

Gas	Helium with < 10 vpm O_2, H_2O, CO and CO_2
Pressure	8 – 25 bar; 1 bar at reduced speed

Temperature	Ambient – 420°C
Speed	1,100 – 12,000 rpm, infinitely variable

In addition, the circulators were designed to be capable of running with air or nitrogen at pressures of 1 – 2 bar, at temperatures between 15 and 350°C, and to withstand rapid changes in temperature, pressure and speed.

A diagram of the circulator is shown in Figure 18. A pressure-tight flanged casing encloses the impeller, shaft, bearings and motor. All bushings leading to the outside are gas-tight, there being no mechanical seals. The casing consists of three main sections welded together: the flange, conical section leading to the cylindrical section, and the dished end. The transition from the conical to the cylindrical part is reinforced to take bushings for the supply to the motor, the instrument leads, the connections for measuring the pressure, and the inlet of jacking gas.

The circulator is a single stage machine with an overhung impeller, the diffuser being parallel and vaneless. There is a squirrel cage motor between the two gas-lubricated journal bearings; at the other end of the shaft is a gas-lubricated thrust bearing. The components are either welded, like the diffuser housing, or machined from solid metal. The impeller is of the type used in radial compressors. It is bolted to the ground end of the hollow shaft and centred by a short stub fitting tightly in the bore. The thrust collar at the other end is similarly attached. The shaft is hollow to save weight and to conduct the internal coolant gas. It is machined to a constant outside diameter, onto which the rotor of the motor is shrunk. The shaft and bearings are made from nitrided steel. The two radial bearings are attached to axially flexible diaphragms in the casing, ensuring that any deformation of the casing is not transmitted to the bearings, which then align themselves with the shaft.

All bearings are provided with gas connections so that they can be supplied with jacking gas below the hydrodynamic load-bearing limit. This ensures that a load-bearing gas film is present right down to a standstill, thereby preventing metallic contact during run-up and run-down. The pipes leading to the bearings are flexible in order to reduce any forces exerted on the bearings. To keep the consumption of jacking gas to a minimum, the run-out time of the shaft is shortened by means of DC braking.

5.2 Thermal considerations

The temperature distribution inside the casing was the subject of a thorough investigation. The temperature of the gas being circulated is 350°C under normal conditions, or up to 420°C under special conditions, although the motor insulation is only designed to withstand a maximum temperature of 180°C. The thermal insulation between the motor compartment and the diffuser housing is provided by stacking alternate sheets of smooth and dimpled stainless steel. The water cooling coil outside the casing disposes of the heat generated by the motor and any heat conducted from the hot side. Heat is transferred to the water by direct metallic contact and through the thin layers of gas between the various parts. The rotor of the motor and the shaft are cooled by internal circulation of the gas drawn through the hollow shaft from the thrust bearing end by a fan at the impeller end, which blows the gas into the motor compartment. As the gas passes through these passages it is cooled, the heat being conducted outwards to the cooling water.

Special attention was paid to the transition from the impeller to the shaft because a temperature difference of 40°C between the shaft and the journal bearing would close the small clearance. To avoid this problem the impeller was shaped so that the part in contact with hot gas is joined to the hub by a long piece with a small cross section. The hub is protected on the hot side by insulation. At the junction with the shaft it has a number of recesses which reduce the contact area. Together with an aluminium insert these recesses form the cooling fan. The high gas velocities and the increased heat conduction resulting from the use of aluminium increase the heat transfer to the coolant gas.

5.3 Testing

The first series of development tests on the prototype were carried out on a small test loop which did not have any means of measuring or throttling the flow. A second, large, test loop with throttling valve, cooler, heater and flow measuring nozzle was used to test the circulators under all specified conditions. The design conditions were easily met in the tests. The pressure rise of 0.4 bar could be reached at a speed 5% lower than anticipated; the pressure rise/mass flow characteristic (see Figure 19) being flatter than expected. This deviation was attributed to a slight alteration in the impeller design. Also, the performance calculations were based on test figures at higher Mach numbers.

The journal bearings operated properly in the test loop, even though they were running at much higher temperatures than in the bearing test machine, and there were temperature differences of up to 70°C between one end and the other of the impeller side bearing under some circumstances. There was one bearing seizure due to running out without jacking gas. This occurrence was attributed to a sudden application of a very high jacking gas pressure. Following one test, severe rubbing marks were found on one bearing, for which there was no conclusive explanation at the time. It was then decided to apply a coating of molybdenum disulphide to the shaft. First, the journals were vapour blasted and fine MoS_2 powder was rubbed into the roughened surfaces. Subsequently, the bearings performed well. The cause of the rubbing marks and difficulties in starting were later attributed to insufficient jacking gas pressure.

Thrust bearing instability, caused by insufficient thrust, gave rise to many failures, and long delays in delivery of the circulators. Early on during the development tests the thrust bearing failed and showed rubbing on the outermost diameter of the thrust plates. Every time a failure occurred the rotor moved backwards, unloading the thrust bearing. Two approaches were tried to overcome this problem. In the first approach, the aerodynamic thrust on the impeller was raised. In the second approach, a new design of thrust bearing was developed. It was thought that a pocket type thrust bearing would be more stable than one with spiral grooves. With the new thrust bearing incorporated, there was no problem operating under normal conditions but under other conditions the original problems recurred. Finally, a thrust measuring device was built in and the conditions under which the thrust was insufficient were mapped out. At the same time a counter thrust bearing which gave a constant additional thrust was developed. With this bearing installed and with some limitations on the running conditions outside the specified range, the circulators passed the acceptance tests.

Some problems also occurred when starting and stopping at high gas temperatures. It was found that when the circulator was stopped the temperature in the impeller side bearing rose at the impeller end, while the temperature at the other end started to fall. Safe operation was possible while the axial temperature difference remained less than 40°C.

One thrust bearing failure was attributed to electric spark erosion. To conduct the static charge from rotor to earth, and because rubbing in dry helium results in severe wear, a contactless conductor was required. A radioactive source was used.

5.4 Friction in gas bearings

For gas bearings, where contact of the moving surfaces occurs only during starting and stopping, freedom from seizure is the most important requirement. In order to obtain information on the start-stop performance of various gas bearing material combinations, a number of continuous running plain bearing tests were carried out during the Dragon Project. Some start-stop tests were also carried out. The tests were carried out in helium with < 20 vpm water and < 10 vpm oxygen.

The continuous running tests were done at 70 kPa contact pressure, at a temperature of 150°C, to provide data on different surface treatments from which comparisons could be made. Hard chrome versus cast iron would hardly run at all. K-monel versus hard chrome showed some improvement but there was still a tendency to seize. The commonly used S-monel versus hard chrome combination gave acceptable performance but by far the best performance was obtained by nitrided steel journals treated with MoS_2, running in nitrided steel bushes. The treatment consisted of vapour blasting with sand, followed by rubbing with fine MoS_2 powder. Start-stop tests confirmed the applicability of the results from the continuous running tests. They also showed that increasing the shaft diameter, the loading and the inertia greatly reduced the number of start-stop cycles possible before damage occurred. For MoS_2, more than 1000 stops were performed with 51 mm shafts. The tests were carried out at contact pressures of 5 kPa and 14 kPa. With a 102 mm diameter shaft, and a contact pressure of 16 kPa, seizure occurred after 750 cycles. Other combinations of materials also gave good results. Such combinations included stellite versus metal impregnated graphite and graphite loaded bronze, and stellite versus sintered bronze with PTFE. MoS_2-loaded carbon showed great potential in continuous running tests at temperatures up to 600°C, exhibiting low wear and friction and complete freedom from seizure.

6.0 LITERATURE REVIEW (APPENDIX A)

In addition to the above review of AGR, Magnox and Dragon experience, a literature review was carried out, covering internal and other documents and papers. Relevant documents from the search were identified and a brief summary of the findings made. A total of 24 documents and papers were reviewed. The review can be found in Appendix A.

A brief summary of the main findings for the UK papers was as follows:

- During hot run testing on the first Magnox reactor, severe damage occurred to the diffuser section and blading on two of the blowers. A large section of the diffuser casing had entered the blower blading causing heavy impact damage. The primary failures were due to metal fatigue arising from an acoustic excitation of greater power than some of the components could withstand. The removal of the inlet guide vanes resulted in the largest single improvement of all the various measures taken and greatly reduced the powerful harmonics previously measured. Also major components involved in the failure, such as diffuser and corner cascades, had been replaced by new units of modified design to meet some of the conditions found to exist in the gas circuit.

- The prototype AGR circulators were the first in a series of submerged circulators supplied to the British AGR programme. They were of small (1.2 MW) capacity and vertically mounted. The later circulators were of 5 MW capacity and horizontally mounted.

  Initially, the circulator drive was located outside the pressure vessel and a balanced pressure seal took the drive shaft through the vessel to drive the gas circulator impeller. As pressure increased, seal development became increasingly difficult and it was more difficult to control the migration of oil into the reactor. To remove the seal problem, the complete drive motor was located into the pressure envelope. This measure proved to be very reliable and well behaved in service. The other common problems faced by the circulators were vibration, interface corrosion and material dimension stability.

The latest AGR stations incorporate experience learned from previous plants. The circulators were designed with so much margin that during the resolution of the reactor control rod gag problems, they were run continuously at 20% overload (6.3 MW). The site experience was good with no related operational problems.

- The main circulators for the Dragon reactor were totally enclosed blowers with hydraulic gas-lubricated bearings. A pressure-tight flanged casing enclosed the working parts of the blower, that is, the impeller shaft, bearings and motors. All bushing leading to the outside were also gas-tight and there was no need for a mechanical seal. The performance of the circulators showed that the design conditions were met and no major problems were recorded.

7.0 OVERALL CONCLUSIONS & FINDINGS

A review of UK past experience on circulators used in gas cooled reactor systems has been carried out to recover specific knowledge from development, design and operation in order to provide information for design investigations and future tests on a mock-up. This work represents NNC's contribution to Raphael Deliverable D CT 2-2.

Failures occurred in the circulators in the two Magnox reactors at Hinkley Point (six per reactor) during commissioning (hot CO_2 test runs). These operated at 11 bar and an inlet temperature of 175°C and were driven by 5.2 MW induction motors. Severe mechanical damage occurred in the diffuser and blading as a result of acoustic excitation. These failures highlighted the need to fully understanding the consequences high levels of excitation and pressure waves can have on the integrity of the inlet guide vanes and blades with large sections cracked or dislodged. The situation was greatly improved by removing the inlet guide vanes. New modified circulators were introduced and adopted.

The AGR gas circulators at Windscale (four per reactor attached to the bottom of the heat exchanger) proved very reliable and were used for 20 years with virtual trouble free operation. They operated at 20 bar and used the submerged circulator concept (introduced in the first commercial AGR design) with the motor inside the pressure envelope. The Dungeness B circulators (four per reactor) were similar to those adopted for the early Magnox reactors with an external motor unit. Flow control was achieved by varying the impeller speed with a scoop controlled fluid coupling.

At Hinkley Point B and Hunterston B eight submerged circulators per reactor were used, operating at 40 bar. An annular diffuser with variable inlet vane control and inlet cone was adopted, the unit being contained within the concrete pressure vessel and designed for removal with the motor and impeller for inspection and maintenance. During development there were some problems with dimensional instability, vibration (mode near to that of the mounting flange) and oscillation of the rotating assembly within the bearing oil film. Two major problems were found in terms of controlling (at pressures above 27 bar) and measuring oil ingress. A standard of acceptance was eventually put on the oil content of the gas and the main impeller rise was used to produce a small gas flow to maintain the motor compartment below reactor circuit pressure and so prevent oil ingress to the reactor.

The pod boilers of Hartlepool and Heysham1 used the submerged circulator arrangement (eight pods per reactor with a circulator in each pod). The main motor (5.3MW, 2970 rpm) is built with a substantial frame and incorporates oil bath lubricated bearings top and bottom. Flow is controlled by an adjustable inlet vane guide and an isolation dome was used to isolate the motor at low pressure during the removal and replacement of the circulator. During development some of the inlet guides became excited acoustically and aero-dynamically. Vibration failure of the stiffening studs spanning the inlet passage occurred (shedding frequencies near the natural frequency of the strut). The problem was solved by machining some spiral strakes onto the surface of the struts. During early engineering trials there was failure of some oil supply pipes caused by oscillations of a motor. It was necessary to change some of the damping parameters in the system and use more rigid pipes to reach safe operation.

The circulators used on the last two stations, Heysham II and Torness, were similar to those of Hinkley Point B and Hunterston B but with a number of improvements and with forged components rather than cast used because of supply problems. There was a sudden and extensive failure of a circulator at Torness in 2002 linked with the development of an unexpected fatigue crack in the impeller. Later that year a vibration problem was noticed on another circulator at Torness and again a fatigue crack was found in the impeller. From these incidences increased attention was given to circulator vibration and a general monitoring of vibration patterns in AGR circulators took place. This led to the development of a revised safety case of operation based on early detection of changes in vibration patterns. The safety case is now based on the presumption that impeller failure is a comparatively frequent event, but that the failure will be contained within the circulator.

In terms of AGR Circulator gas dynamics a number of conclusions were drawn from an investigation of the circulator on Hinkley Point B and a comprehensive balancing procedure was developed using low speed balancing plus trim balancing at normal speed when the circulators are tested in an air rig. Vibration induced wear was found on the Hartlepool/ Heysham I design which was alleviated by using a 150 µm layer of Detonation Gun coating LW5 (WC-NiCr) on the mating surfaces. A wear projection equation was developed linked with accelerated (increased frequency) wear fretting experiments to confirm the benefits and estimate the projected life of the affected components (extended by 10 years to 30 years).

The Dragon reactor used six gas circulators designed to work with helium at 420°C and between 1 and 25 bar. The machine has a single stage with an overhung impeller of the type used in radial compressors and a cooled hollow shaft. The bearings are supplied with gas connections so that jacking gas can be used below the hydrodynamic bearing load limit, to ensure a load bearing gas film is present right down to standstill. A thermal investigation was carried out and improvements were made to the impeller shape and to increase heat conduction in order to limit the temperature difference between the journal bearing and the shaft, because of risk of closure of the small clearances involved. Prototype tests were carried out in a test loop and these confirmed that the design conditions were easily met. The journal bearings operated satisfactorily in the test loop however some rubbing problems were experienced and a coating of Molybdenum disulphide (MoS_2) was applied to the shaft; the rubbing was later attributed to the use of insufficient jacking pressure. Some problems occurred connected with starting and stopping at high temperature, also electric spark erosion of the thrust bearing. Thrust bearing instability also gave rise to a number of failures and delays in the delivery of the circulators. The failures resulted in backward movement of the rotor and an unloading of the thrust bearing. A thrust bearing measuring device was installed to monitor the effect and a counter thrust bearing developed to provide a constant additional thrust. With this bearing installed and with limitations on the running conditions the circulator passed the acceptance tests.

To investigate friction in the gas bearings some continuous plain bearing tests were carried out also some start-stop tests. The continuous running tests were done at 70 kPa contact pressure and a temperature of 150°C. Different combinations of materials were tried and a number gave good results. The best performance (continuous and stop-start) came from nitrided steel journals treated with MoS_2. MoS_2 –carbon also showed great potential in terms of non-seizure, low wear and low friction in the continuous running tests at temperatures up to 600°C. Increasing the shaft diameter, the loading and the inertia greatly reduced the number of allowable stop-starts before damage occurred.

The literature review identified 24 documents of interest. A brief summary of each has been made and included in Appendix A.

Overall it was concluded that the experience from the early commissioning failures on the Magnox designs, the measures taken to greatly reduce the powerful harmonics and vibrations, plus the experience from the early and later designs of AGR circulators have greatly contributed to the development of a series of reliably operating (5.2 MW) submerged circulators for the UK AGR programme. These circulators, which operate with CO_2 gas at nominal temperatures and pressures of 350°C and 40 bar continue to perform well in current commercial AGR stations in the UK. The Dragon reactor used totally enclosed blowers (around 4 MW) with hydraulic gas lubricated bearings that were designed to operate in Helium at higher temperature (420°C). Although the requirement for the VHTR gas circulator is much more severe (10-15 MW, He temperatures and pressures of 390°C and 55 bar), the specific knowledge from the development, design and operational experience identified, should provide a useful basis and starting point for the future RAPHAEL component development activities for the VHTR circulator. The work reported here is to be combined with German HTGR experience to form deliverable D SP CT 2-2 to be used for future design and test considerations.

TABLES

Table 1 References from the literature review (Appendix A)

Ref No	Title	Authors	Year	Reference
1	Development of CO_2 circulators	Donaldson, J. (James Howden and Co. Ltd, Renfrew (UK))	1987	Specialists' meeting on gas-cooled reactor coolant circulator and blower technology. San Diego, CA (USA).
2	Considerations on the design of a helium circulator for a high temperature modular reactor system	Dumm, K. (Internationale Atomreaktorbau G.m.b.H. (INTERATOM), Bergisch Gladbach (Germany, F.R.)); Donaldson, J. (James Howden and Co. Ltd, Renfrew (UK))	1987	Specialists' meeting on gas-cooled reactor coolant circulator and blower technology. San Diego, CA (USA).
3	A review of submerged gas circulators as applied to advanced gas cooled reactors	W M Fraser (James Howden & Co. Ltd)	1985	Journal of the British Nuclear Energy Society, Volume 24
4	Investigations into the failure of gas circulators and circuit components at Hinkley Point nuclear power station	W. Rizk, D.F Seymour	1964-65	The Institution of Mechanical Engineers, Proceedings, Volume 179, Part I, Number 21
5	Gas circulator repairs	A W Gould	1987	The Institution of Mechanical Engineers, Proceedings, Volume 201, Number A3

Ref No	Title	Authors	Year	Reference
6	The role of gas bearing circulators in the Dragon reactor	W F Shilling	1963	Proceedings of meeting on Rotating Machinery for Gas-Cooled Reactor Application, Tennessee, 1963
7	Experience of the reliability of steam and electrically driven circulators for GCRs	L Cave, R S Gow	1977	Nuclear Engineering International
8	Gas blowers for Dungeness	T E Adams	1962	AEI Engineering
9	Measurement techniques for AGR circulators in a full-density rig	I Watson, R R Wilson	1976	Institute of Physics Conference
10	The main circulators for the Dragon reactor		1963	The Brown Boveri Review
11	Gas-circulator problems in reactor development	J R Ridley	1958	GEC Atomic Energy Review, Volume 1
12	Some aspects of the dynamics of AGR gas circulators	K M A Kamesh (CEGB Scientific Services Department)	1982	British Nuclear Energy Society Journal

Ref No	Title	Authors	Year	Reference
13	Vibration data and its employment for component life projections in AGR circulators	T C Chivers, S C Gordelier, J Roy	1978	British Nuclear Energy Society, Vibration in Nuclear Palnt, Keswick, UK
14	Component design for High temperature Reactors using Helium as a coolant: Circulator design for HTR	D G Penry	1972	Institute of Mechanical Engineering, London
15	Circulator performance during THTR trial and post-commissioning operation	Glahe, E. (Hochtemperatur-Kernkraftwerk G.m.b.H. (HKG), Hamm (Germany, F.R.)); Stoelzl, D. (Brown, Boveri und Cie A.G., Mannheim (Germany, F.R.))	1987	Specialists' meeting on gas-cooled reactor coolant circulator and blower technology. San Diego, CA (USA).
16	Operating experience with gas-bearing circulators in a high-pressure helium loop	Sanders, J.P.; Gat, U.; Young, H.C. (Oak Ridge National Lab., TN (USA). Engineering Technology Div.)	1987	Specialists' meeting on gas-cooled reactor coolant circulator and blower technology. San Diego, CA (USA).
17	Design features and test results of the main circulators for the Dragon Reactors	H. Baumann (Brown-Boveri Corporation Baden, Switzerland)	1963	Dragon Project Engineering Symposium, Bournemouth

Ref No	Title	Authors	Year	Reference
18	Two decades of excellent AGR circulator operating performance at AVR Juelich	Ziermann, E.L. (Arbeitsgemeinschaft Versuchs-Reaktor G.m.b.H., Juelich (Germany, F.R.)); Engel, J. (Brown, Boveri und Cie A.G., Mannheim (Germany, F.R.))	1987	Specialists' meeting on gas-cooled reactor coolant circulator and blower technology. San Diego, CA (USA)
19	Recent research and development of bearings for helium circulator	Taniguchi, S.; Ezaki, Z.; Kawaguchi, K.; Matsumura, N.; Kozima, M. (Mitsubishi Heavy Industries Ltd, Nagasaki (Japan))	1987	Specialists' meeting on gas-cooled reactor coolant circulator and blower technology. San Diego, CA (USA)
20	Main circulator design features for HTR 100, HTR 500 and space heating plants	Engel, J.; Glass, D. (Brown, Boveri und Cie A.G., Mannheim (Germany, F.R.))	1987	Specialists' meeting on gas-cooled reactor coolant circulator and blower technology. San Diego, CA (USA)
21	Gas erosion of impeller housing in the operation of a high-temperature, high-pressure helium circulator	Sanders, J.P.; Heestand, R.L.; Young, H.C. (Oak Ridge National Lab., TN (USA))	1987	Specialists' meeting on gas-cooled reactor coolant circulator and blower technology. San Diego, CA (USA)
22	Design of the HTR-10 helium circulator with active magnetic bearing	Diao Xingzhong, Zhao Lei, Zhou huizhong, Zha Meisheng, Wang Jie, Yu Suyan.	2004	2nd International Topical Meeting on High Temperature Reactor Technology, Beijing, CHINA, 2004

Ref No	Title	Authors	Year	Reference
23	Operating experience of gas bearing helium circulators in HTGR development facility	Shimomura, H.; Kawaji, S.; Fujisaki, K.; Ihizuka, T. (Japan Atomic Energy Research Inst., Tokai, Ibaraki. Tokai Research Establishment)	1987	Specialists' meeting on gas-cooled reactor coolant circulator and blower technology. San Diego, CA (USA).
24	Helium circulator design concepts for the modular high temperature gas-cooled reactor (MHTGR) plant	McDonald, C.F.; Nichols, M.K.; Kaufman, J.S. (GA Technologies, Inc., San Diego, CA (USA))	1987	Specialists' meeting on gas-cooled reactor coolant circulator and blower technology. San Diego, CA (USA).

FIGURES

Figure 1: The Magnox gas circulator, original design

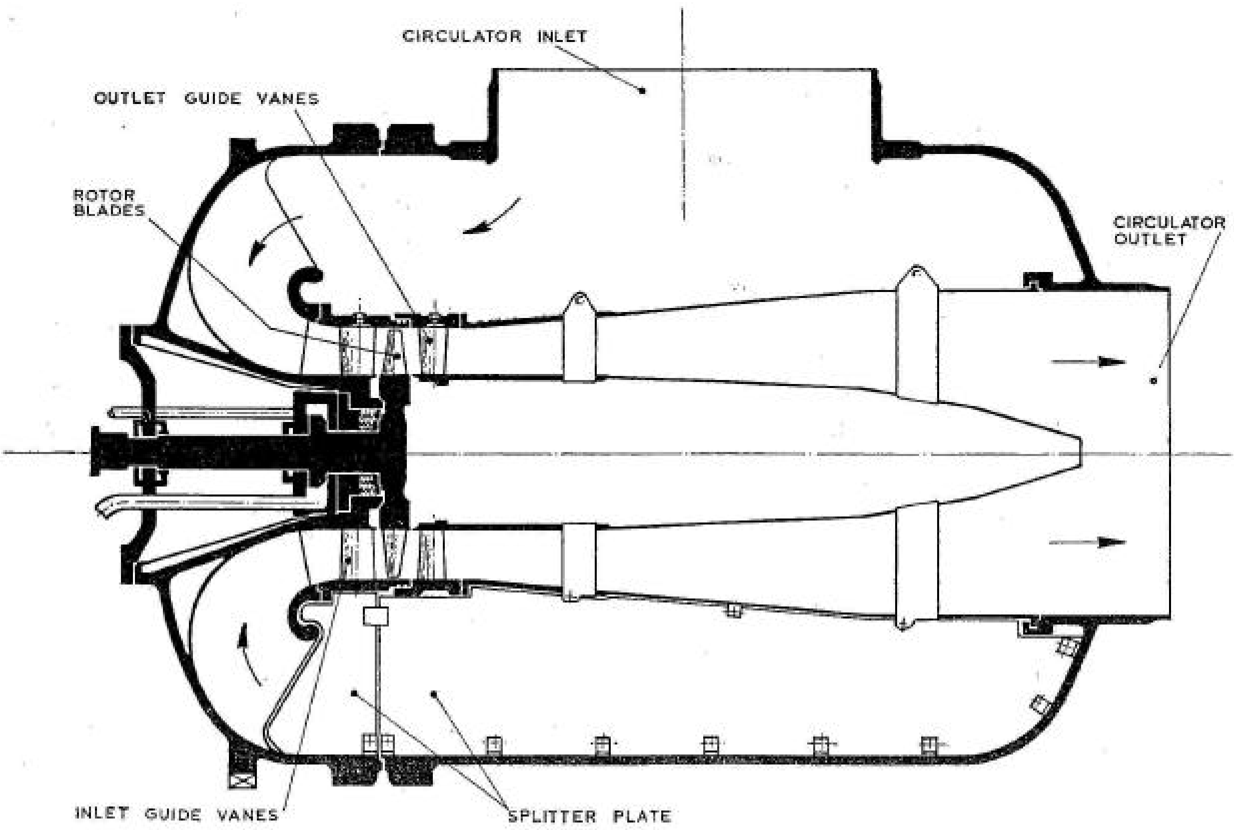


Figure 2: Failed Magnox gas circulator

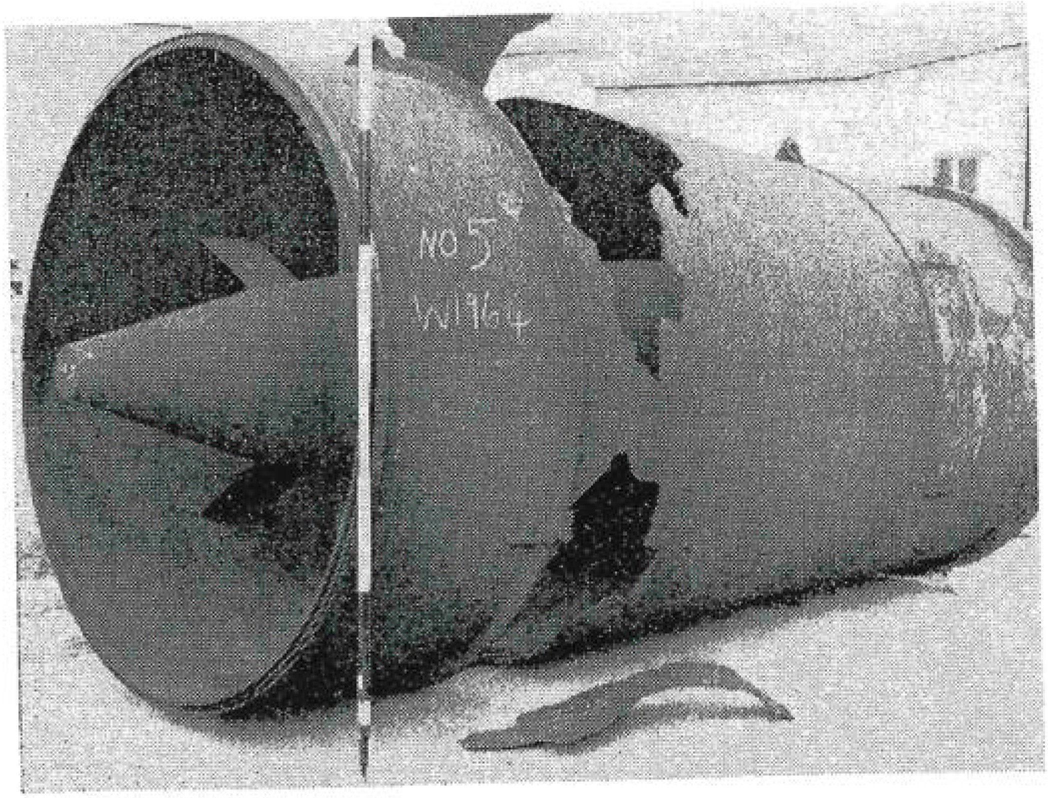


Figure 3: Fatigue cracking on bullet section of Magnox gas circulator

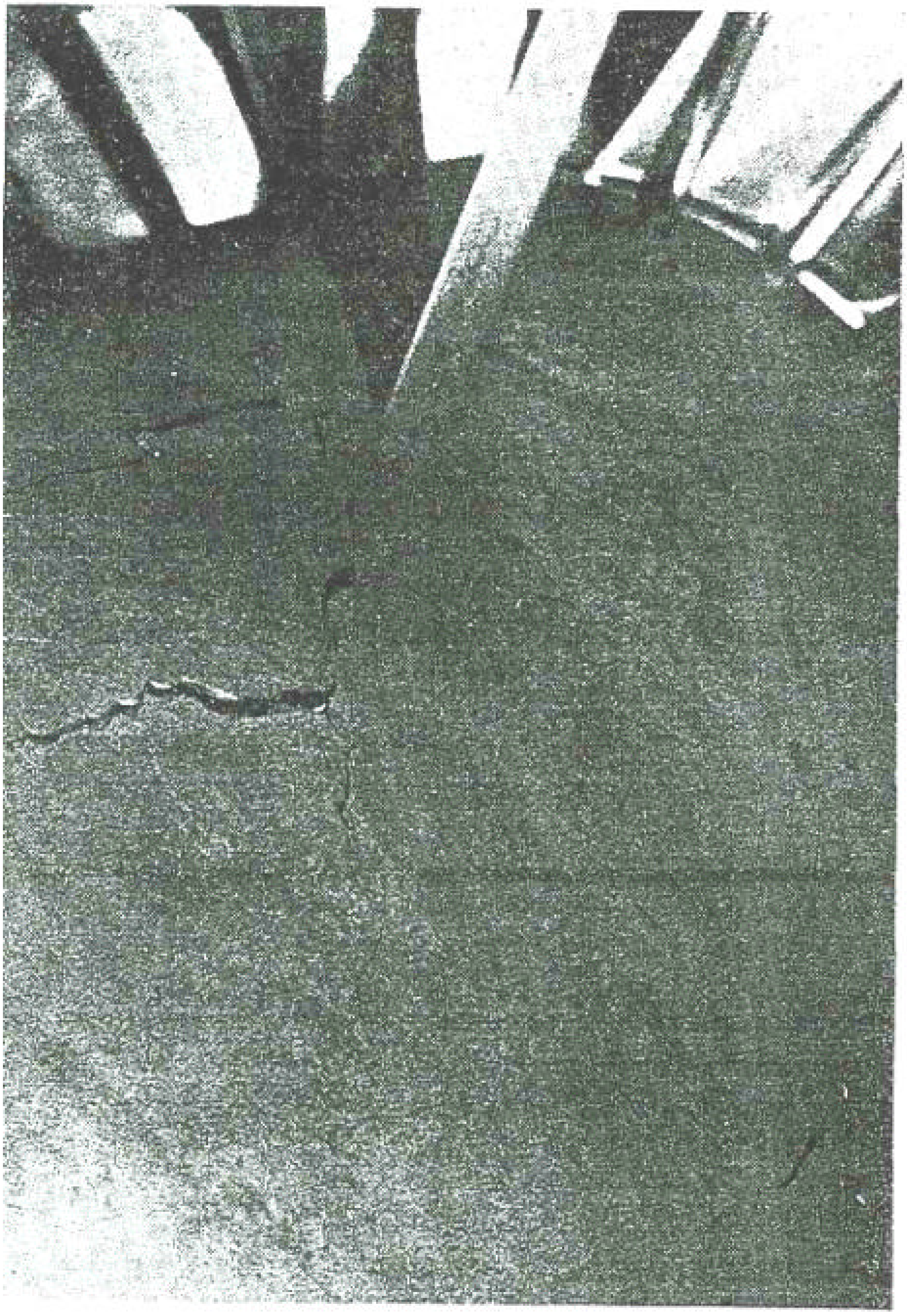


Figure 4: Fatigue cracks near main spokes in diffuser of Magnox gas circulator

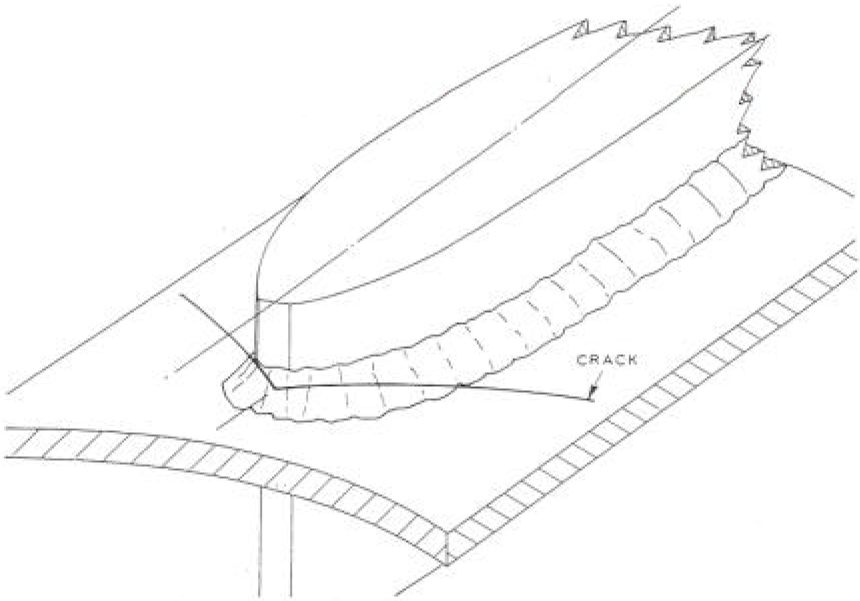


Fig. 9a. Sketch of crack near spoke (circulator Number 5)

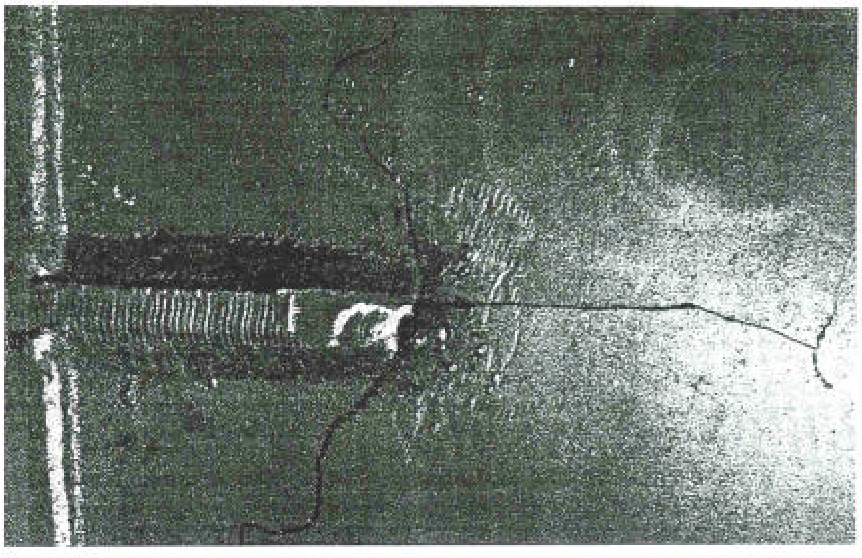


Figure 5: Cracked rotor blade fork of Magnox gas circulator

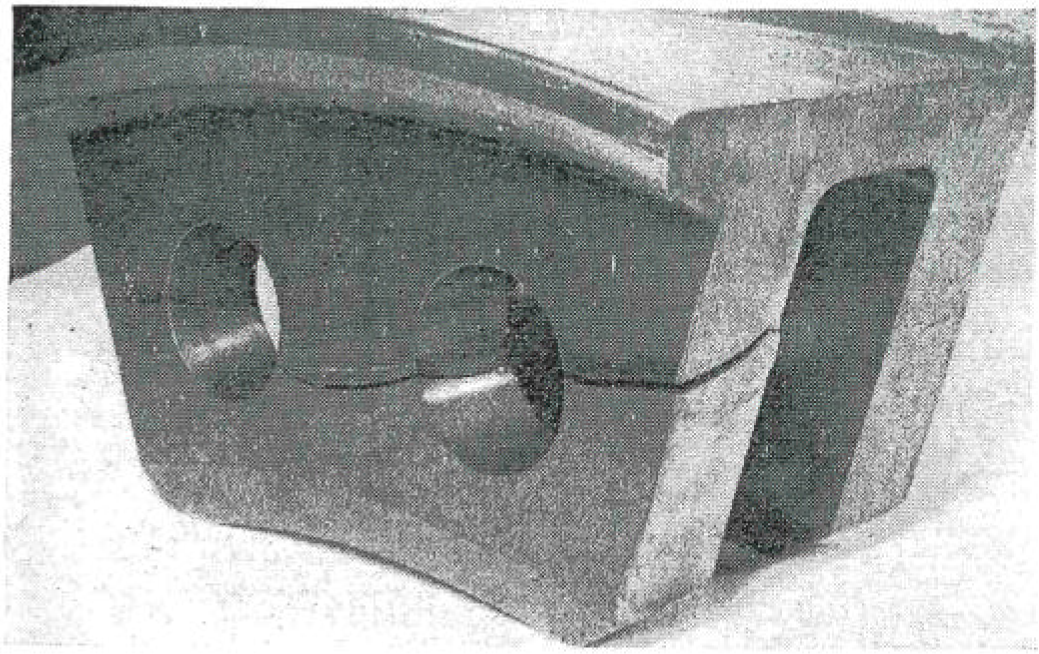


Figure 6: Damaged inlet guide vane ring of Magnox gas circulator

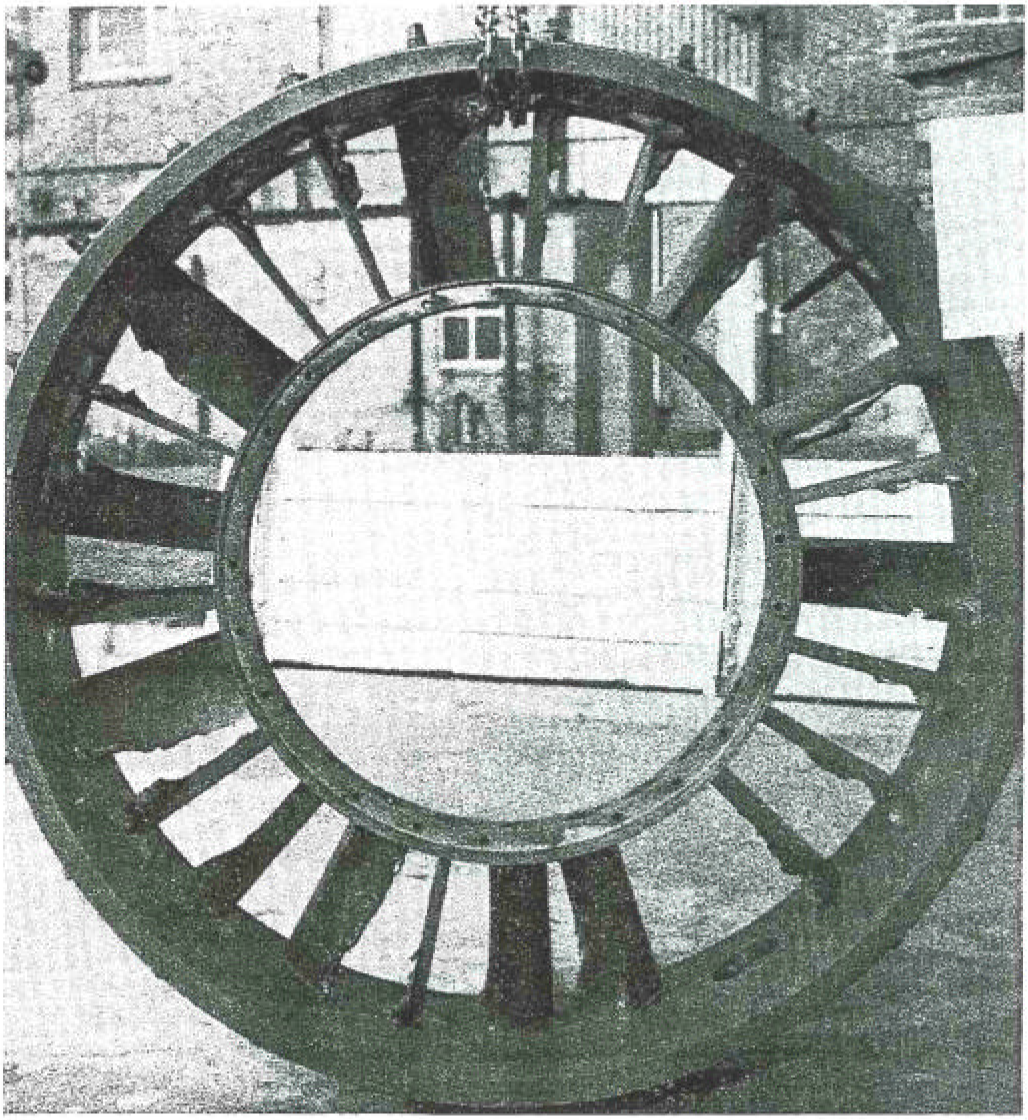


Figure 7: Modified Magnox gas circulator

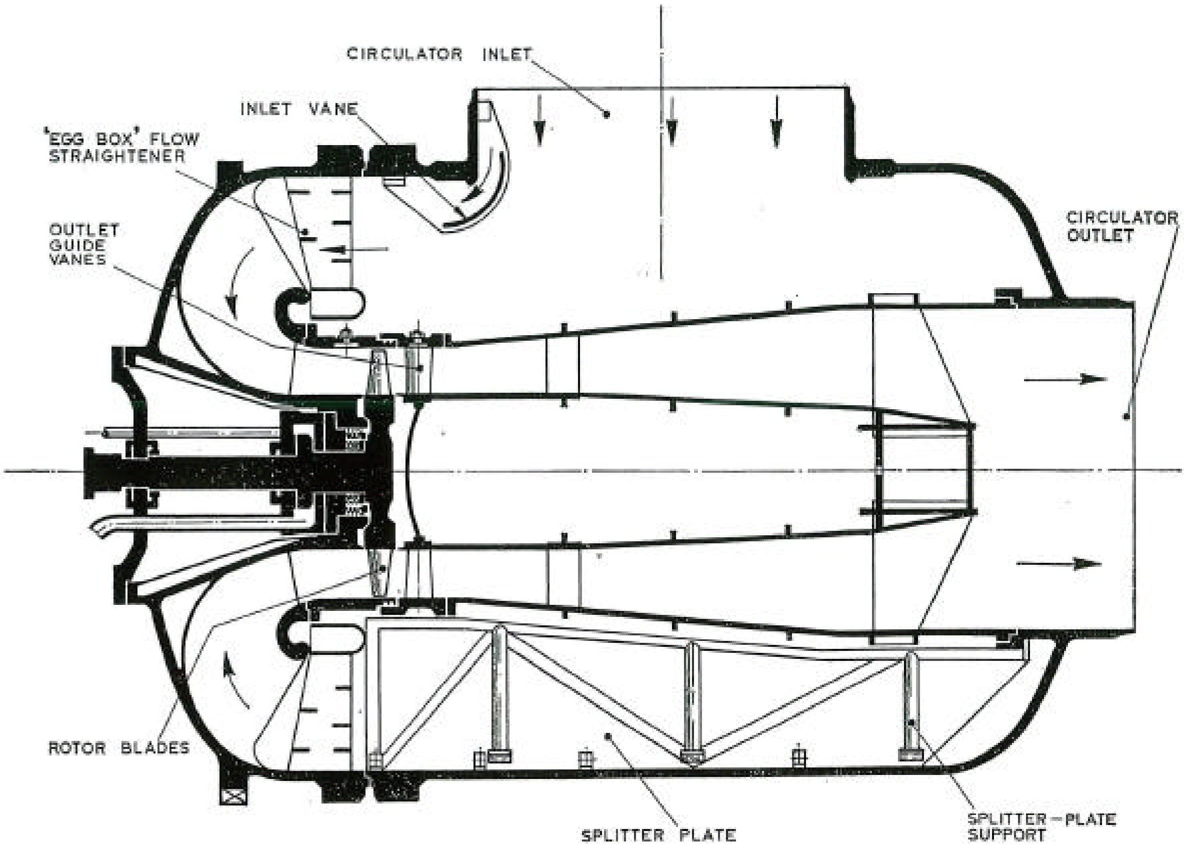


Figure 8: Vertical shaft submerged circulator, prototype AGR

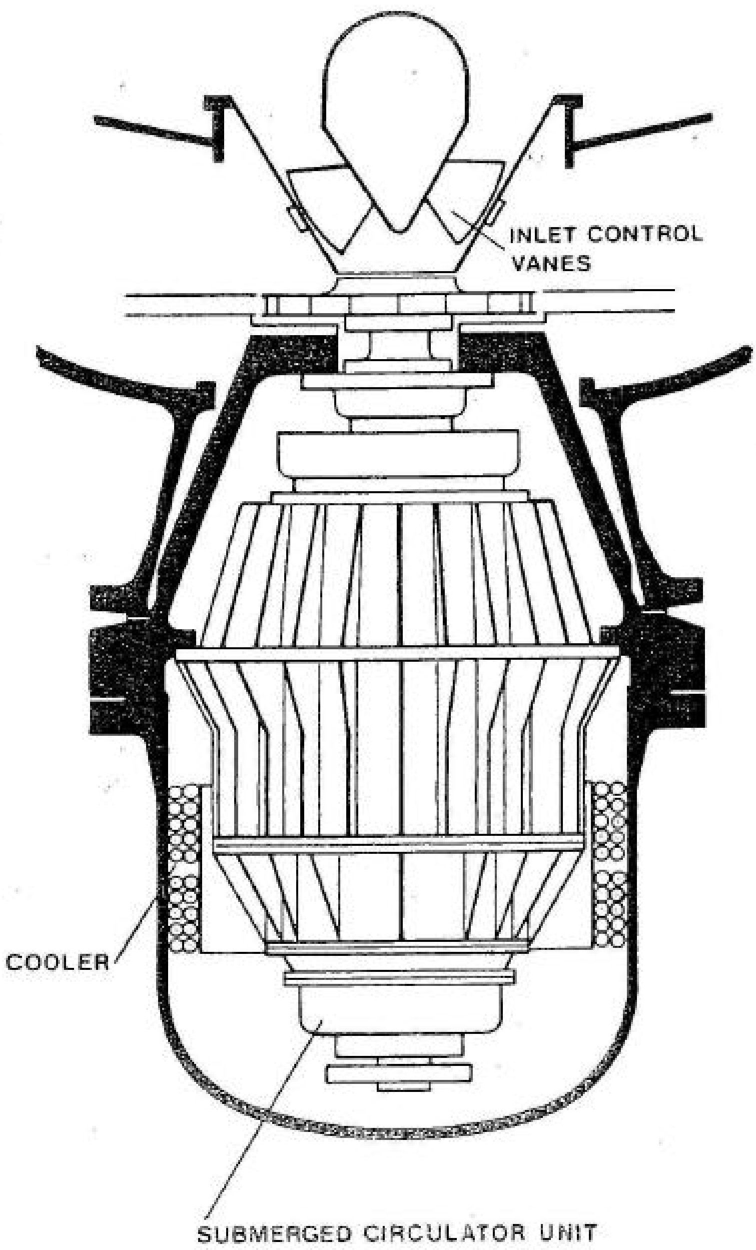


Figure 9: Schematic diagram of the AGR submerged circulator unit

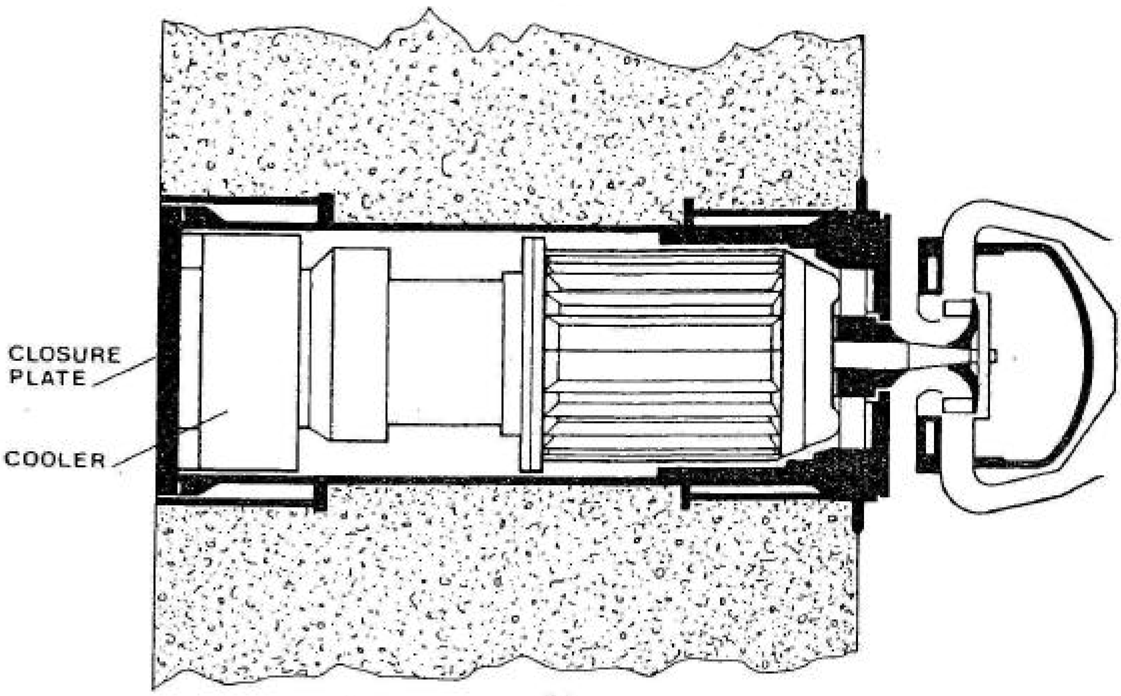


Figure 10: AGR gas circulator, Hinkley Point B and Hunterston B

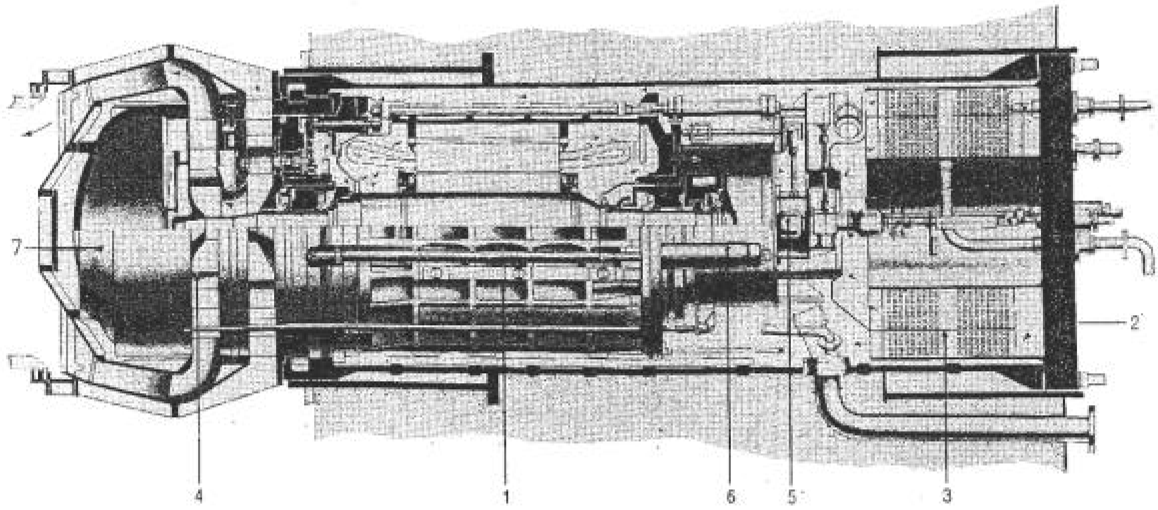


Figure 11: Inlet sub-assembly with vane control, AGR submerged gas circulator

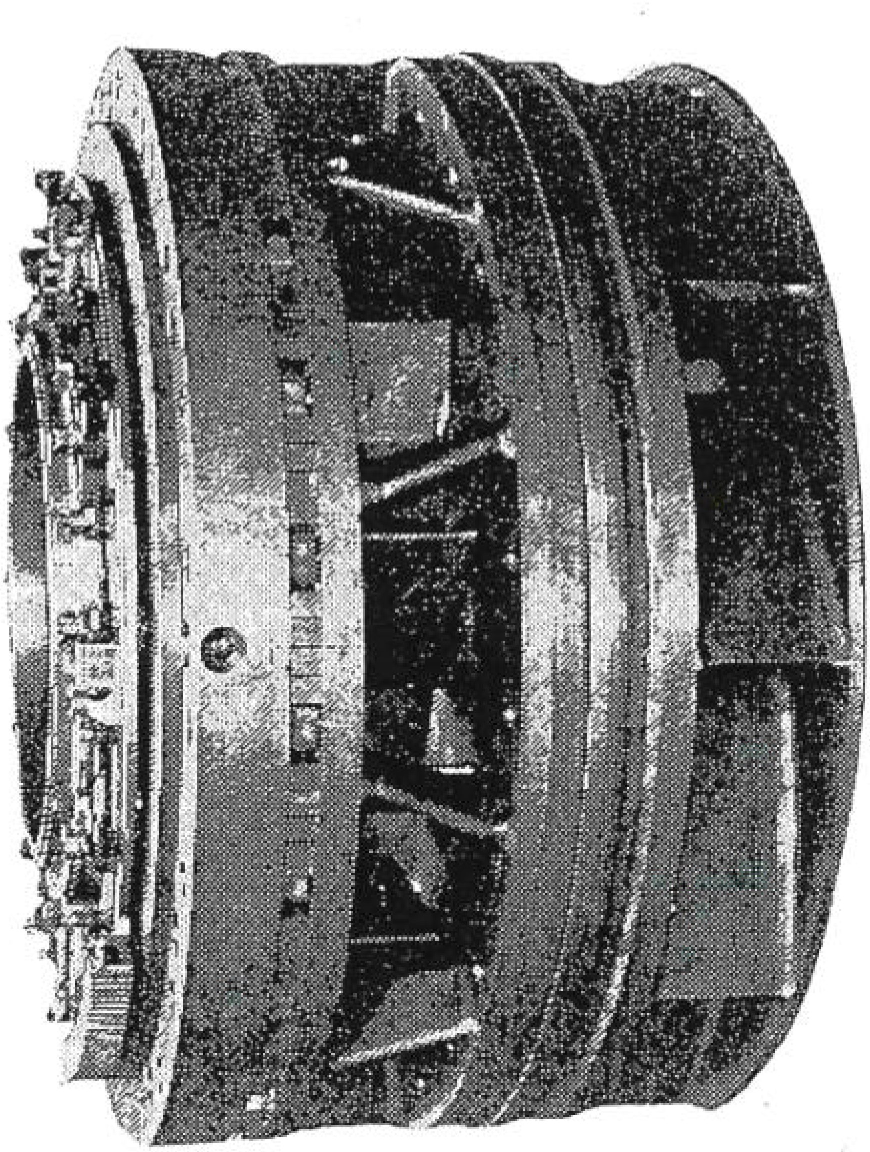


Figure 12: Circulator casing, AGR submerged gas circulator

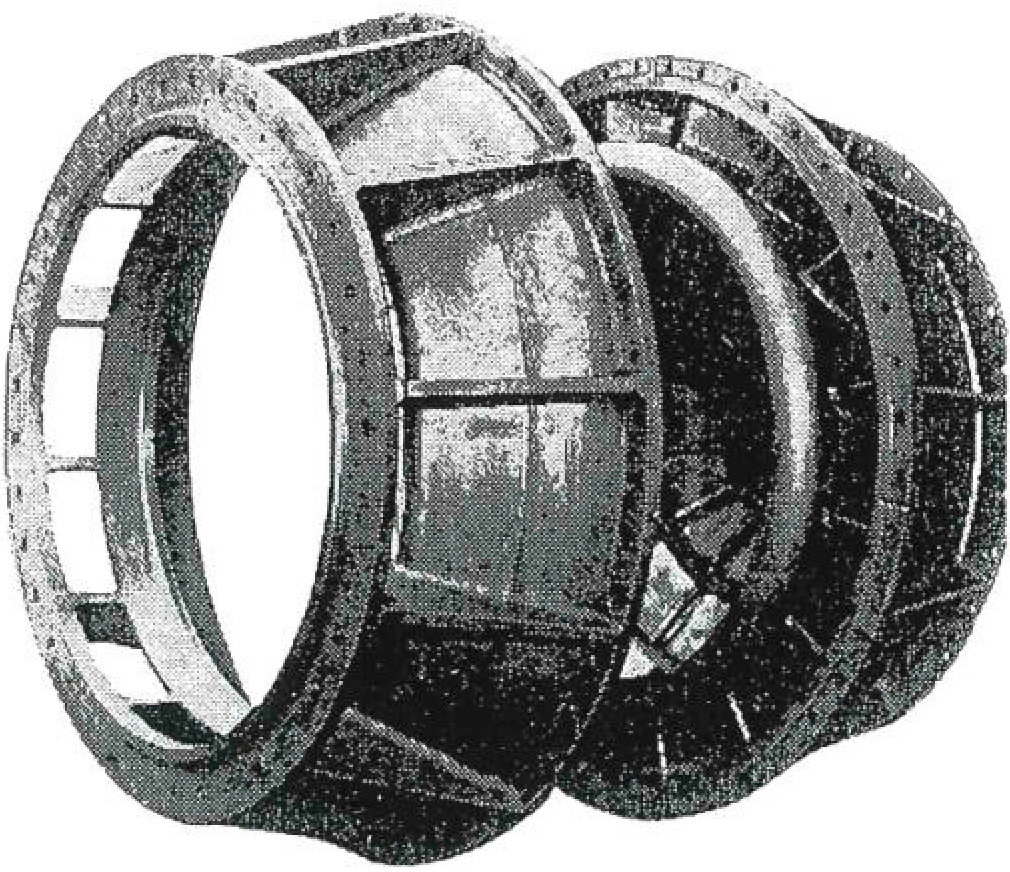


Figure 13: Circulator impeller, AGR submerged gas circulator

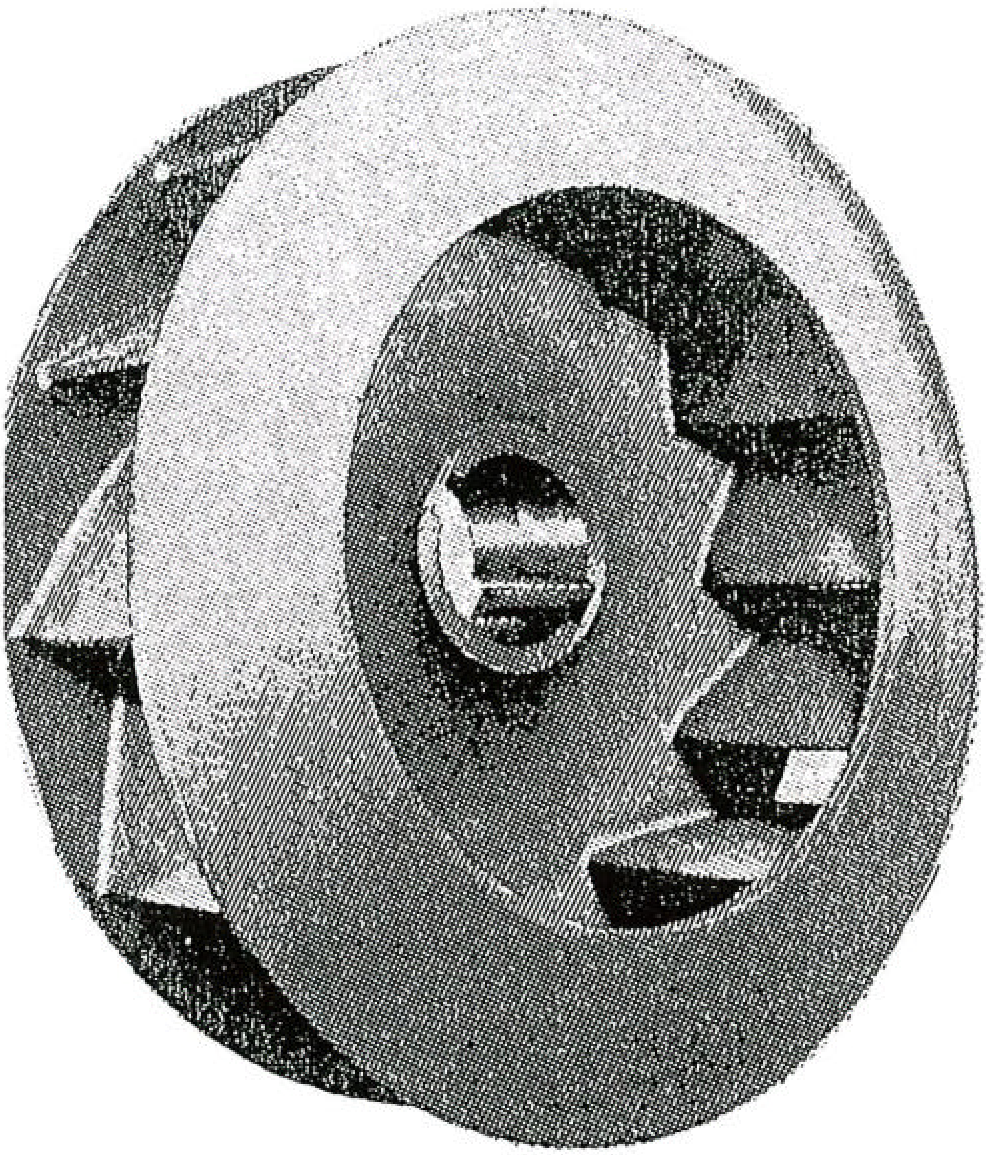


Figure 14: Gas circulator, Hartlepool and Heysham I

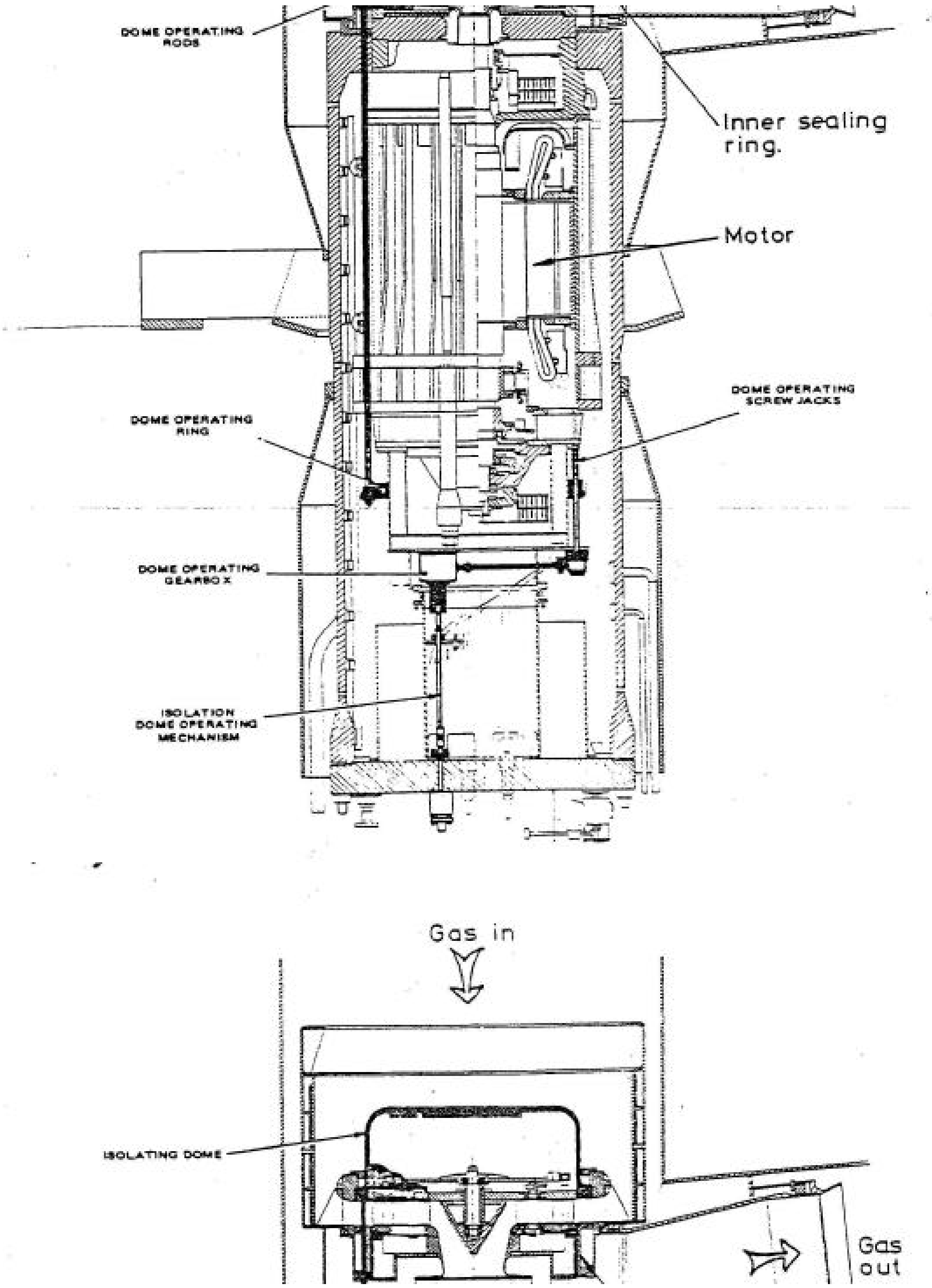


Figure 15: Gas circulator, Heysham II and Torness

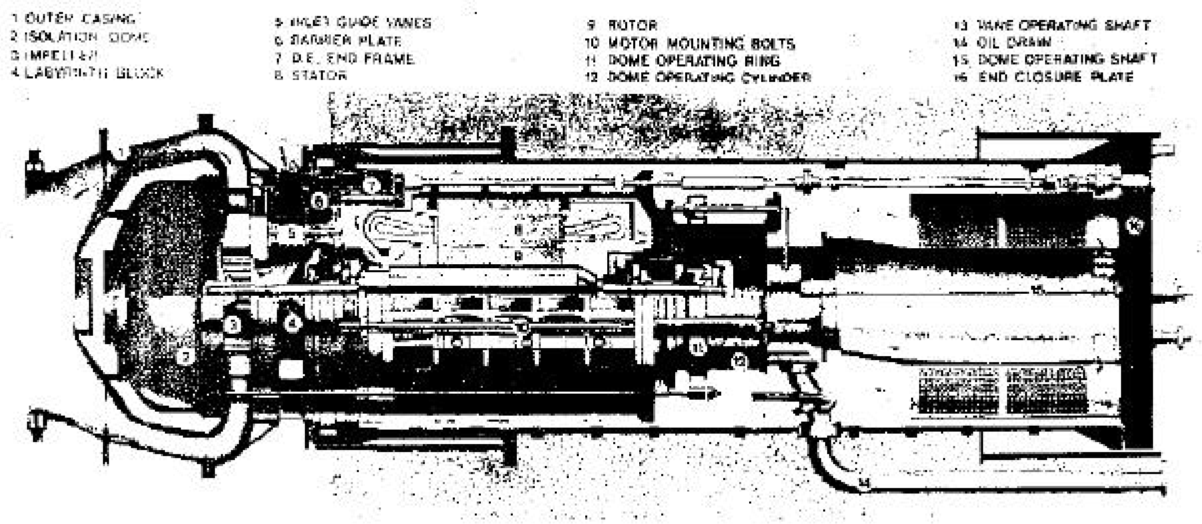


Figure 16: Typical vibration signature of a Hinkley Point B gas circulator frame

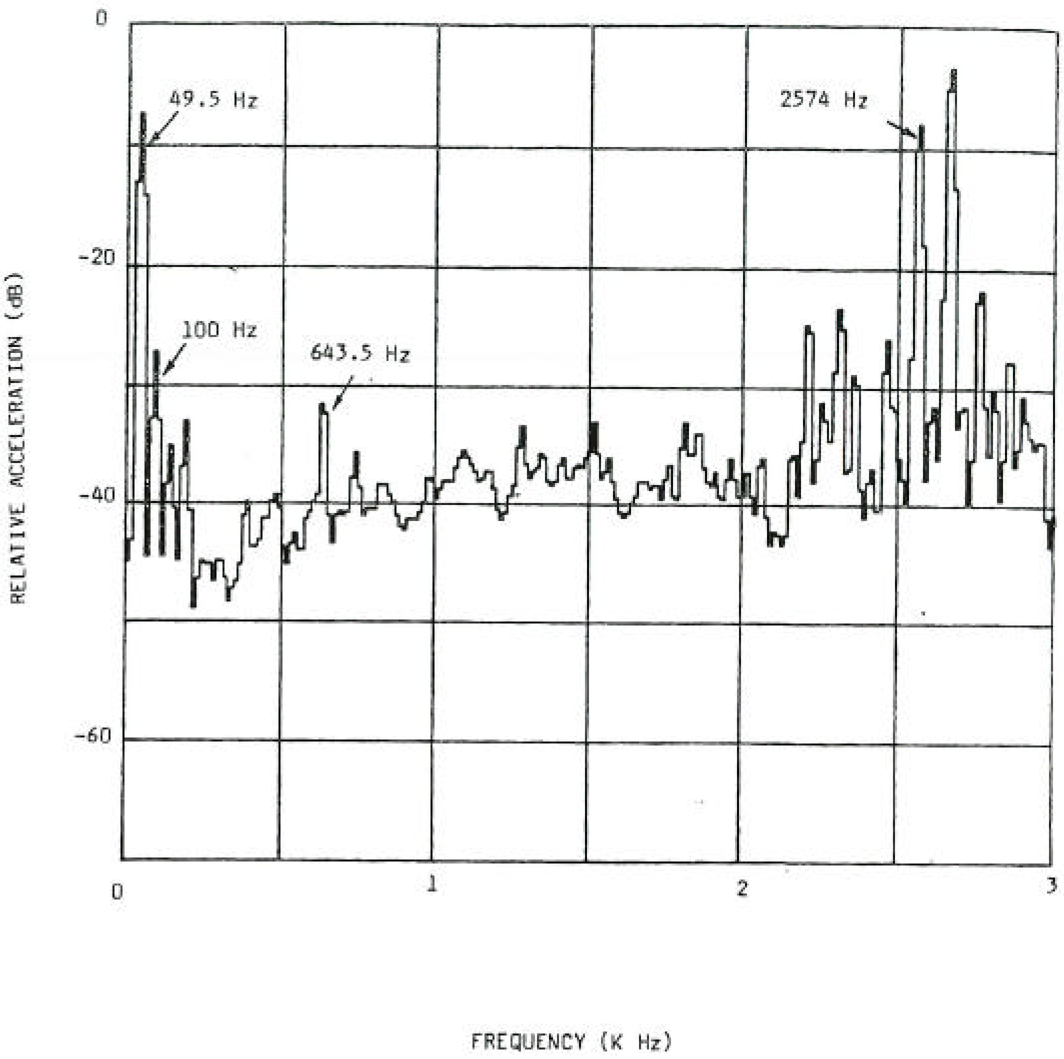


Figure 17: Dragon primary heat exchanger and gas circulator

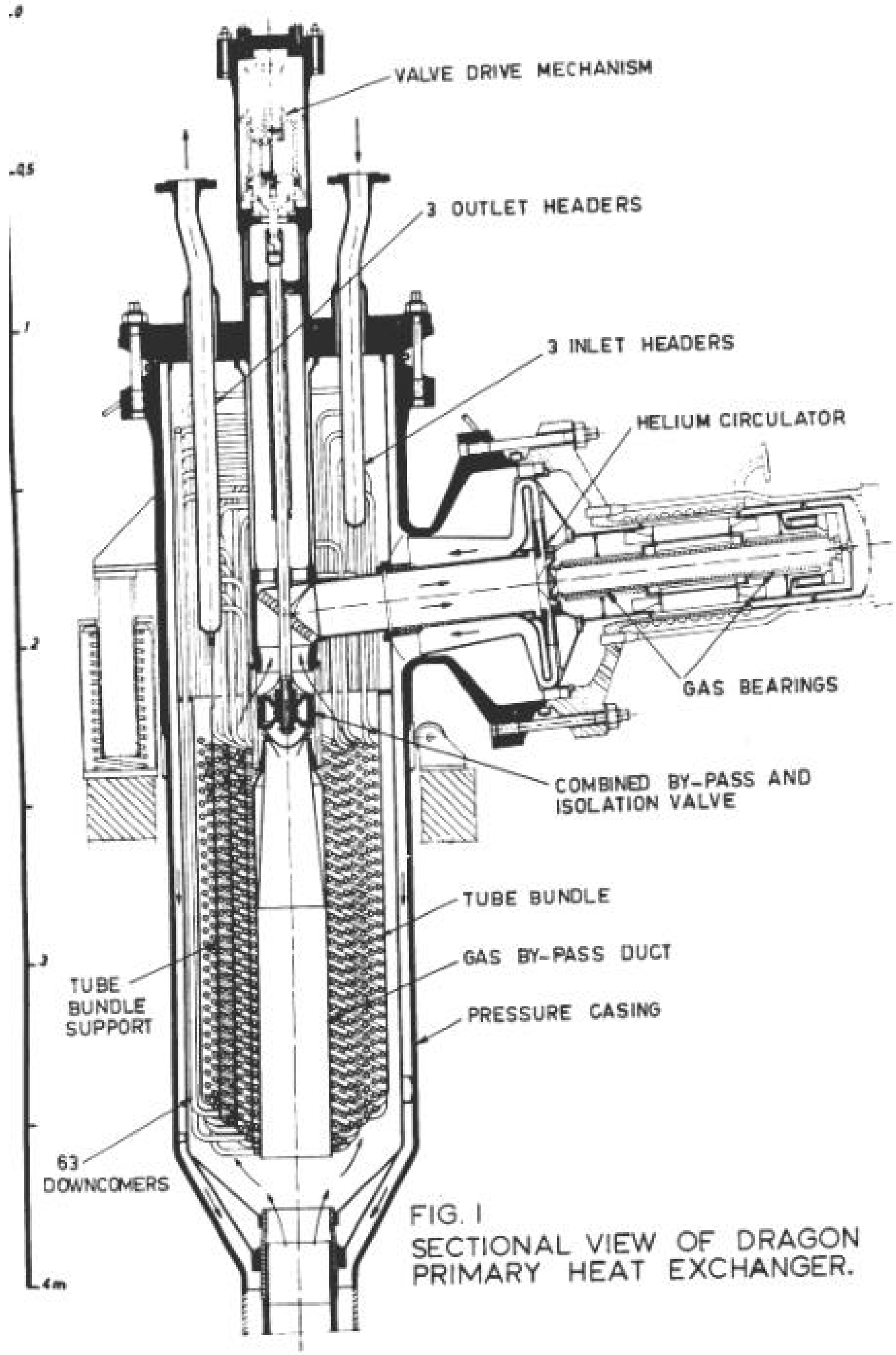


FIG. 1
SECTIONAL VIEW OF DRAGON PRIMARY HEAT EXCHANGER.

Figure 18: Dragon gas circulator

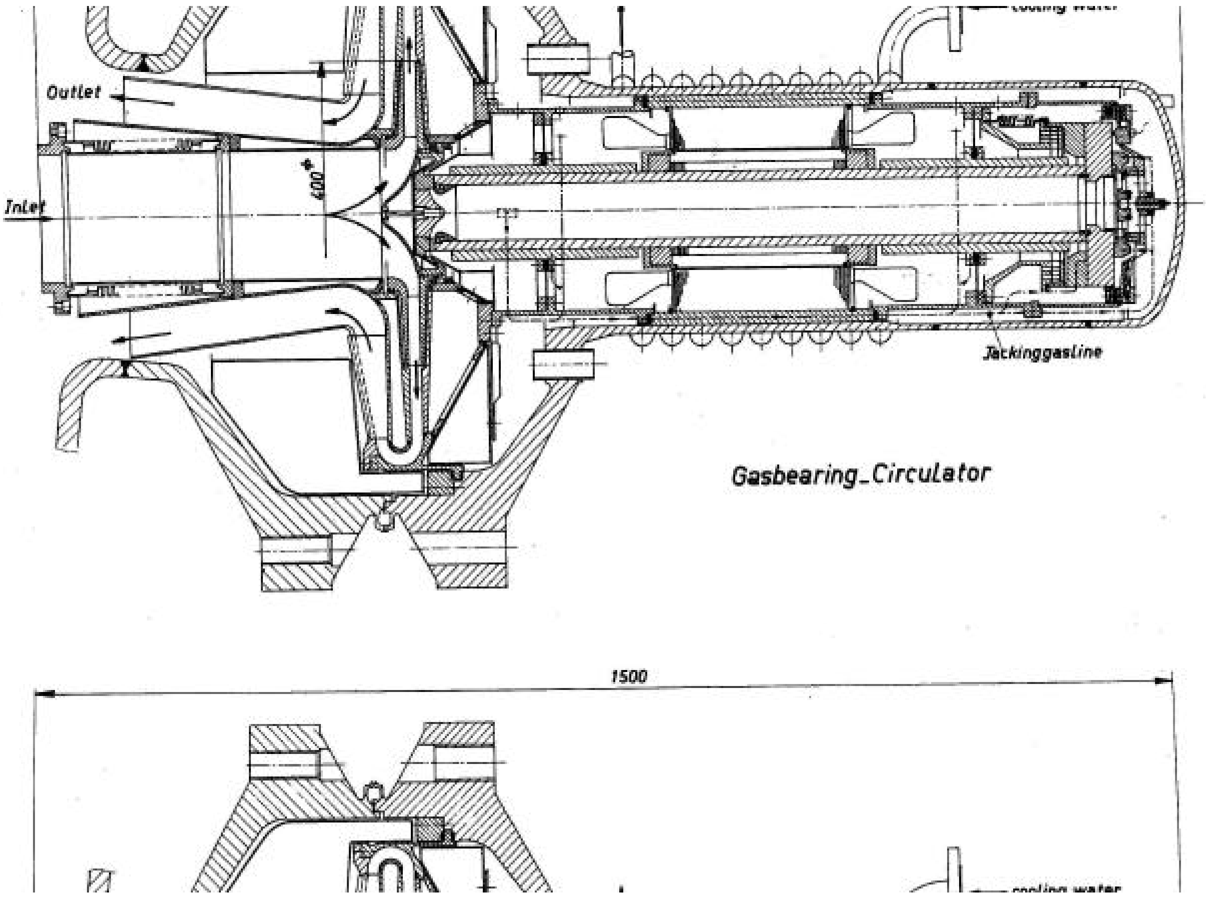
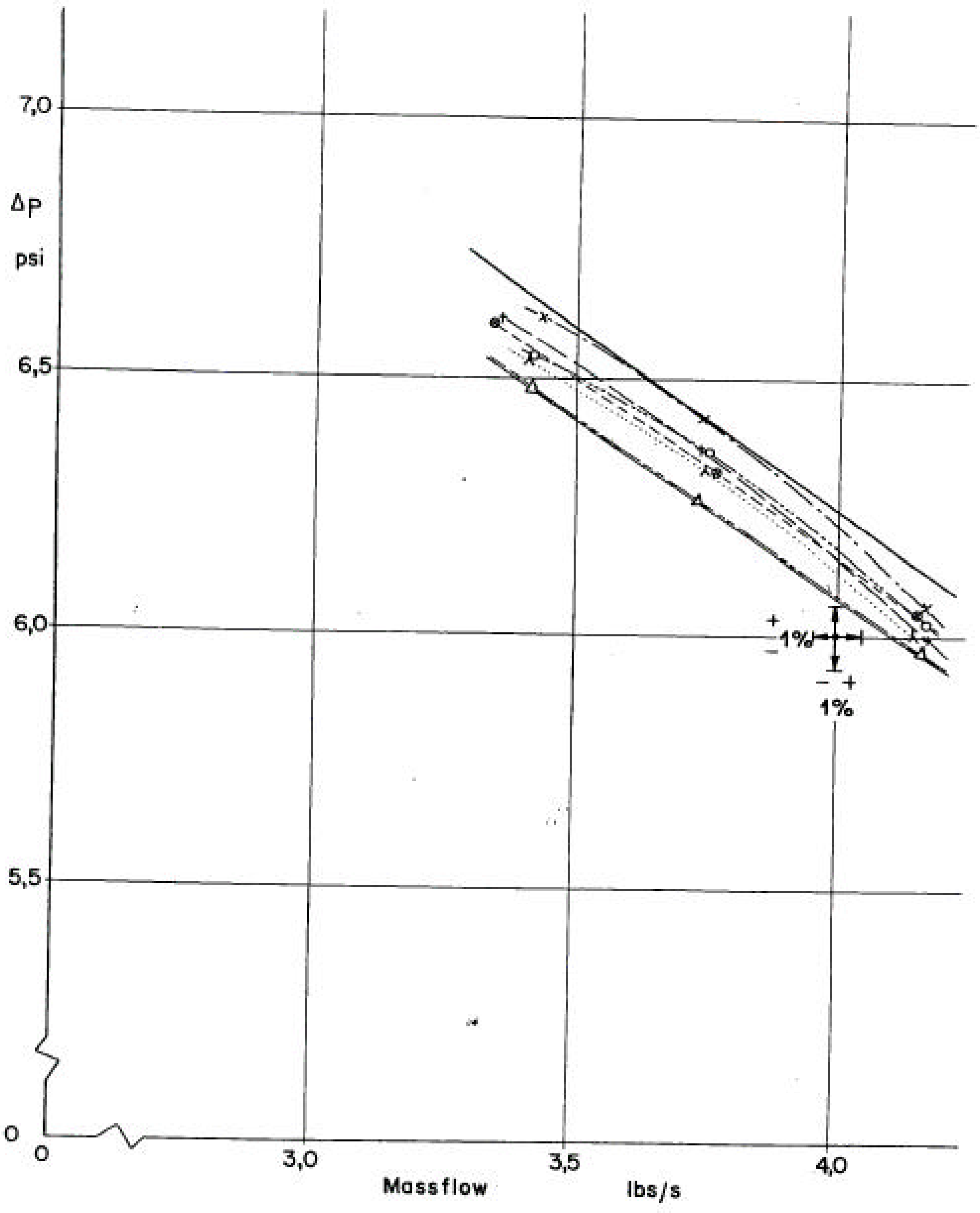


Figure 19: Pressure rise/mass flow characteristic for the Dragon prototype and circulators 1 – 5, at 30 bar, 350°C and 11400 rpm.



Appendix A. LITERATURE REVIEW

1. Introduction

The purpose of this literature search is to gather information on past experience with high temperature components, specifically gas circulators (also known as blowers) used in various industries, both nuclear and non-nuclear. This will utilise a bibliographic review of past experience from UK power generation and HTR research and development programmes (Magnox, AGR and Dragon) as well as experience gained from other countries where research and development programmes on high temperature components has taken place.

2. Literature search

The literature review is based on the database and documents that are in AMEC NNC's possession, as well as conference papers, other published papers and documents found in searches on the Internet.

Following these actions, papers that were most relevant to the subject of this document were considered. A summary of the documents was drawn up which includes the title and abstract, and a description of any relevant data contained within the document. The literature review is divided into two sections: UK experience and International experiences, which includes other European countries, Japan, China and the USA.

3. Relevant documents from the literature search (Table A-1)

3.1 UK Experience

Reference 1

Development for CO_2 circulators
Donaldson, J. (James Howden and Co. Ltd, Renfrew (UK))
Specialists' meeting on gas-cooled reactor coolant circulator and blower technology, San Diego, CA (USA), 1987

The Windscale (prototype AGR) circulators supplied in the 1960s were the first in a series of submerged circulators supplied to the UK AGR programme. They were small 1.2 MW vertically up circulators with an inlet temperature of 237°C. Oil leakage problems occurred and were cured in the works test facility and the machine went into service with no other problems.

The Hinkley/Hunterston AGRs were fitted with horizontal 5 MW circulators, which faced vibration problems, interface corrosion problems and material dimension stability problems. Oil ingress problems did not show up in test work but were later reported from site, which were initially exaggerated due to the measuring techniques that took operators some time to resolve.

In the vertical 5 MW machines at Hartlepool and Heysham I, there were two interesting problems: firstly a spar failure and secondly shaft axial instability. Many of the problems were due to modifications at site or the inability to model all aspects of site installation.

The latest stations, Torness and Heysham II, incorporate experience learned from previous plants. The circulators have been design with so much margin that during the resolution of the reactor control rod gag problems, the circulators were run continuously at 20% overload (6.3 MW). From an initial accident case inlet temperature of 350°C, it was increased to 458°C and now stands at 585°C. The site experience to date is good with no operational problems reported.

Reference 2

Considerations on the design of a helium circulator for a high temperature modular reactor system
Dumm, K. (Internationale Atomreaktorbau G.m.b.H. (INTERATOM), Bergisch Gladbach (Germany, F.R.)); Donaldson, J. (James Howden and Co. Ltd, Renfrew (UK))
Specialists' meeting on gas-cooled reactor coolant circulator and blower technology, San Diego, CA (USA), 1987

A modular helium-cooled high temperature reactor system especially for cogeneration of electricity and process heat, with a thermal output of 200 MW per reactor has been developed by the KWU Group (Kraftwerks Union-Interatom).

One circulator per reactor maintains the flow of the reactor coolant, helium at 60 bars and 250/700°C. The circulator is driven by a variable speed Siemens asynchronous motor and is submerged in the helium primary system. All active parts are mounted on an intermediate pressure vessel flange, which, normally under pressure, is designed to withstand in both directions the full operational pressure of 60 bars. The only connection between the motor compartment and the main primary system is via the shaft's labyrinth penetrations in the intermediate flange. For operational reasons high reliability and availability of the circulator is required. The operational requirements and the circulator design is presented in more detail in this paper.

The actual design has been carried out in close cooperation with the designer and manufacturer of all submerged circulators operating in AGR plants in the UK: James Howden & Co., Renfrew, Scotland. Proven components such as oil bath lubricated bearings are primary selected. Nevertheless the comparably new technology of active magnetic bearings offers some strong advantages for the future provided that the problems of catcher bearings and electrical interactions are satisfactorily solved. Also replacement of the journal bearing with a magnetic bearing has been proposed.

Reference 3

A review of submerged gas circulators as applied to advanced gas cooled reactors
W M Fraser (James Howden & Co. Ltd)
Journal of the British Nuclear Energy Society, Volume 24, 1985

In the 1950s, reactors were designed typically for a gas pressure of 300 lb/in^2 or below. It was normal to locate the circulator drive outside the pressure vessel and to use a balanced pressure seal to take the drive shaft through the vessel to drive the gas circulator impeller. As pressure increased, seal development became increasingly difficult and it was harder to control the migration of oil into the reactor.

For the Windscale prototype AGR the engineers at UKAEA decided to eliminate potential seal difficulties by locating the complete drive motor inside the pressure envelope. This does not eliminate the need for a shaft seal against full reactor pressure differential; a simple labyrinth was all that was necessary. At Windscale circulator (4 per reactor), which were designed, developed, built and tested in just over two years, proved to be very reliable and well behaved in service. They gave virtually trouble-free operation for 20 years before the reactors were taken out of service in April 1981.

The first commercial AGR station – Dungeness B, which operates at 450 lb/in^2, did not make use of the submerged circulator concept, but it has been adopted on all subsequent AGR stations.

The horizontal submerged circulators supplied for Heysham II and Torness power stations are fully developed second generation machines in which all the possible significant improvements have been made. They have been performing well on test and there are no grounds for seeking further improvement. Given that duties remain unchanged, they are suitable for incorporation in future AGR stations without any change. In the event of a modest up rating of duties being required, to enable reactor output to be increased beyond the present design figure, further scope is possible with little or possibly no change to the circulator design.

Reference 4

Investigations into the failure of gas circulators and circuit components at Hinkley Point nuclear power station
W. Rizk, D.F Seymour
The Institution of Mechanical Engineers, Proceedings, Volume 179, Part I, Number 21, 1964-65

Serious failure that occurred at the Hinkley Point Nuclear Power Station is dealt in this paper. The failure occurred during the hot run testing on the first reactor, which was unfuelled at the time. Several damage have occurred to the diffuser section and blading on two of the blowers, as well as to other gas circuit components such as corner cascades. The severe blading damage was largely caused by flying debris from the damaged diffusers.

The first indications of trouble was recognised when some drop of the mass flow and the current of the driving motor had occurred. On examination, a large section of the diffuser casing had entered the blower blading causing heavy impact damage. Virtually all failures in the steel plate of the diffuser were of the fatigue type, the only evidence to the contrary being where the outer shell, having suffered extensive fatigue cracking, was no longer able to withhold the gas loading on a large section and had suffered a large tear.

Examination of the inlet guide vanes of the circulators have shown that the blades had been subjected to severe vibration and had suffered extensive damage to their shanks on the inner diameter. There has been rapid wear on the washer and extensive loosening of the nut on nearly every blade but as the latter was held captive between the inner fixing ring and the end casing of the circulator, the nut has not fallen off and had caused considerable erosion of the parts in question. The resultant wear on the shank was enough to cause the total disappearance of the threaded portion of both components. In some cases the shank had fractured leaving the remnant of the threaded position in the nut itself.

The primary failures at Hinkley Point were due to metal fatigue arising from an acoustic excitation of greater power than some of the components could withstand. The removal of the inlet guide vanes resulted in the largest single improvement of all the various measures taken and greatly reduced the powerful harmonics previously measured. Improvements in the inlet flow distribution further reduced the excitation, which in this case was of a random and low frequency nature. The major components involved in the failure, such as diffuser and corner cascades, have been replaced by new units of modified design to meet some of the conditions found to exist in the gas circuit.

Reference 5

Gas circulator repairs
A W Gould
The Institution of Mechanical Engineers, Proceedings, Volume 201, Number A3

The thrust bearing of a gas circulator on the Magnox gas-cooled reactor at Oldbury-on-Severn power station failed in May 1983, while running at full speed and power. This gave rise to problems that was not previously experienced in the maintenance and repairs of circulators. Investigations revealed defects that were traced to original manufacturing standards and testing procedures. The trust bearing failure prompted a more critical examination of maintenance dismantling/rebuild procedures and standards, which led to changes in the organisation and quality control of circulator maintenance activities.

Investigation into the thrust bearing failure eliminated incorrect operation and attention was then centred on maintenance history and the quality standards achieved in maintenance work. Checks made on the geometry of circulator 1 and on other circulators have revealed poor original manufacturing standards in the alignment of components associated with the thrust bearing. A programme has been adopted to check and improve as necessary the build standards of all eight circulators.

On removal of the blades from the disc to inspect the blade roots, cracks was revealed in the dowel holes on four of the blades out of the total of eight. Analysis of the incident and operational history could not support the formation of these cracks in service or during the incident. The investigation was broadened to include examination of the limited information available on original manufacture, assembly and testing, combined with measurements of blade and dowel fit up. The information collected, combined with metallurgical examination and stress analysis, provided a good measure of evidence to support formation of the cracks during original testing, with growth in service being unlikely.

Since four of the original blades had cracks and dimensional inaccuracies were present in the blade slots, the decision to fit a complete new set of blades were taken. The disc was considered recoverable. The fitting of the oversize dowels would also eliminate dimensional errors and was necessary due to some scoring of holes in removing the dowels. Fitting a bolted-on make-up piece to restore the standstill seal face repaired the main casing. To deal with the damage on the shaft trust collar, the shaft was remachined without unacceptable reduction in strength and shimming of the trust bearing assembly accommodated the dimensional changes.

Also in addition to the replacement of thrust pads, it was considered necessary to fit a device to each circulator that would continuously monitor shaft axial movements to give an early warning of thrust bearing failure. As the rate of collapse and consequential shaft movement was predicted to be very rapid, the device had necessarily to be sensitive with remote indication in the central control room.

<u>Reference 6</u>

The role of gas bearing circulators in the Dragon reactor
W F Shilling
Proceedings of meeting on Rotating Machinery for Gas-Cooled Reactor Application, Tennessee, 1963

The original specification for the Primary Gas Circulators was mainly influenced by the magnitude of pressure excursions in the circuit, due to the reaction of water from the secondary coolant circuit with the hot graphite in the core and reflector, which could occur in the event of tube failure in the primary heat exchangers. To limit the amount of water available in the event of a tube burst, six independent secondary circuits were used. This division of circuits reduced the primary flow per circuit to a region where a gas bearing circulator became a feasible proposition.

The six main circulators are mounted together with the heat exchanger at the top of the vertical coolant ducts that contain concentric inner liners and carry the primary gas flow to and from the heat exchangers. This location of the circulators gave easy access for maintenance as the circulator is outside the area of high neutron activity and enables sufficient convection head to be created in the event of a complete circulator failure for the decay heat from the reactor to be removed by natural circulation of the primary coolant.

A by-pass valve is used to control the temperature of the gas at entry to the circulator by mixing hot gas at the tube bundle entry with the cooled gas leaving the tube bundle. The speed of operation of the valve allows a rate of temperature not exceeding 1°C per second on the circulator during normal reactor operation.

The safety and emergency requirements that were incorporate are as follows:

a) In the event of an electrical input failure to the circulators, they can be operated from an independent supply.

b) The units must sustain pressure changes due to a rapid depression of the circuit and be capable of running at a minimum speed of 4 000 rpm in helium at 350°C and atmospheric pressure.

c) The circulators should be capable of running with a gas inlet temperature of 420°C, this condition would arise if it became necessary to anneal out the effect of neutron irradiation on the main pressure vessel.

d) They should be capable of running at a pressure in excess of normal, 350 psia instead of 289 psia after sustaining a rapid pressure rise.

e) An impeller failure must not create a breach of the pressure circuit.

f) The units should withstand a temperature change of 3°C per second.

g) The circulators must be able to be topped and restarted quickly with a coolant gas temperature of 350°C.

If for any reason one circulator changes its speed relative to the remaining units, the reactor trips and all units run down to 1 300 rpm. The failed unit run down to standstill, back flow through the failed unit will not be sufficient for auto rotation of the impeller. The remaining circulator can then be accelerated up to maximum speed if necessary after the isolated valve on the failed unit has been closed. Also if the reactor is 'scrammed' for any reason, all circulators run down from their operating speed of 4 000 rpm to 1 300 rpm under control of the main VFGS within 30 second.

Reference 7

Experience of the reliability of steam and electrically driven circulators for GCRs
L Cave, R S Gow
Nuclear Engineering International, 1977

The first generation of gas-cooled reactors were not standardised at all and major components were often a once-off design. The circulators, being the most dynamic component in the primary circuit, were required to maintain high reliability for both safety and economic reasons.

The UK source of detailed information about the reliability of steam driven circulators comes from the operation of the CEGB Magnox stations at Dungeness A and Oldbury which had some 160 circulator years of operational experience. The experience with various type of electrical drive is more extensive, the CEGB stations alone providing over 600 circulator years.

In the UK designs each circulator has its own independent oil pump and redundant pumps are provide in the various systems (lubrication, control and seal oil). Thus it is expected that the main cause of loss of all circulators would be loss of electrical supplies to the main drives or in the case of steam drives, loss of feed to all boilers.

The frequency of loss of all main circulator drives is about 0.26 per reactor year for steam-driven circulators. For the AC motor drives, supplied from the grid or unit generation the frequency is somewhat lower, about 0.13 per reactor year, but the figure for variable frequency drives taken alone is 0.7. The frequency of failures in steam drives when used in conjunction with once-through boiler could be reduced substantially by improvement of the reliability of the feed train.

The ability to 'run-through' following a single circulator trip varies markedly between stations. A frequency of 0.29 per reactor year for reactor outage caused by a single circulator failure appears to be representative for the CEGB Magnox reactors. Circulator faults do not make a major contribution to the frequency of forced reactor outages (about 0.3 per reactor year), although one of the stations using steam-drives (Dungeness A) is noticeably worse than the average in this respect.

Reference 8

Gas blowers for Dungeness
T E Adams
AEI Engineering, 1962

AEI were building eight gas blowers for circulating carbon dioxide through the reactors and heat exchangers at Dungeness Nuclear Power Station. The blower would have spherical outer casings and would be situated in the station immediately below the heat exchangers.

Increased internal gas pressure losses have a markedly adverse effect on the overall efficiency of a blower. To find a design, which has low losses, several different scale models of blower casings were tested in a wind tunnel. A comparison was made between spherical and cylindrical outer casings the pressure losses between the inlet flange and the rotor blading is 0.6 and 1.5 for the top-inlet spherical outer casing and top-inlet cylindrical outer casing respectively. In the spherical design a boundary layer control slot is introduced in the inner nose of the internal fairing to feed air to the annulus just before the rotor blading. Model testing showed that air distribution was improved.

The Berkeley blower, which has a cylindrical casing, is cheaper and simpler because of its low losses and gives an overall blower efficiency of approximately 2% better than the internally faired spherical design of Dungeness. Also the Berkley blowers were easier to service due to their unobstructed inlet casings and their position in the station directly under the blower-house crane. On the contrary the Berkeley design tends to straighten out under gas pressure, so that serious mal-alignment of the drive shafts could occur. The Berkeley gas duct circuit had to be counted the pressure losses of the two extra cascaded 90° bends, which have been added to resolve the duct circuit. This increased the cost due to the extra bends and greater civil engineering works.

The seals, hydraulic gear and rotor for Dungeness were of similar design to those of Berkeley, with the bladed impeller held to the shaft by a single through-bolt and Hirth coupling. The Mitchell bearing which locates the shaft is contained in a cylindrical housing so designed to both housing and bearing can slide axially in the main outer casing. The movement of the Mitchell bearing housing in an axial direction, however, can only take place after hydraulic pistons have turned a castellated locking pillar into the 'open' position. Other sets of hydraulic pistons can force this housing axially in either direction, and the axial movement directed towards the coupling causes a flange on the impeller to enter a matching spigot recess on the blower casing, so holding one side of the impeller. This movement at the same time brings into operation two flexible steel stationary gas seals located at the hub.

Reference 9

Measurement techniques for AGR circulators in a full-density rig
I Watson, R R Wilson
Institute of Physics Conference, 1976

In an advance gas-cooled reactor (AGR), high pressure CO_2 gas is pumped round the reactor core and boiler circuits by a number of motor driven gas circulators acting in parallel. Safety and reliability are essential in a nuclear plant and the circulator has been design to last for the life of the station, which is 30 years. Routine reactor shutdowns are planned for inspection and maintenance of moving and rotating parts.

During commissioning of the Hinkley 'A' Magnox reactor, serious fatigue damage occurred in some of the axial blower components and very extensive rectification was required. Investigations revealed that these axial blower failures were caused by acoustically induced vibration leading to the propagation of fatigue cracks. Because of this the electricity authorities decided that the AGR circulators should be tested in a full-density rig (36 kg m^{-3}), which would simulate the most adverse conditions that the circulators would experience in the reactors. Two arrangements of circulator are used, that is, they are mounted with their axes horizontal or vertical.

The failure of the axial blowers of the Magnox reactors highlighted the main potential source of problems in the AGR circulators. For the specified gas densities and flow rates, very high broadband sound pressure levels are unavoidable. At the sound-pressure levels of 172 dB (reference 2×10^{-5} Pa), which occurs, the corresponding peak-to-peak cyclic pressure is about 22 kPa. Components of the circulators and other parts of the reactor exposed to the high noise levels must be designed to withstand the acoustic exciting energy.

Since theoretical prediction of acoustically induced fatigue failure or fretting was at an early stage of development, it was considered necessary to use the test rig to measure the dynamic stresses and movements of critical components. The rig allowed the circulators to be run continuously at conditions corresponding to the maximum measured dynamic, sound and vibration levels and components examined for possible fretting or fatigue damage. This was a very sever test since it was not anticipated that the circulator would be run at this arduous duty for prolonged periods.

Furthermore this paper gives the description of the test techniques developed for these circulator investigations, outlines some of the problems that came up, as well as the solution found.

Reference 10

The main circulators for the Dragon reactor

The Brown Boveri Review, 1963

The main coolant circulators for the Dragon reactor at Winfrith in England are totally enclosed blowers with hydraulic gas-lubricated bearings. In addition, the circulators were specified to be capable of running with air or nitrogen at pressures of 1 to 2 Kg/cm^2 and temperature between 15°C and 350°C. The blowers should be able to withstand relatively rapid changes in temperature, pressure and speed. It should be able to stop at high temperatures and restart at any time.

A pressure-tight flanged casing encloses the working parts of the blower, that is the impeller, shaft, bearings and motors. All bushing leading to the outside are also gas-tight and there were no need for mechanical seals. The casing consisted of three main sections welded together, which were the flange with conical section leading to the cylindrical section and the tank at the bottom. The transition from the conical to the cylindrical part is reinforced to take the bushings for the supply to the motor; the instrument leads as well as the connections for measuring the pressure and for the inlet of gas under pressure. Also the cooling coil was welded outside the cylindrical part and provided very effectively water-cooling.

The circulator is a single stage blower with over hung impeller, the diffuser being parallel and vaneless. Between the two gas-lubricated radial journal bearings is the squirrel cage motor and at the other end of the shaft is the gas-lubricated thrust bearing. The components of the circulator were either welded or machined from solid metal. The impeller was of a normal type, as used in radial compressors, adapted to the particular requirements. It is bolted on to the ground end of the hollow shaft and centred by a short stub fitting tightly in the bore.

To monitor the operation of the totally enclosed circulation, a number of internal sensing elements are incorporated. Thermocouples were fitted in the bearings, the stator winding and in the gas stream. The speed was determined by inductive pickups. The stage pressure rise was measured by tappings at the inlet and outlet of the blower. A vibration meter was fitted outside the casing.

The trials for the circulators for the Dragon reactor showed that the gas-lubricated bearings were perfectly reliable. They were robust in service and were not sensitive to impurities in the surrounding atmosphere as might be expected from small clearance in the bearings.

Reference 11

Gas-circulator problems in reactor development
J R Ridley
GEC Atomic Energy Review, Volume 1, 1958

The problems dealt in this paper were those faced during the design of circulators for the Hunterston Nuclear power station.

Because of the nature of the duty of the circulators and the extreme reliability required, a centrifugal blower with an impeller having backward-curving vanes was chosen. This type of machines was already used in industry that time and was proven reliable. In addition, the motor chosen was a twin-armature machine of the type commonly used for large rolling mill drives.

To obtain the operating characteristic of the blower, a rig was set up with a scale down model of the circulator. The rig was to provide accurate readings of pressure, temperature, speed and power and in which a considerable range of speeds and gas flows could be covered. To maintain the correct Mach number of the gas flow, and the correct relation between the blower and gas velocities, the given test-rig running speed was approximately three times the corresponding speed of the design blower.

The other component that was considered was the seal, which in this type of application, the duty were very stringent. The main requirement was that the leakage occurring should be very small and at the same time the seal must require very little maintenance, be completely reliable under all operating conditions, not cause contamination of the gas circuit and to be foolproof. Four types of seal were chosen which were:

1. Oil-flushed face-type seal, as used in hydrogen-cooled alternators
2. Carbon rubbing-face seal
3. Gas-lubricated rubbing-face seal
4. Viscous seal.

Tests done on the carbon rubbing-face seal and the viscous seals are explained more in detailed in this paper. The oil-flushed face-type seal and the gas-lubricated rubbing-face seal were rejected due to their high leakage rate under operating conditions.

Reference 12

Some aspects of the dynamics of AGR gas circulators
K M A Kamesh (CEGB Scientific Services Department)
British Nuclear Energy Society Journal, Volume 2, 1982

Various type of vibration found on gas circulators of the AGR are described and categorised in this paper and more specifically the Hinkley Point 'B' design is look at. The need for maintenance free running of the circulators for long period of time is of critical importance. Amongst other things that affect their performance, vibration could be a major source of damage and, as in any rotating machinery; the dynamic design characteristics of these circulators have direct influence on their degree of sensitivity to the various sources of vibration excitations.

The different types of vibration that can be detected in the AGR circulators are:

1. Mechanically induced vibration – caused by forces generated by a rotor unbalance or by a permanent bend in the rotor. The effect of these vibrations can be a fretting damage to main journal bearing mounting surfaces, isolating dome operating rods and inlet guide vanes bearings and their control mechanism. Also this type of vibration can also cause severe vibrations to ancillary equipment mounted on the non-drive end of the main motor frame.

2. Gas flow induced vibration – Gas pressure fluctuations generated by a rotating stall in the impeller occurring at about 30 Hz. This was found to occur at low inlet guide vane setting and can cause shaft vibrations with limit the operational range. Gas pressure fluctuations generated by inlet guide vanes/impeller/diffuser interaction normally occurs at very low level, in terms of displacements, but can cause fretting damage to inlet guide vane bearings and their control mechanism. Also gas pressure fluctuations can cause resonance vibration near components. This can occur in components that are situated in severe turbulent flow regions like the inlet guide vane section of the circulator.

3. Electromagnetically induced vibration – This occurs from inherent electromagnetic forces associated with the stator and occurs at twice the main frequency and harmonics. Normally they are low in terms of displacement and no damage had been attributed to this phenomenon. Also electromagnetically induced vibration occurs from rotor bars/stator windings electromagnetic interaction. Changes in these vibrations can be used for detection of rotor bar defects.

Reference 13

Vibration data and its employment for component life projections in AGR circulators
T C Chivers, S C Gordelier, J Roy
British Nuclear Energy Society, Vibration in Nuclear Palnt, Keswick, UK, 1978

Vibration behaviour is undeniably an extremely important facet of plant analysis, both in nuclear and conventional plant. A consideration of the failures that can result from adventitious vibration shows that they usually belong to one of three general categories:

i. Control failures

ii. Wear failures

iii. Fatigue failures

In the first category, control failure, vibration behaviour makes the plant performance unacceptable. In the remaining two categories it is the secondary, mechanical consequences of the vibration behaviour that manifest themselves as failure mode. In this paper wear fatigue failure modes, with unacceptable wear behaviour resulting from unwanted and unexpected vibration, is examines. The plant items of interest are components within the sealing dome closure mechanisms of the gas coolant circulators for Hartlepool and Heysham Advances Gas Cooled Reactors.

The fretting wear of Hartlepool circulator closure components were studied and it can be demonstrated that a serious vibratory wear problem did not exist. The more general conclusions were:

- The occurrence of characteristic fretting damage is an obvious indication of vibration between mating components.

- Examination of the wear scars can provide an early indication of the direction and relative severity of vibration movement. This information may be of use in sitting instrumentation.

- Laboratory scale tribology experiments are often necessary to assess vibration wear problems and remedial measures. Only by an adequate knowledge of component vibration characteristics can realistic tribology experiments be conducted.

- Evidence exists that specific wear rates are not independent of amplitude in the vibratory wear regime. Firm qualification of this effect would be great benefits in the assessment of potential vibration induced wear failures, and the measurement and analysis techniques developed by vibration specialists could assist in the understanding of this phenomenon. A modification is proposed to the wear projection equation, which permits inclusion of a variable in specific wear rate.

- To extrapolate wear from a component test on the basis of a linear volumetric removal rate with time need not necessarily be correct. Knowing the vibration conditions during both experiment and normal operation can this projection be realistically approached. An equation is presented in this paper, which permits this more accurate projection.

<u>Reference 14</u>

Component design for High temperature Reactors using Helium as a coolant: Circulator design for HTR
D G Penry
Institute of Mechanical Engineering, London, 1972

This paper concentrate on the effects of the use of helium as the coolant gas had on specific areas of circulator designs. Also a comparison of the values of the properties of helium at the pressure and temperature of the reactor with corresponding values for carbon dioxide, the gas used as reactor coolant for both the Magnox and the AGR is given.

Helium is a gas of relatively low density; therefore in spite of the fact that the mass flow is noticeably reduced in the HTR, the volume flow at inlet to the circulator is considerably increased. Helium having a high value of specific heat and also of specific heat ratio, the design pressure rise is achieved with much higher blade speeds even though the pressure ratio is lower. These facts make is possible for axial as well as centrifugal designs for HTR circulators to be taken into consideration.

Being an inert gas and a high level of purity will be maintained, a certain degree of impurity will be inevitable in the helium gas. Surface oxidation will be minor and therefore corrosion of the metal, that is, loss of surface I not expected to any degree, even at higher temperature. The impurity is the gas would be expected to be hydrogen, nitrogen and sulphur. These impurities also exist in the CO_2 of the AGR, but in these reactors oxide films protect the steels, whereas the helium there is the absence of any substantial oxide film on the surface. Therefore, trace elements are absorbed by the steels and lead to internal oxidation, nitriding, carburisation, sulphur attack and hydriding. In the lower temperature range there is evidence that this leads to a strengthening of the steel, but some embrittlement of the alloy steels, particularly nickel steels, is also present.

A source of difficulty with the lubrication systems on the AGR circulators is that of oil frothing owing to the high absorption of CO_2 into the oil. This is of particular importance during depressurisation. However, tests conclusively show that the absorption of helium into oil and water is negligible. The choice of oil as lubricant was favoured over water due to difficulties encountered in the use of water as lubricant, which is further discussed in this paper. The choice of lubricant is important because of the vertical arrangement of the circulators above the boiler can cause leakage of lubricant from the circulators naturally from gravitation into the reactor gas stream.

Other factors like oil sealing, buffer helium, electric motor drive and circulator noise are further discuss in this paper.

3.2 International Experiences

Reference 15

Circulator performance during THTR trial and post-commissioning operation
Glahe, E. (Hochtemperatur-Kernkraftwerk G.m.b.H. (HKG), Hamm (Germany, F.R.)); Stoelzl, D. (Brown, Boveri und Cie A.G., Mannheim (Germany, F.R.))
Specialists' meeting on gas-cooled reactor coolant circulator and blower technology, San Diego, CA (USA), 1987

The THTR-300 is a helium-cooled high-temperature reactor fuelled by 675 000 spherical fuel element of 60 mm diameter arranged in the core as a pebble bed. The coolant gas circulator used in the THTR 300 nuclear power plant has to perform the following duties:

- As an operational device it has to circulate the cooling medium helium when in operating condition, that is, at 40 bar and 160°C, at various gas flow rates according to the output of the nuclear power plant.

- During the commissioning phase, it has to circulate nitrogen at temperatures up to 300°C.

- The circulators must also serve as components of the guarantee decay heat removal system with all the safety-related requirements involved. These requirements have been taken into account in the fabrication, the control, design and redundancy of the auxiliary equipment for the circulators as well as for the execution of the component protection system.

For the first runs, the circulators have scored more than two years of trouble free operation. Six circulators were ordered which were equipped with oil bearings and each provided with a separate oil system whose pressure corresponds to that of the primary system. Safety aspects resulting from the licensing requirements led to extensive efforts regarding the oil systems.

During the commissioning phase it has been verified that the internal barrier helium system of the circulator is capable to retain the lubrication oil inventory within the circulator range, even if the external make-up barrier helium supply from the helium purification system is shut off. Thus it is ensured that the leakage of oil into the primary helium system is ruled out by the shaft seal system.

Further development work on the circulators was currently being continued for the only reason that active magnetic bearings permit vertical arrangement of the circulators with the impeller at the lower end without requiring the operation of an extremely complicated and expensive oil system. Apart from that, the experience gained with the THTR operation did not result in any changes in the design characteristics, which had already been used in the AVR circulators.

<u>Reference 16</u>

Operating experience with gas-bearing circulators in a high-pressure helium loop

Sanders, J.P.; Gat, U.; Young, H.C. (Oak Ridge National Lab., TN (USA). Engineering Technology Div.)
Specialists' meeting on gas-cooled reactor coolant circulator and blower technology, San Diego, CA (USA), 1987

A high-pressure engineering test loop has been designed and constructed at the Oak Ridge National Laboratory for circulating helium through a test chamber at temperatures to 1,000 deg. C. The purpose of this loop is to determine the thermal and structural performance of proposed components for the primary loops of gas-cooled nuclear reactors.

Three gas-bearing circulators, mounted in series, provide a maximum volumetric flow of 0.47 m^3/s and a maximum head of 78 kJ/kg at operating pressures from 0.1 to 10.7 MPa. Control of gaseous impurities in the circulating gas was the significant operating requirement that dictated the choice of a circulator that is lubricated by the circulating gas. The motor for each circulator is contained within the pressure boundary, and it is cooled by circulating the gas in the motor cavity over water-cooled coils. Each motor is rated at 200 kW at a speed of 23,500 rpm.

The circulators have been operated in the loop for more than 5,000 h. The flow of the gas in the loop is controlled by varying the speed of the circulators through the use of individual 250-kVA, solid state power supplies that can be continuously varied in frequency from 50 to 400 Hz. To prevent excessive wear on the gas bearings during start-up, the circulator motor accelerates the rotor to 3,000 rpm in less than one second.

During operation, no problems associated with the gas bearings, as such, were encountered. However, related problems pointed to design considerations that should be included in future applications of circulators of this type. The primary test that has been conducted in this loop required sustained operation for several weeks without interruption. After a number of unscheduled interruptions, the operating goals were attained. During part of this period, the loop was operated with only two circulators installed in the pressure vessels with a guard installed in the third vessel to protect the closure flange from the gas temperatures. Unattended operation was achieved, and the design safety controls operated dependably to prevent damage to either the test item or the loop components.

<u>Reference 17</u>

Design features and test results of the main circulators for the Dragon Reactors
H. Baumann (Brown-Boveri Corporation Baden, Switzerland)
Dragon Project Engineering Symposium, Bournemouth, 1963

The main coolant circulators for the OECD High Temperature Reactor Dragon at Winfrith in England are totally enclosed blowers with hydrodynamic gas-lubricated bearings. The development and production of these bearings involved the solution of a number of problems. Having regards to the fact that the Dragon reactor is to be used for experimental work, a very wide working range was specified for the circulators. The stipulated data was that the coolant should be very pure helium with less than 10 vpm of O_2, H_2O, CO and CO_2, at pressure between 8 and 25 kg/cm^2 and at temperature between ambient and 420°C. Also the speed range is between 1 100 and 12 000 rev/min, infinitely variable with the aid of frequency changers.

A pressure-tight flanged casing encloses the working parts of the blower, that is, the impeller, shaft, bearings and motor. All bushing leading to the outside are also gas-tight, there being no need whatsoever for mechanical seals. The design of the circulators along with test performed is fully described in this paper.

The performance of the circulator proper showed that the design conditions were easily met; in fact, the pressure of 6 psi could be reached at 5% lower speed than anticipated. Because of the variable frequency drive the adjustment presented no problem. The pressure rise-mass flow characteristic was somewhat flatter than predicted. This deviation from the calculated performance can be explained by the fact that the calculations had to be based on test figures at much higher Mach numbers, and that the impeller has been slightly altered compared with the standard design used at Brown Boveri. The motor also gave hardly any trouble, except that the shrink fit was too weak at the beginning. After it was doubled, the motor gave very satisfactory service.

Reference 18

Two decades of excellent AGR circulator operating performance at AVR Juelich

Ziermann, E.L. (Arbeitsgemeinschaft Versuchs-Reaktor G.m.b.H., Juelich (Germany, F.R.)); Engel, J. (Brown, Boveri und Cie A.G., Mannheim (Germany, F.R.))

Specialists' meeting on gas-cooled reactor coolant circulator and blower technology, San Diego, CA (USA), 1987

During the twenty years' operation period there were only a few events connected with circulator operation, which were of interest. In 1970 the frequency converter was modernized: The mercury-vapour rectifier was replaced by thyristors. In 1974 the helium core outlet temperature was increased from 850 to 950 deg. C.

In 1977 after 72,000 operating hours a leak of about 3 mm^2 occurred in a superheater pipe in the steam generator. As a consequence 27 t of water penetrated into the primary system. Also the circulators were flooded to half their height. After drying and final revision of the reactor and its auxiliary systems, due to negligence one of the cooling water seals in the oil system had not been properly tightened. Thus there was water ingress into the bearing oil followed by a temperature rise in one circulator bearing. Consequential damage was prevented by immediate shutdown. Disassembly of the circulator and replacement of the bearings supplied valuable information about the handling of contaminated circulator parts. Incidentally, it was stated when the bearing had been disassembled that the state of the bearing would probably have permitted further operation without exchange.

In 1980 the AVR was adapted to the new safety requirements. The helium circulators including the oil systems and the electrical systems were not involved in this process. In the report about general operating experience the operating parameters are discussed in detail. An outlook is given on the further operating mode of the plant. Based on a record of 115,000 operating hours of the circulators, it can be said even today that a service-free operation of the circulators in gas-cooled reactors will be possible for several decades.

Reference 19

Recent research and development of bearings for helium circulator
Taniguchi, S.; Ezaki, Z.; Kawaguchi, K.; Matsumura, N.; Kozima, M. (Mitsubishi Heavy Industries Ltd, Nagasaki (Japan))
Specialists' meeting on gas-cooled reactor coolant circulator and blower technology, San Diego, CA (USA), 1987

Since a helium circulator is the only revolutionary machine, which rotates at high speed condition in high temperature gas reactor, extremely higher reliability is demanded than the same turbo machine operating under an ordinary atmosphere. As the circulator is supported by bearings radially and axially, it is no exaggeration to say that these bearings are imposed the great responsibility for the reliability of reactor.

This paper mainly describes recent studies and successful applications of water lubricated bearing and gas lubricated bearing. Both types of bearing seem to be suitable for a turbo machine installed in an atomic energy plant - such as the helium circulator of a HTGR - not to be affected by radioactivity.

The former was investigated theoretically taking account of turbulent flow due to the low viscosity of water, and compared with the experimental data. Good agreement was obtained, and a successful example applied to a small-sized high-speed air compressor is shown.

The latter was investigated using a large-sized bearing test rig simulated to an actual machine. The tilting pad journal bearing and the tilting pad thrust bearing were taken and improved for some aspects. These bearings have been taken into service on an actual circulator and are now operating successfully. Currently, a magnetic bearing is being studied to pay special attention to endurance for an earthquake and catcher bearing system.

Reference 20

Main circulator design features for HTR 100, HTR 500 and space heating plants
Engel, J.; Glass, D. (Brown, Boveri und Cie A.G., Mannheim (Germany, F.R.))
Specialists' meeting on gas-cooled reactor coolant circulator and blower technology, San Diego, CA (USA), 1987

All design alternatives for modern high-temperature reactors have a common circulator concept: It is based on a vertical shaft design with a flying impeller. The circulators are equipped with active magnetic bearings and are driven by induction motors connected to variable-speed static converters.

Due to their multiple functions during normal reactor operation and under accident conditions, extremely high requirements are made to safety-relevant circulators, since with the reactor pressurized as well as under depressurized conditions specified delivery heads and flow rates have to be ensured.

The use of active magnetic bearings permits to obtain maintenance-free operation and functional safety to an extent, which had not been achieved before. Magnetic bearings are therefore provided for the total range including primary gas circulators of a drive power of several MW as well as circulators for helium loops of reactor auxiliary systems.

The essential feature for using active magnetic bearings is the retainer bearing technology, preventing contact between rotor and static circulator parts upon unintended de-energisation of the magnets. Results of current experiments are reported.

Another aspect to be considered for reliable long-term operation for several decades is the effect of rotor dynamics. The various natural frequencies resulting from torsion and bending modes in view of a drive by a frequency-controlled induction motor have to be considered as well as the specific characteristics of the active magnetic bearings.

Special attention has to be directed to the internal cooling loop so as to ensure that reactor temperature excursions in the event of deviation from normal operation can be overcome without damage. For circulator components exposed to temperature fields the design characteristics are determined by combining experimental and analytical methods.

The coordination of all component parts is currently being optimized on a prototype circulator whose detailed design is underway. This circulator will be tested in a test stand designed for test runs of all different circulator sizes.

Reference 21

Gas erosion of impeller housing in the operation of a high-temperature, high-pressure helium circulator
Sanders, J.P.; Heestand, R.L.; Young, H.C. (Oak Ridge National Lab., TN (USA))
Specialists' meeting on gas-cooled reactor coolant circulator and blower technology, San Diego, CA (USA), 1987

Three gas-bearing circulators are installed in series in a high-pressure, high-temperature loop to provide helium flow up to 0.47 m^3/s at a total head of 78 kJ/kg. The design pressure is 10.7 MPa, and temperatures of 1000°C can be obtained in the test section. The inlet temperature to the circulators is limited to 450 °C. The 200 kW motor for each circulator is enclosed in the pressure boundary, and circulating the gas within the cavity over a water-cooled coil cools the motor. The full operating speed is 23,500 rpm.

A full-flow filter, absolute for particulate above 10 mum, is installed upstream of the circulator to protect the gas bearing surfaces. The minimum clearances between these surfaces during operation are in the range of 15 to 30 μm.

During a routine examination of the circulator, deep V-shaped grooves were found in the stationary surface of this cavity. At the same time, a very fine, dark particulate was observed in crevices of the housing. At first it was assumed that the grooves were formed by particulate erosion. However, examination of the grooves and discussions with persons experienced with large circulator operation changed this opinion.

Erosion caused by particulate is characteristically rounded on the bottom and has a greater width to depth aspect than the V-shaped grooves, which were observed. Analysis of the particulate indicated that it was essentially the material of the housing that had undergone reactions with impurities in the circulating gas. It was subsequently concluded that the impeller housing had not been heat treated in a sufficiently oxidizing atmosphere after machining to form an adherent oxide coating. This suboxide coating was eroded by the shear forces in the gas. The exposed layer of metal was then further oxidized by the impurities in the gas, and these layers of oxide were successively eroded to produce the grooves. This erosion problem was eliminated by machining a ring of the same material, heat treating it to form an adherent stable oxide, and bolting it in place in the cavity.

Reference 22

Design of the HTR-10 helium circulators with the Active Magnetic Bearings
Diao Xingzhong, Zhao Lei, Zhou huizhong, Zha Meisheng, Wang Jie, Yu Suyan.
2nd International Topical Meeting on High Temperature Reactor Technology, Beijing, CHINA, 2004

The 10 MW High Temperature Gas-Cooled Reactor-Test Module (HTR-10) requires the helium circulator to have features of high speed, long duty lifetime, pollution free and low maintenance cost, therefore an active magnetic bearing (AMB) circulator has been designed. Compared with the traditional ones, the AMB circulator has longer duty lifetime and demand less maintenance cost due to its outstanding features, that is, non-contact support, no mechanical wear and no friction.

The AMB will be used to support the turbomachine rotor in the pressure vessel of the HTR-10, the design and manufacture of the AMBs shall meet the requirements of the safety and quality assurance of nuclear reactor equipment.

The AMB system consists of catcher bearings, sensors, controllers, power amplifiers, A/D and D/A conversion, electromagnets, power supply, etc, which are divided into elements inside the primary boundary and elements outside the primary boundary. The catcher bearings, electromagnets and sensors are located in the primary boundary, while other AMB control system equipments are located beyond the primary boundary, including computer facilities and power modules.

The motor shaft is supported by two radial and one axial AMB. One radial and the axial AMB are mounted in the upper position of the motor shaft, to carry a combination of the radial and thrust loads. In the lower position, the other radial AMB is mounted to carry mainly the radial load. Catcher bearings is a part of the AMB and support the AMB helium circulator in the following cases:

- Scheduled shutdown of the AMB helium circulator when the AMB is de-energized.
- Ensure the AMB helium circulator shutdown when AMBs fail to work.

- Protect the AMB helium circulator when dynamic loads exceeding AMB load-carrying capacity.

AMB is intended to take up radial and axial loads and provide stabilized supporting of the AMB helium circulator in operation. The design carrying forces of the radial and axial AMB as well as the rotor dynamics are further explained in this paper.

Reference 23

Operating experience of gas bearing helium circulators in HTGR development facility
Shimomura, H.; Kawaji, S.; Fujisaki, K.; Ihizuka, T. (Japan Atomic Energy Research Inst., Tokai, Ibaraki. Tokai Research Establishment)
Specialists' meeting on gas-cooled reactor coolant circulator and blower technology, San Diego, CA (USA), 1987

The large scale helium gas test facility HENDEL (Helium Engineering Demonstration Loop) was constructed at Japan Atomic Energy Research Institute in March 1982 and is being operated to develop HTGR components.

Electric driven circulators with dynamic gas-bearings was chosen due to their compactness, gas tightness, easy maintenance and free from contamination. Two centrifugal type circulators connected in series as a circulator set was used for the larger two loops of the facility and a regenerative circulator for the smaller loop. The helium gas was of 4 MPa and 400°C in the loop and the circulators had variable speed of 3 000 to 12 000 rpm.

The centrifugal type gas circulators, except one which was installed later, had been operated for more than 6 700 hours without remarkable troubles, but one regenerative circulator was encountered bearing troubles twice through its over 8 400 hours of operation. After test and measurements of the circulators, it was presume that the first problem on the regenerative type was caused from excess unbalance force by the falling off of a small pin from the rotating part and the whipping in the gas bearing caused the second problem. It was recognised that five balancing of the rotors and delicate clearance adjustment of the bearings were important for the rotor stability.

The monitoring technique for the gas bearing, which could be damaged in a very short time, should be fast and predictive to prevent serious damage. The vibration spectrum monitoring method seemed to be predictive and useful for early detection of the shaft instability.

It was concluded that the gas bearing machine is an excellent system in its design philosophy, but needs highly precise machining and delicate maintenance techniques.

Reference 24

Helium circulator design concepts for the modular high temperature gas-cooled reactor (MHTGR) plant
McDonald, C.F.; Nichols, M.K.; Kaufman, J.S. (GA Technologies, Inc., San Diego, CA (USA))
Specialists' meeting on gas-cooled reactor coolant circulator and blower technology, San Diego, CA (USA), 1987

The Modular High-Temperature Gas-Cooled Reactor (MHTGR) power plant has two helium circulators, which are:

1. The main circulator, which facilitates the transfer of reactor thermal energy to the steam generator.

2. A small shutdown cooling circulator that enables rapid cooling of the reactor system.

Both circulators are vertically orientated, have submerged electric motor drives, and embody rotors that are supported on active magnetic bearings. Both machines have been conservatively designed based on established practice, as well as features and characteristics that have evolved from actual plant operating experience, mainly Fort St. Vrain, AGR, AVR and THTR.

The active magnetic bearings consist of two fully redundant circuits, which include sensors, electromagnets and electronic controls. Provision is made for accommodating both radial and axial loading in the magnetic bearing system. The thrust bearings, located in the upper part of the machine assembly has adequate margin of overload capacity to react to all gravitational (including seismic) and aerodynamic axial loads. One of the magnetic bearing systems is supplied via an uninterruptible power supply, backed up by batteries, while the other system is supplied from the plant electrical system.

Antifriction ball bearings are used as catcher bearings to ensure that no harmful rotor-to-stator contact occurs in the event of both primary and secondary electrical power sources are lost. The clearances in the catcher bearings are such that the inner race of the bearings is not in contact with the rotor during normal operation.

Further in this paper, conceptual design aspects of the circulators are discussed, together with the significant technology bases.