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HTR-E

Requirements on HTR Helium Circulators

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1. Executive Summary

Even direct cycle gas turbine HTR need diverse additional coolant circulation systems for different purposes such as:

- Start-up blower system for the turbo compressor group
- Blowers for (active) decay heat removal or Core Conditioning System (CCS)
- Gas circulation within the gas purification system
- Back-compression behind the purification system
- Evacuation pumps for cleaning of the primary circuit
- Compressors within the pure gas storage system
- Pressure vessel conditioning systems (RPVCS) to keep pressure vessel temperatures at low level

The power of such circulators range from some ten till some hundreds of Kilowatts. As far as axial or radial compressors are applicable, such blowers should also be equipped with magnetic bearings to avoid ingress of lubricants and to reduce the auxiliary systems for the bearings. Permanent magnetic bearings seem to be capable to cope with the requirement for such circulators and to reduce auxiliary systems and to a minimum. They will also need less precautions for catcher bearings.

It is recommended to collect more relevant data on such applications within actual projects like PBMR and GT-MHR for defining some standardized blower types as a basis for the development of innovative blowers and compressors for HTR use.

Additional needs for blower developments are seen for HTR steam cycle plants or nuclear process heat plants using intermediate heat exchangers which call for large scale blowers in the primary and secondary circuit. This also applies for combined cycle HTR with gas and steam turbine and combined heat and power generating HTR using intermediate heat exchangers.

It has been shown that the main coolant circulators of modular plants having only one gas loop require much higher power than was the case for former multi-loop designs of similar electric output. Therefore, it is recommended to cover the requirements for the bearing technology not only for large scale gas turbines but also for large scale blowers in the power range of several Megawatts.

Experience from former HTR projects have shown that the auxiliary systems for the blowers have been rather complex and even more expensive than the blowers itself. Magnetic bearings can contribute to reduce cost and enhance the reliability. They also reduce the danger of fire as is the case with oil lubrication and eliminate the discharge of contaminated lubricants.

More compact high-speed designs for circulators (and gas turbines) are another option to enhance economics as compared to the actual low-speed configurations.

As magnetic bearings are not yet applied in nuclear industry, it is also advised to clarify the licensing requirements in an early stage. The catcher bearing development and qualification under helium conditions and dry lubrication will have to attract considerable R&D efforts.

2. Introduction

Gas circulation in gas cooled reactors and HTR is required for different purposes as e.g.:

- Turbo-compressors / turbo-generators for direct cycle helium gas turbine plants
- Start-up blower system for the turbo compressor group
- Operational coolant gas circulation for heat transfer to the heat exchangers in case of steam cycle or process heat HTR with intermediate heat exchangers
- Coolant gas blowers in intermediate helium circuits
- Safety-related blowers for (active) decay heat removal or Core Conditioning System (CCS)
- Gas circulation within the gas purification system
- Back-compression behind the purification system
- Evacuation pumps for cleaning of the primary circuit
- Compressors within the pure gas storage system
- Blowers for pneumatic transport of fuel pebbles in the fuel handling system
- Pressure vessel conditioning systems (RPVCS) to keep pressure vessel temperatures at low level
- Ventilation systems within the confinement

Whereas the turbo compressors and turbo generators attract most attention within the R&D programs, other applications for blowers and compressors as can be seen in figure 1 are equally important for the functionality and availability of the complete reactor system, too.

Even if the direct cycle gas turbine represents the reference design for the present near-commercial HTR concepts, it is recommended also to cover the requirements for large blowers within the R&D scope as Nuclear Process Heat (NPH) applications will most probably apply Intermediate Heat Exchangers (IHX) for separation of the Nuclear Heat Supply System (NHSS) from the heat utilization system and thermochemical reactors. In these cases high power blowers instead of turbocompressors would be needed to circulate the coolant in the primary and secondary cycles.

The IHX would also allow for combined cycle gas and steam turbine in the secondary circuit which could reach much higher thermal efficacy as compared to the Brayton cycle. The other advantage is that such a plant design would be able to supply electricity and high quality steam as needed for industrial Cogeneration of Heat and Power (CHP).

In contrast to most former HTR designs, Modular High Temperature Reactors (MHRs) are characterised by the fact that they only have one loop for the power conversion system and not a multi-loop design of smaller blower / heat exchanger units as was e.g. the case in the 300 MW_{el} Thorium High Temperature Reactor (THTR-300) with six blowers and six steam generators. As will be shown later, this fact will lead to much increased requirements because the MHR are slowly approaching the same power level than former multi-loop HTR demonstration plants. On the other hand, the size and functionality of common systems like gas purification system and emergency coolers will be very comparable to actual MHR systems.

Therefore, a compilation of data and requirements from former HTR projects will provide some still relevant orientation for new HTR designs.

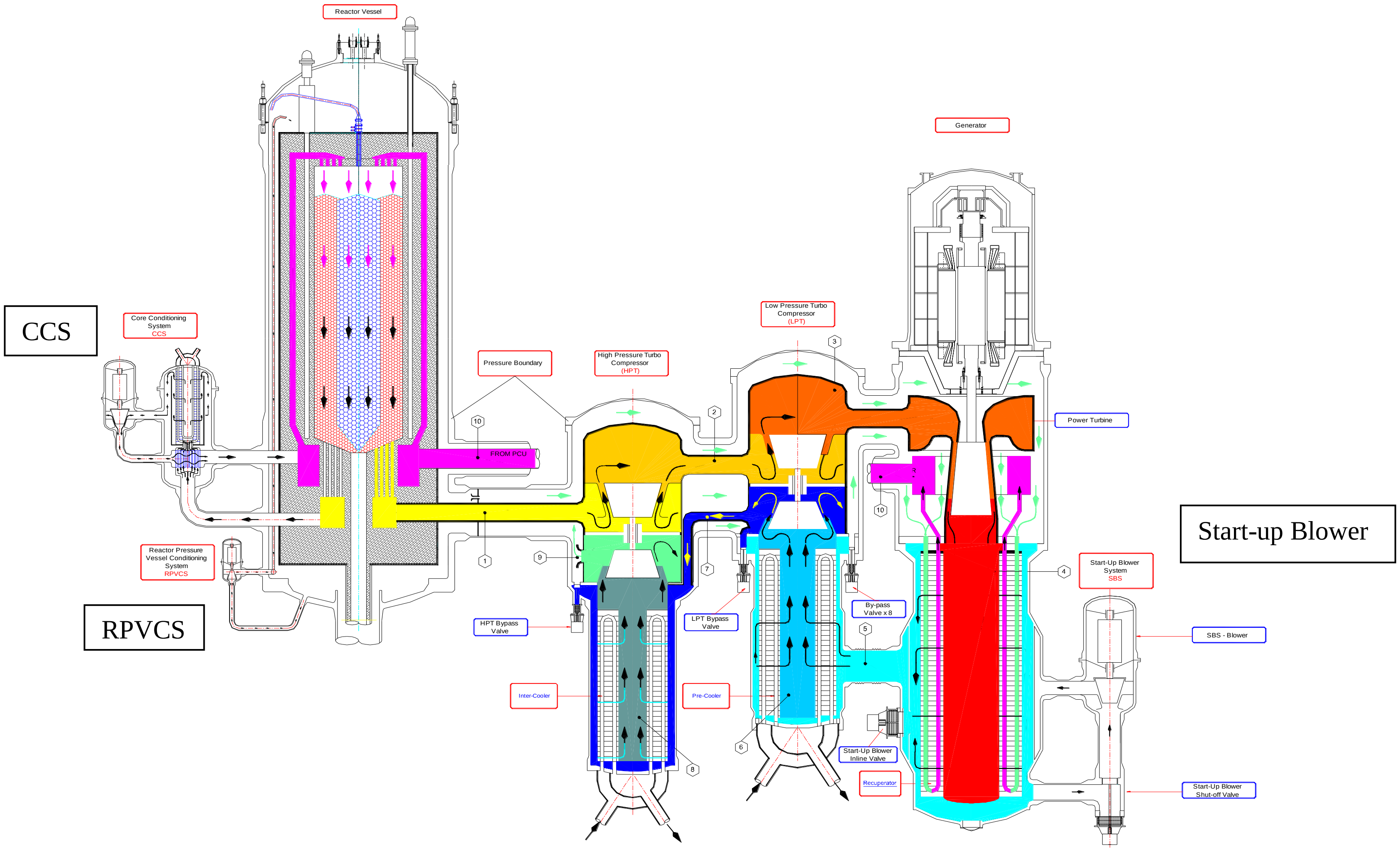

Figure 1: Pebble Bed Modular Reactor with turbo compressors and auxiliary blowers

3. General Requirements

The general requirements for HTR coolant blowers can also be transposed to other circulators:

- High availability
- Secure separation of coolant and lubricants
- Reduction / elimination of risk for fire (problematic in the case with oil lubricant)
- Permanent rotor control
- Long maintenance intervals
- Ease of inspection and repair
- Low radiation dose for personnel
- Design freedom for vertical or horizontal mounting of blower
- Reduction of contaminated lubricants to be discharged

These general requirements lead to the decision to use electromagnetic bearings for circulators and turbo compressors in future HTR designs instead of oil, water or gas lubricated bearings which have been used in former HTR projects as will be discussed later.

Another complication for the circulators are the wide span of operational requirements with regard to the pressure level and mass flow due to the fact that a part of the systems have to be operated under full system pressure and/or in case of depressurization at ambient pressure, too.

Membrane compressors have been used in some early HTR projects for avoiding leakages and ingress of lubricants. But several breaks of membranes lead to a replacement by piston compressors for those applications where the compression ratio is rather high and cannot be provided by radial or axial circulators.

Considerable experience for blowers in gas-cooled reactors are available from MAGNOX and AGR. Nevertheless, separate developments were made for most HTR projects as will be reported in the following chapters.

4. Features of HTR Coolant Circulators

4.1 DRAGON

The 20 MW_{th} DRAGON Reactor Experiment (DRE) in Dorset, UK, was the very first HTR being built and was performed as an international OECD project including 12 European countries. It achieved first criticality in 1964 and was operated for more than 10 years. The primary coolant circulators were developed and manufactured by BBC Brown Boveri in Germany. The circulator was equipped with gas bearings.

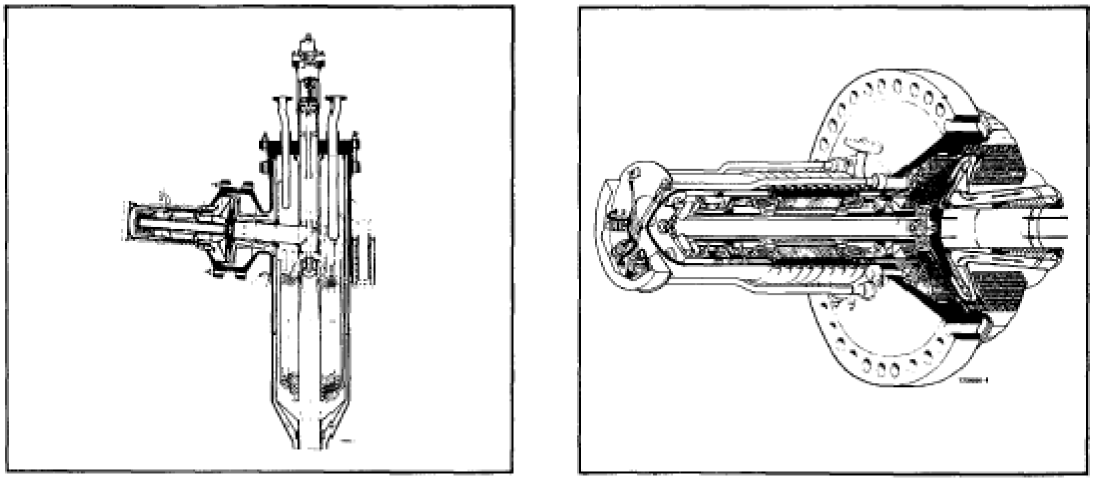

Figure 2: DRAGON Coolant Circulator Arrangement and Sectional View

Figure 1 shows that the circulator was nearly horizontally connected to the heat exchanger system /[1]/. The blower was slightly inclined to exert a defined load on the gas lubricated axial bearing for avoiding instabilities which were observed during preliminary tests.

The design features for this blower are still valid for modern design:

- Integrated induction motor with overhang radial impeller wheel
- Axial-radial bearing arranged opposite to the wheel
- Internal cooling system to remove the heat of the rotor and motor

The main design data for the six DRE blowers are:

Rotating speed:	1100 – 12000 r.p.m.
Coolant pressure:	8 – 25 bar
Coolant Temperature:	< 420°C
Coolant mass flow:	< 2,5 kg / sec

Despite the principal benefits of gas bearings in an HTR environment and high reliability in DRE (e.g. 7 years of operation without inspection and repair), this type of bearing was given up for further HTR projects due to the following reasons:

- Extrapolation limits (weight increases with third power of dimensions; bearing surface increases only with second power)
- Tolerance for the gap is more problematic for larger sizes
- Reduced specific bearing capability both for pad-type and sleeve type gas bearings.

Due to the high shaft rotation speed the blower was very compact. The internal cooling worked without any problem. Vibrations were very low as well as noise generation which simplified the operation very much.

All these features would also apply for magnetic bearings.

4.2 AVR

The two horizontally mounted blowers of the AVR in Juelich, Germany, were also designed and manufactured by Brown Boveri. The reactor started operation in 1967 for 21 years. The blowers were equipped with oil bearings. In contrary to the DRE blowers, the internal cooling was not done via a hollow shaft but with a small auxiliary fan on the shaft. The further principles with full integration of the motor and overhang radial wheel was not changed.

The circulators were originally designed for operation in a helium / neon mixture (22 / 78 %) to increase the specific density of the coolant (by a factor of four) and the heat transfer conditions but later on only operated under pure helium.

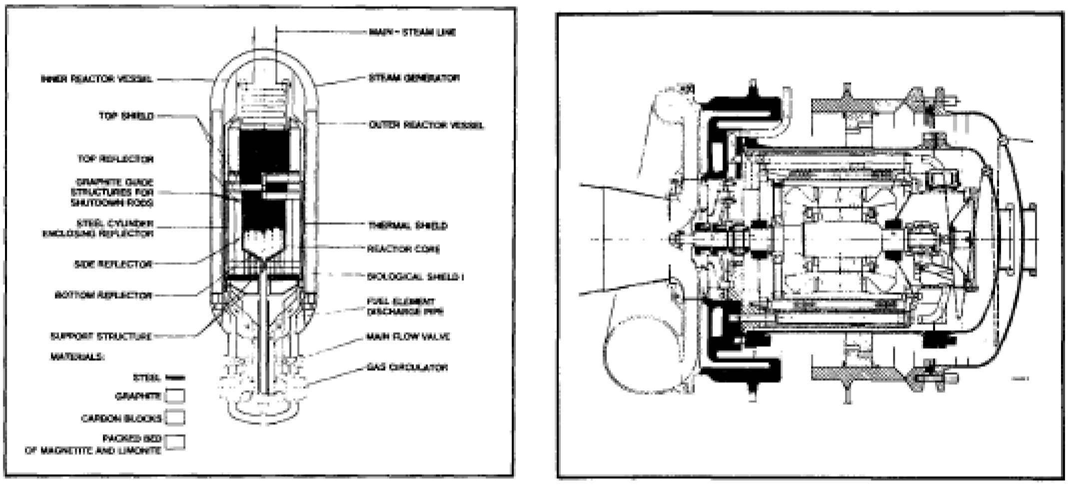

Figure 3: AVR blower arrangement and cross-section of the blower

The main data of the AVR circulators are as follows /2/:

Rotating speed:	400 – 4.400 r.p.m.
Coolant pressure:	~ 10 bar
Pressure difference:	65 mbar
Coolant Temperature:	175 - 350°C
Coolant mass flow:	< 9 kg / sec

The pressure difference of the blowers were also used to drive the pneumatic fuel ball transportation system. The oil lubricated journal bearings were equipped with a labyrinth sealing to prevent oil ingress into the primary and auxiliary gas circuits. The motor speed was varied by phase control but could also be directly connected to the grid which allowed for 80% of reactor power.

Up to the water ingress accident in 1978, both circulators operated practically without maintenance. During the course of the water ingress, both blowers were partially immersed in water which caused a damage in one of the oil bearings due to the poor bearing capacity of the oil-water emulsion.

After repair, both blowers were operated normally till shut-down of the AVR and accumulated more than 140.000 hours of operating experience.

4.3 Thorium High-Temperature Reactor (THTR-300)

In the THTR-300, six oil lubricated coolant gas circulators were horizontally arranged in the wall of the Pre-stressed Concrete Pressure Vessel (PCRV) as modular units for each of the steam generator loops. The longitudinal cross-section of the blower (see figure 4) shows the single-stage radial compressor wheel in overhung position, the downstream diffuser and the integrated induction motor with 2540 kW power /[3]/. Seal gas systems prevented oil ingress into the helium circuits. The blowers were manufactured by BBC, too.

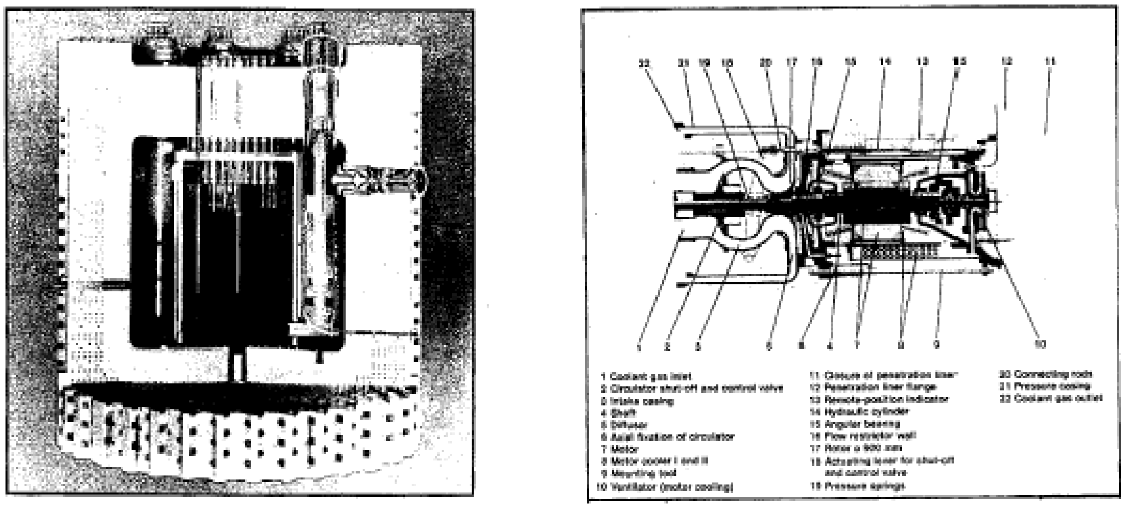

Figure 4: THTR blower arrangement and cross-section

Each circulator is equipped with own oil lubrication systems with redundant lubricating motors (see figure 5). More than 1000 liters of oil were contained in each unit and posied additional pre-cautions for fire protection. The control valve is directly combined with the intake casing. The motor is cooled by water coolers and an internal helium circulation system driven by an auxiliary impeller.

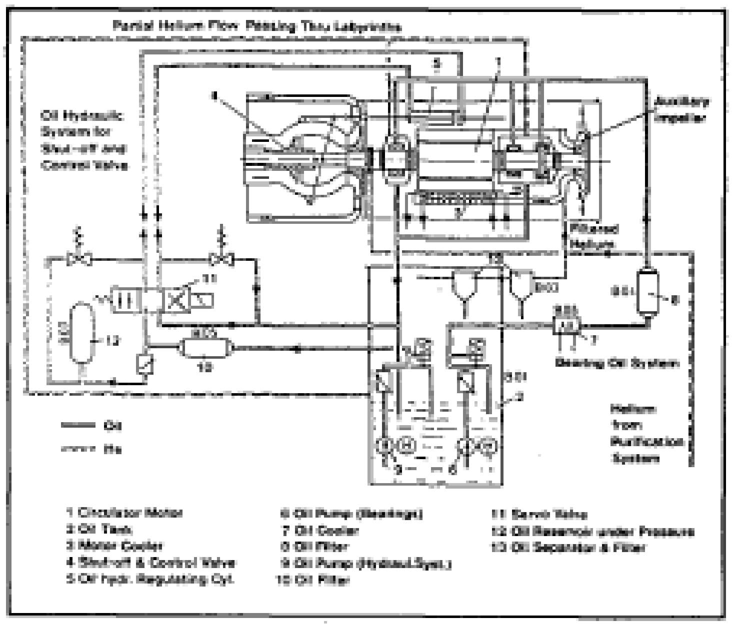

Figure 5: Oil and Seal gas system of THTR blowers

The complexity of these auxiliary systems and the danger for fires are crucial arguments for using magnetic bearings in future projects. But this technology was not available yet when THTR was designed. The cost for the oil and seal gas auxiliary system was twice as much as the cost of the blower itself.

The main data of the THTR circulators are as follows:

Rotating speed:	2800 – 5600 r.p.m.
Power:	2,54 MW
Coolant pressure:	1 -38 bar
Coolant Temperature:	< 300°C
Coolant mass flow:	< 50 kg / sec

The circulators were extensively tested before and after insertion into the reactor and showed very reliable behavior. One circulator however, exhibited shaft vibrations at 5680 rpm due to the occurrence of ‘oil whip’. Since 5375 rpm were sufficient for 100% power operation, this effect did not lead to a real problem.

4.4 Fort Saint Vrain (FSV)

The arrangement and design of the blowers in the American 330 MW_{el} HTR demonstration plant /4/ being built about 40 miles North of Denver differed very much from the above described circulators for DRE, AVR and THTR.

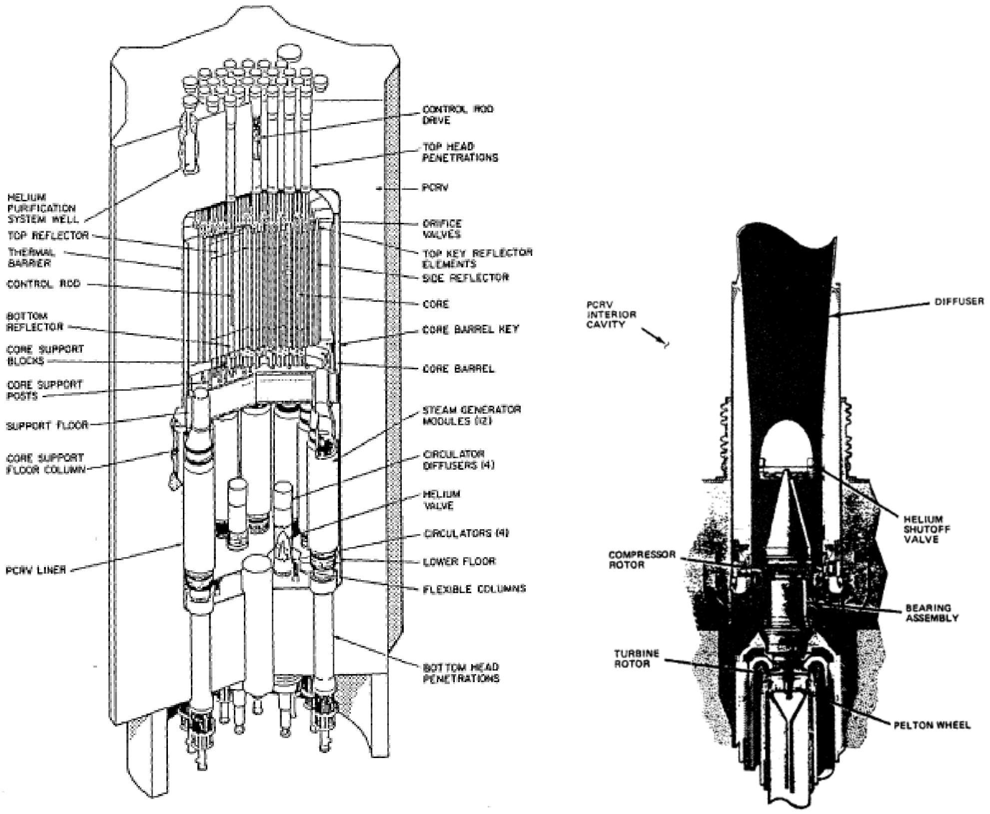

Figure 6: FSV Reactor Arrangement and blower cross-section

The FSV blowers were vertically situated at the bottom of the PCVR within standpipes under the steam generators. As shown in figure 6 and 7, they had a single stage axial compressor and were driven by a steam turbine stage and a Pelton wheel for emergency cooling as back-up drive.

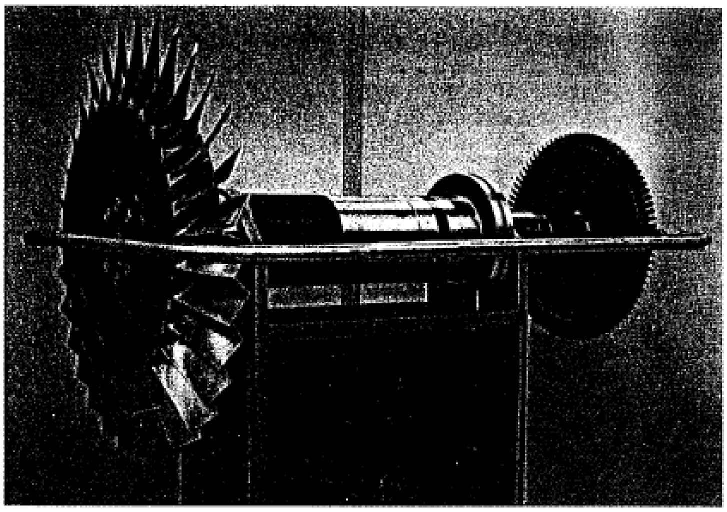

Figure 7: FSV Circulator Rotating Devices *(axial coolant compressor left)*

All circulator bearings were water lubricated and were supplied by two of three multi-stage pumps. A complex sealing and water separation system as shown in figure 8 should hinder water ingress into the helium coolant gas system. This system included several thousands (!) of valves and components as pumps, compressors, heat exchangers, vessels etc. leading to a poor overall performance and high cost /[5]/.

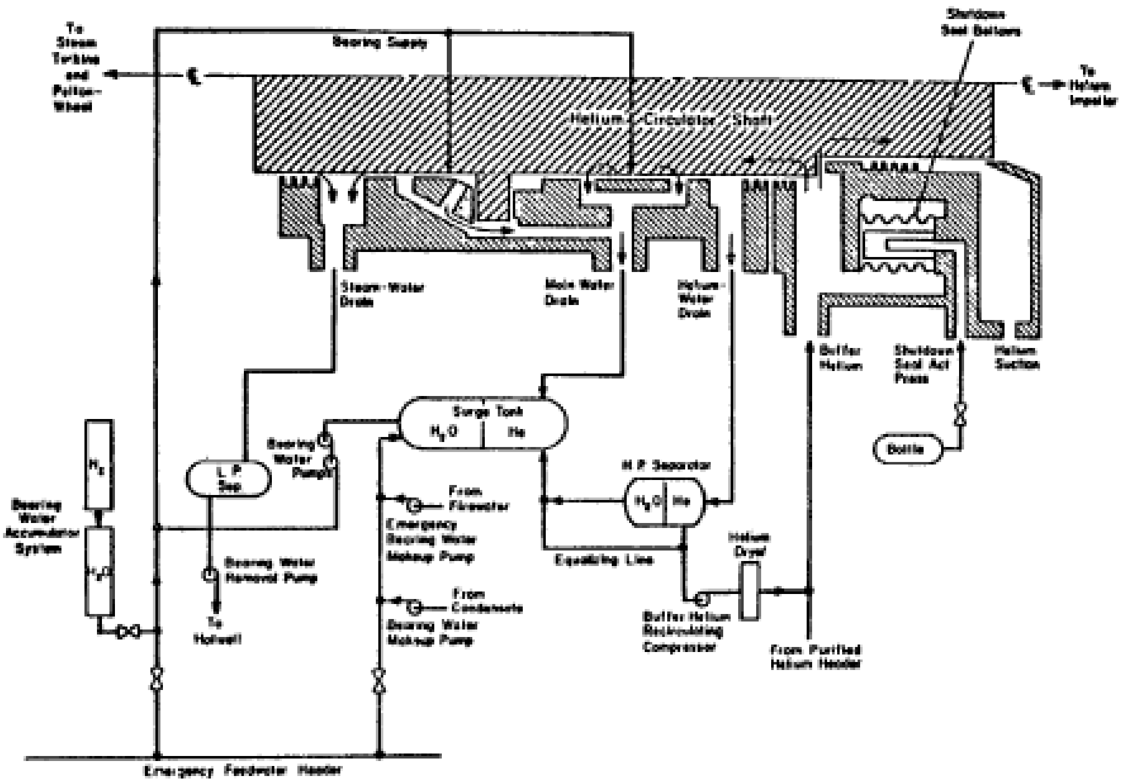

Figure 8: FSV Circulator Auxiliary Systems

The main data of the FSV circulators are as follows:

Max. rotating speed:	10.800 r.p.m.
Steam turbine power:	4,1 MW
Coolant pressure:	1 – 47,3 bar
Coolant Temperature:	< 394°C
Coolant mass flow:	< 109 kg / sec

The combined operating history for the FSV blowers accounts to about 250.000 hours and had principally proven the design. However, many problems have been experienced with cavitation damage at the Pelton wheels, leaks of bellows, degradation within the steam turbine drive, water ingress into the primary circuit and malfunctions of the complex auxiliary system. This sequence of trouble with the blowers being mainly of prototypical nature finally contributed to the early decommissioning of FSV.

As an alternative it was discussed at the end of the FSV project to exchange the blowers against circulators with electric drive and magnetic bearings. The experience with the FSV blowers mainly gave rise to change the type of bearings and to foresee magnetic bearings for future HTR projects.

4.5 Modular High-Temperature Gas-Cooled Reactors (MHTGR)

In US, some consideration on axial or radial compressors /[6]/ were continued with regard to steam cycle Modular High-Temperature Gas-Cooled Reactors (MHTGR) being discussed as follow-up projects to FSV. The reasons for this discourse have to be seen in the relatively low pressure drop via the block core as compared to the pebble bed core which exhibits rather large coolant circuit resistance.

CONSIDERATION	AXIAL FLOW COMPRESSOR	RADIAL FLOW COMPRESSOR
DESIGN STATUS	CONCEPTUAL DESIGN	CONCEPT EVALUATED
MEETING DESIGN PRESSURE RISE REQUIREMENT (13.2 PSI)	SINGLE STAGE ADEQUATE	SINGLE STAGE
PRESSURE RISE MARGIN CAPABILITY (25% ABOVE DESIGN)	CAN BE ACCOMPLISHED WITH SINGLE STAGE	SINGLE STAGE HAS CAPABILITY FOR MUCH HIGHER PRESSURE RISE (WELL SUITED TO PBR PLANT)
EXPERIENCE/TECHNOLOGY	COMPRESSOR VERY SIMILAR TO FSV IMPELLER THAT PERFORMS WELL	INDUSTRIAL COMPRESSORS
PERFORMANCE	SELECTED AXIAL COMPRESSOR NEAR OPTIMUM PARAMETERS	LARGE DIAMETER IMPELLER, AND LOW SPEED FOR EFFICIENT OPERATION
PRIMARY SYSTEM GAS FLOW PATH COMPATIBILITY	SELECTED FLOW DIRECTION THROUGH IMPELLER GREATLY REDUCES THRUST BEARING LOAD	GAS FLOW PATH RESULTS IN THRUST AND ROTOR WEIGHT BEING ADDITIVE
MACHINE ENVELOPE/WEIGHT	COMPACT SMALL DIAMETER MACHINE ASSEMBLY	INCREASED DIAMETER (WEIGHT ASSEMBLY)
SIMPLICITY/RUGGEDNESS	DEMONSTRATED IN FSV	SIMPLE ROTOR, VERY RUGGED
DESIGN CONSERVATISM	MACHINE WELL WITHIN STRESS LIMITS	CONSERVATIVE (LOW SPEED)
MEETS SYSTEM REQUIREMENTS	YES	YES
GAS-COOLED REACTOR EXPERIENCE	FSV EARLY MAGNOX PLANTS (CO_2)	PEACH BOTTOM, AVR, THTR 116 MACHINES BUILT FOR AGR (CO_2)
OVERALL SUMMARY	COMPATIBLE WITH REACTOR SYSTEM COMPRESSOR SIMILAR TO FSV UNIT THAT PERFORMS WELL NEAR OPTIMUM	RADIAL COMPRESSOR WELL SUITED TO PLANTS (SUCH AS THE PEBBLE BED REACTOR) WILL HIGH CIRCUIT PRESSURE LOSS

Table 1: Axial or Radial Compressor Comparison for MHTGR

The arguments in Table 1 pro and contra axial or radial compressors are still valid today and show that the choice is mainly governed by the specific requirements. The comparison also reflects the option for high speed and compact blowers which might be of interest for future HTR circulators.

The fact that modular HTR only have one coolant loop instead of six as was the case with FSV and THTR lead to a significant increase in power size and reliability requirements for their blowers as shown in Table 2. It can be seen that the power for an MHTGR circulator is about 3 times higher than for THTR. This trend has also been discussed for the German HTR-Modul plant /[7]/ having been designed for 200 MWth instead of > 350 MWth for the US MHTGR concept. In the German case, the choice was made for an oil lubricated vertical blower incorporating the experience of CO_2-cooled AGR.

COMPRESSOR TYPE	AXIAL FLOW		RADIAL FLOW	
COMPRESSOR DESIGN	MHTGR MAIN CIRCULATOR	FSV CIRCULATOR	MHTGR MAIN CIRCULATOR	THTR CIRCULATOR
HELIUM FLOW, LB/SEC	348	278	DATA	112
INLET TEMP, °F	491	742	AS	482
INLET PRESSURE, PSIA	911.8	686	FOR AXIAL	551
PRESSURE RISE, PSI	13.2	14.0	FLOW	18.0
INLET DENSITY, LB/FT^3	0.358	0.213	COMPRESSOR	0.218
VOLUMETRIC FLOW, FT^3/SEC	972	1,304		514
ADIABATIC HEAD, FT	5,310	9,465		11,890
IMPELLER O/D, IN.	35.0	28.0	44.0[a]	35.4
SPEED, RPM	6,200	9,550	3,600	5,600
TIP SPEED, FT/SEC	947	1,167	691	865
SPECIFIC SPEED, N_s	311	360	180	111
SPECIFIC DIAMETER, D_s	0.80	0.64	1.0	1.35
NUMBER OF STAGES	1	1	1	1
POWER, HP	4,250	5,300	APPROX. 4,600	3,083
PRESSURE — RISE GROWTH CAPABILITY	• 25% Δp INCREASE CAN BE ACCOMMODATED WITH SINGLE AXIAL STAGE		• GOOD GROWTH CAPABILITY RADIAL STAGE CAN ACHIEVE MUCH INCREASED ADIABATIC HEAD	

[a] VALUE SELECTED FOR CONCEPTUAL DESIGN, RECOGNIZING ENVELOPE CONSTRAINT. FOR OPTIMAL RADIAL COMPRESSOR PRAMETERS (i.e., N_s = 100, D_s = 1.5) THE COMPRESSOR DIAMETER AND SPEED WOULD BE 68 IN. AND 2000 RPM, RESPECTIVELY, AND NOT PRACTICAL FROM INSTALLATION STANDPOINT.

Table 2: Comparison of Design Requirements for Multi-loop and Modular HTR

Contrary to the German approach, the US MHTGR still planned for a separate decay heat removal (DHR) or shutdown cooling system as shown in figure 9 as a core heat up incident would occur with any disturbance in the main coolant circuit. Such a function of emergency cooling was ‘hidden’ in the German design, too, by having the option to remove decay heat via the blower and the coolers of the gas purification system.

In case of the GT-MHR, such a separate DHR system is still part of the design. The core conditioning system (CCS) of the PBMR as shown in figure 1 is the equivalent counterpart of a DHR system without requesting strongly for redundancy and very high reliability requirements due to the passive decay heat removal capabilities of MHR via the surface of the Reactor Pressure Vessel (RPV). Therefore, DHR blowers should be addressed in the R&D programs on direct cycle gas turbine HTR projects, too.

As these circulators only have to remove the decay heat which is about 1-10% of the nominal power, the requested power size for the blower is rather low. On the other side, these blowers have to remove the heat also under Loss-of-Coolant Accident (LOCA) conditions at ambient pressure and have to be designed for this case.

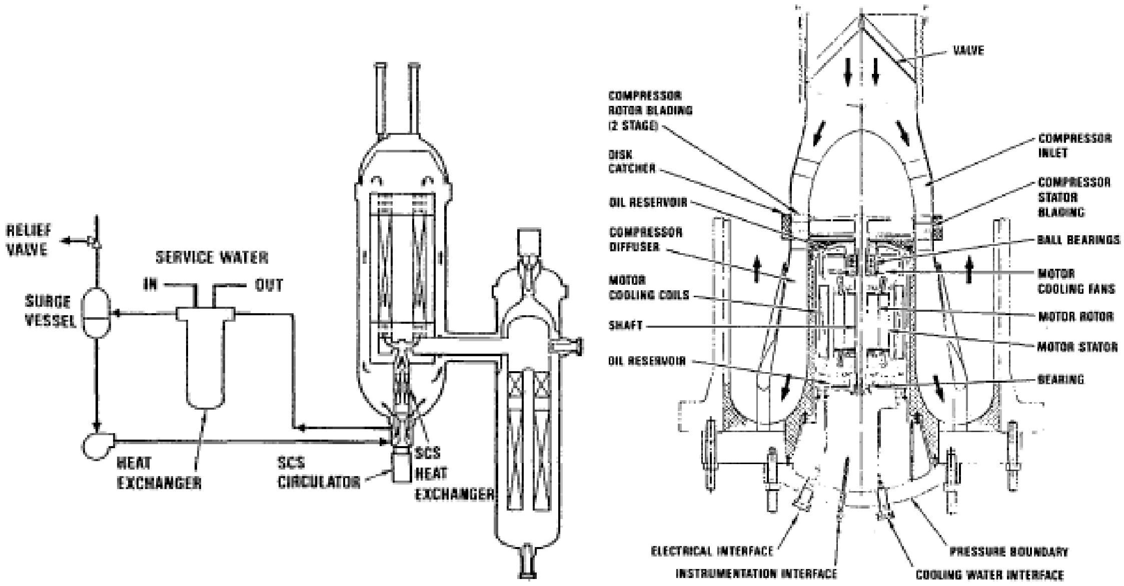

Figure 9: Shutdown Cooling System (SCS) and SCS blower of 350 MWth MHTGR

COMPRESSOR TYPE	AXIAL FLOW			RADIAL FLOW	
COMPRESSOR DESIGN	MHTGR 2 STAGE DESIGN	MHTGR 1 STAGE CONCEPT	FSV MACHINE (FOR COMPARISON)	MHTGR CONCEPT	THTR CIRCULATOR (FOR COMPARISON)
MACHINE STATUS	CONCEPTUAL DESIGN	DATA POINT	OPERATIONAL	CONCEPTUAL DESIGN	OPERATIONAL
NUMBER OF STAGES	2	1	1	1	1
PRESSURE RISE, psi	0.71	0.50	14.0	0.71	18.0
HELIUM FLOW, LB/SEC	6.36	6.36	278	6.36	112
INLET TEMP, °F	240	240	742	240	482
OUTLET PRESSURE, psia	14.0	14.0	700	14.0	569
INLET DENSITY, LB/FT^3	0.00708	0.00708	0.213	0.00708	0.218
VOLUMETRIC FLOW, FT^3/SEC	898	898	1304	898	514
ADIABATIC HEAD, FT	14,500	10,170	9485	14,500	11,890
IMPELLER O/D, IN.	29.0	25.0	28.0	38.0	35.4
SPEED, RPM	10,000	10,000	9550	5400	5600
TIP SPEED, FT/SEC	1266	1265	1167	895	865
SPECIFIC SPEED, N_s	381	286	360	123	111
SPECIFIC DIAMETER, D_s	0.75	0.81	0.64	1.22	1.35
POWER, HP	207	150	6300	220	3883
PRESSURE RISE CAPABILITY	SINGLE STAGE AXIAL LIMITED TO ABOUT 0.5 psi PRESSURE RISE TWO STAGE AXIAL HAS CAPABILITY TO 0.90 psi (APPROX. 25% MARGIN ABOVE DESIGN VALUE)			LOW SPEED RADIAL HAS CAPABILITY TO GIVE HIGH PRESSURE RISE (> 0.9 psi)	

Table 3: Comparison of Requirements for Decay-Heat Removal Circulators

The design requirements for the DHR blowers of a 350 MW_{th} MHTGR in table 3 give some orientation for a typical application also for a direct cycle gas turbine plant. These values have to be up scaled according to the power size (600MW_{th} for GT-MHR; 400 MW_{th} for PBMR).

Much smaller blowers are requested for the reactor pressure vessel cooling system (RPVCS) if the RPV should be kept at lower temperatures despite rather hot coolant inlet temperatures. Four 33,3% RPVCS have e.g. been designed for a former PBMR concept with 268 MW_{th} each capable to deliver 3150 m^3/hr which is less than 1 m^3 /sec. This marks the lower end of requirements for coolant circulators of modular HTRs.

It is obvious from the statements on complex auxiliary systems made above for THTR and FSV that such blowers for DHR and RPVCS should be as simple as possible. Even active magnetic bearings request non-negligible auxiliary systems for power supply and control.

The development of permanent magnetic bearings for this class of circulators and a compaction of design by high speed rotors would be very beneficial to improve economics and reliability.

5. Blowers / Compressors / Pumps for Auxiliary Systems

Little has been reported in literature about the requirements on helium circulators for diverse applications in HTR auxiliary systems like:

- Coolant gas blowers in intermediate helium circuits (which have to fulfil nearly the same requirement as the primary circuit blowers)
- Gas circulation within the gas purification system
- Back-compression behind the purification system
- Evacuation pumps for cleaning of the primary circuit
- Compressors within the pure gas storage system
- Blowers for pneumatic transport of fuel pebbles in the fuel handling system
- Pressure vessel conditioning systems (RPVCS) to keep pressure vessel temperatures at low level
- Ventilation systems within the confinement (which principally can also equipped with magnetic bearings)

Some rough preliminary data on the gas purification system (circulation and back-compression), on the vacuum system and on the gas storage systems have been collected for AVR and THTR to give an orientation on the main requirements.

Function	AVR		THTR	
	Pressures (bar)	Flow rate (Nm^3/hr)	Pressures (bar)	Flow rate (Nm^3/hr)
Pure gas compression	1 - 200	20 - 40	1 - 140	100 -1000
Purification system blower	1 - 50	100	20 - 50	1500 - 3000
Back-compression	1 - 10	10 - 100	1 - 50	10 - 80
Vacuum system	0,01 - 1	50 - 700	0,001 - 1	50 - 2000

Table 4: Requirements for gas circulation in auxiliary systems of AVR and THTR

Membrane compressors that have been used in AVR in early days have all been exchanged against dry piston type compressors due to breaks and leakages of membranes. Rotating piston compressors are used in the vacuum system and for back-compression in the purification plant for both AVR and THTR.

The blower of the gas purification system in THTR is equipped with gas bearings and showed some problems during commissioning. As was stated during the re-design of the gas purification plant for the HTR-Modul of KWU /[8]/ such blowers or membrane compressors should be replaced by encapsulated radial compressors using magnetic bearings. A typical power size for such blowers is in the range of some hundred kW.

Such applications could also be covered by permanent magnetic bearings to reduce cost and enhance reliability.

For all types of magnetic bearings, the licensing requirements should be clarified at an early stage of development. A first attempt into this direction was undertaken within the German development of HTR blowers with magnetic bearings /[9]/ requesting e.g. redundancies of functions, influence of earthquakes, the establishment of simulation models for the mechanical and electrical interaction as well as a better understanding of failure mechanisms of the catcher bearings.

Appendix

Acronyms

AVR	Arbeitsgemeinschaft Versuchs Reaktor (Working Group Test Reactor)
DRE	DRAGON Reactor Experiment
DHR	Decay Heat Removal
FSV	330 MW HTR demonstration reactor at Fort Saint Vrain, US
GT-MHR	Gas Turbine Modular HTR
HHT	High Temperature Reactor with Helium Turbine
HTR	High-Temperature Reactor
HTTR	High-Temperature Test Reactor
IHX	Helium / Helium Intermediate Heat Exchanger
KVK	Komponenten Versuchs Kreislauf (10 MW Component Test Circuit)
LOCA	Loss-of-Coolant Accident
MHR	Modular High Temperature Reactor
MHTGR	Modular High-Temperature Gas-Cooled Reactors
NHSS	Nuclear Heat Supply System
NPH	Nuclear Process Heat
PBMR	Pebble Bed Modular Reactor
PCRV	Pre-stressed Concrete Pressure Vessel
PNP	Prototype Nuclear Process heat
RPV	Reactor Pressure Vessel
RPVCS	Reactor Pressure Vessel Conditioning System
THTR	Thorium High Temperature Reactor

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[1] D. Stoelzl; Twenty Five Years of BBC Experience in Development, Design and Fabrication of Circulators for HTGR; IAEA Proceedings, IWGGCR/17; San Diego, 30 November – 2 December 1987,

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