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HTR-E WP3: Catcher Bearings Tests - Past experience from the German HTR R&D Programme -

Werner von Lensa

FZJ

Germany

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1. Executive Summary

Many design alternatives for modern high-temperature reactors have a common circulator concept: It is based on a vertical shaft design with an overhung impeller. The circulators are equipped with active magnetic bearings and are driven by induction motors connected to variable-speed 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. In addition, it avoids any potential for lubricant ingress as e.g. experienced at Fort Saint Vrain, USA. 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 challenge 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 or malfunction of the electronics. Results of experiments within the former German HTR programme are reported.

The reference design for the test of the catcher bearings was the HTR-500 auxiliary blower for decay heat removal having a impeller diameter of 1,25 m. A specific test facility has been built (FLP 500) to simulate the conditions during coasting of the blower from 6000 rpm. The FLP 500 represented the largest experimental facility for magnetic bearings with a vertical rotor and a weight of 1320 kg. The facility has been transferred to the 'Institute of Process Technique, Process Automation and Measurement' at the Technique University of Applied Sciences Zittau/Goerlitz, Germany, and is available for further testing.

The catcher bearing itself represents a complex system consisting of friction cones and ball bearings. The friction cones avoid unacceptable high acceleration of the ball bearings and serve as a emergency redundancy in case of blockage of the ball bearings.

The requirements for the design of the catcher bearings are illustrated and lead to dry lubrication and a minimum of 16 actuations over a lifetime of 40 years.

The ball bearings have been improved step-by-step ending up in a version with inner and outer rings made of stainless steel with MoS_2 in-situ coating and steel cage with segmented PTFE + 60% Bz bushings.

Higher temperatures at the bearings near to the impeller have to be taken into account. The FLP 500 was prepared for such tests with a heating device. But such experiments have not yet been performed and should be made in the test facility at Zittau.

Permanent magnetic bearings could possibly also be applied either as stand-alone catcher bearings or as supplement bearings to reduce the forces on the catcher bearing.

2. Objectives of the R&D Programme

Although good experience has been gained in Germany with the oil-lubricated bearings of the horizontal blowers at AVR and THTR, the development of blowers for future HTR was re-oriented towards magnetic bearings and vertical shafts. The reason was mainly that vertical caverns and penetrations could more easily be realized for a pre-stressed concrete vessel (PCRV) of large HTR like HTR-500 which was –more or less – a larger version of THTR but having a power output above 500 MWel. Horizontal penetrations at the periphery of the PCVR create the problem that the circumferential tendons cannot be applied in this area. Therefore, it was decided to insert the circulators from the top or from the bottom of the PCRV as can be seen in figure 2.1 by making use of penetrations which existed anyhow for insertion of the steam generators and decay heat removal coolers.

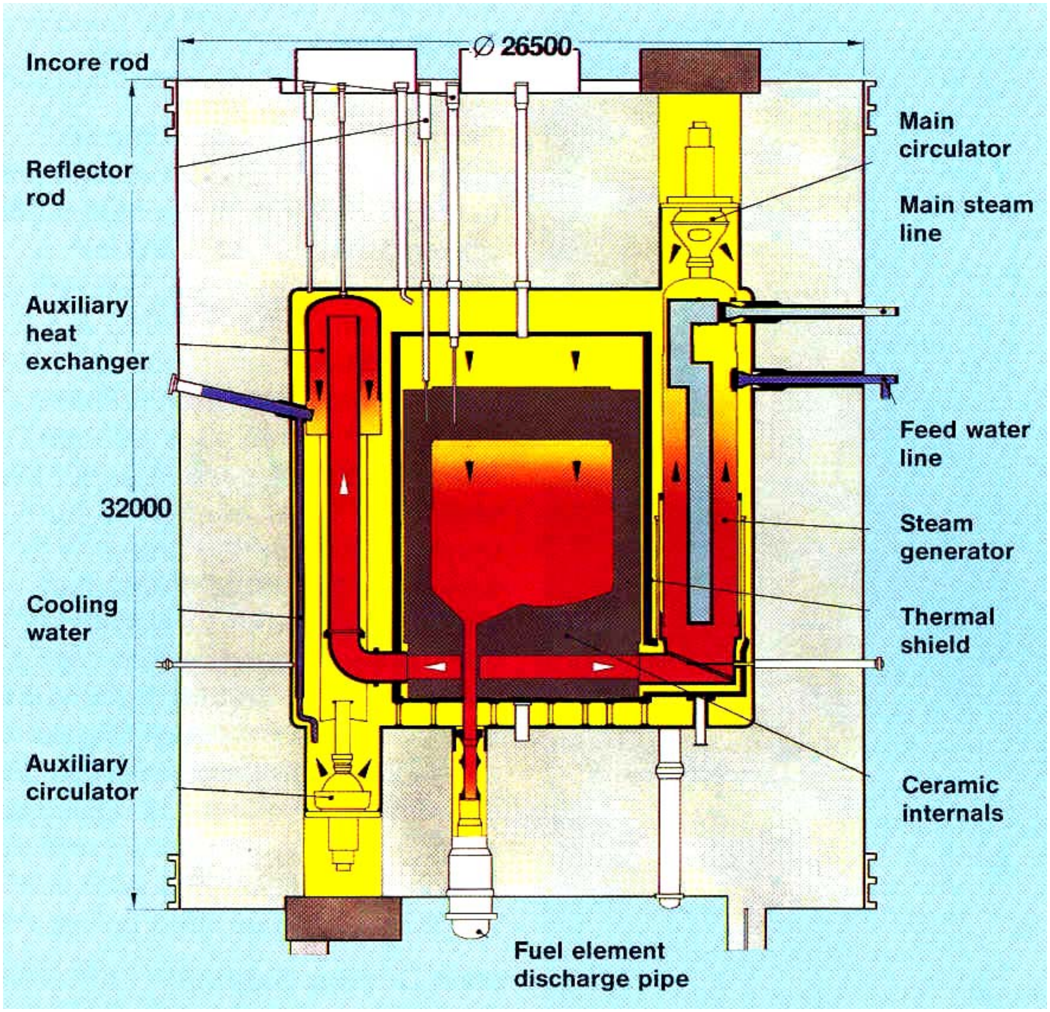


Figure 2.1: Cross-section of HTR 500

In case of the HTR-500 there were two types of circulators:

- Six main circulators (one for each steam-generator loop)
- Two auxiliary blowers (one for each decay-heat removal loop)

Another problem was correlated to the design change from horizontal shafts towards vertical shafts with regard to potential oil leakage from the vertical shaft into the primary circuit. Although some solution was found to prevent oil ingress for the vertical circulator of the 200 MW HTR-Modul design, as a short-term concept, further blower-related R&D was focused on magnetic bearings.

The HTR circulator development in Germany - as performed in the 1980s – had to cover the requirements of different designs of large HTR, on the one side, and modular HTR designs, on the other. Due to the fact that the large HTR had six separate loops, the power of the circulators was lower or comparable to the single blower of a modular HTR which had only one loop and one circulator. This fact also posed higher reliability requirements on the blowers of modular reactors because the large HTR could also be operated with a reduced number of loops. The next table shows the main data of circulators for the HTR-500 which was chosen as the reference for the circulator development.

Technical Data	Units	HTR-500 Main Blower	HTR-500 Auxiliary	HTR-500 Auxiliary Depressurised
Mass Flow	Kg/s	106	22,6	4,1
Helium Pressure	bar	55	55	1
Helium Temperature	°C	260	260	120
Pressure Rise	bar	1,4	0,03	0,07
Helium Density	Kg/m^3	4,9	4,9	0,123
Impeller Diameter	m	1,0	1,25	
Speed Range	min^{-1}	700-4900	570	5280
Motor Power	kW	4100	25	430
Position		Impeller down	Impeller on top	
Rotor Mass	kg	3000	2100	
Number of blowers		6	2	

Table 2.1: Main design data for HTR-500 circulators

As can be seen from table 2.1, the auxiliary blower for decay heat removal has the larger impeller wheel and higher speed, in case of a depressurised reactor primary system. This was due to the fact that considerable quantities of helium had to be circulated at low pressure and only a large impeller with high speed can fulfil this operation mode. Therefore, the auxiliary blower has been taken as a reference for the circulator development and the associated magnetic bearings and catcher bearings, respectively. In addition, the auxiliary circulators had very stringent safety requirements as the final safety of the plant was dependent on the reliability of active decay heat removal. The six blowers had no direct safety engineering requirements.

The next figure illustrates the vertical position of a blower for the 200 MWth HTR-Modul as designed by Siemens-INTERATOM.

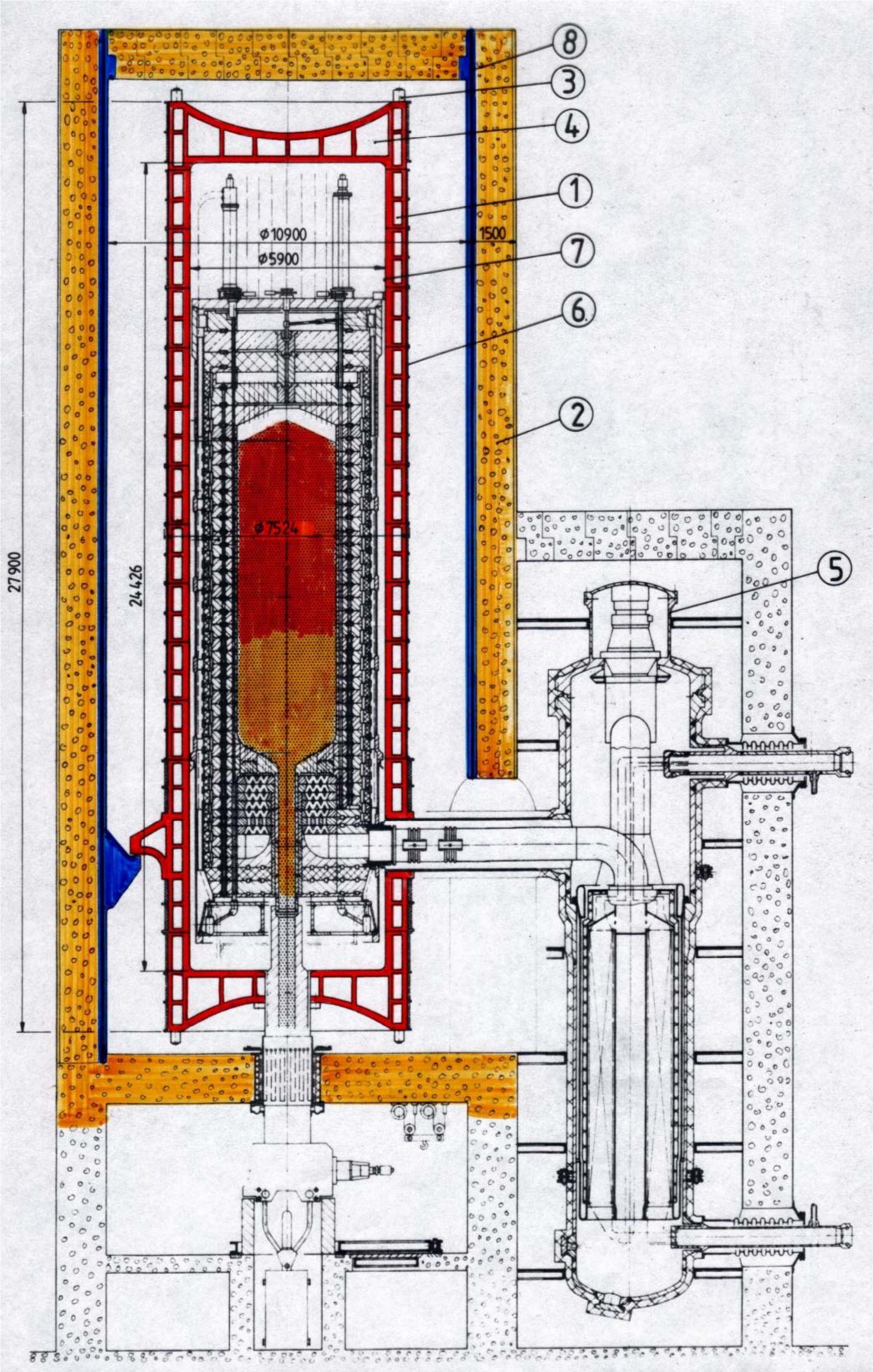
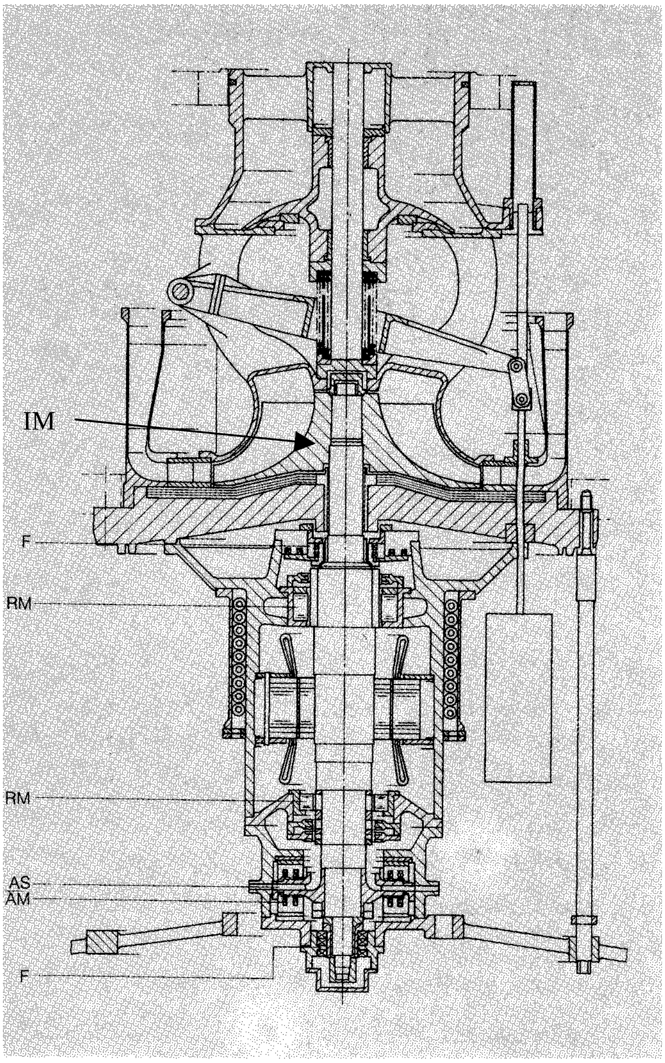


Figure 2.2: Blower (5) position in a HTR Modul (here with pre-stressed cast-iron vessel)

3. Circulator Design

For better understanding of the function and requirements of the catcher bearings, the design of the prototype circulator with magnetic bearings (MALVE 1) is shortly illustrated (see figure 3.1).



F - Catcher Bearings

RM – Radial Magnetic Bearing

AS – Axial Magnetic Bearing Disk

AM - Axial Magnetic Bearing

IM – Impeller Wheel

Figure 3.1: Cross section of vertical circulator prototype (MALVE 1)

On top of the impeller wheel, there is the shut-down valve of the auxiliary blower which is closed during normal operation to prevent bypass flows when the main circulators are under operation. Similar valves are foreseen for the main circulators being closed when the auxiliary blowers are activated. Under the support flange, the upper radial catcher bearing is situated. The lower catcher bearings are at the bottom of the rotor. They have the function of axial and radial stabilisation of the rotor in case of malfunction of the magnetic bearing. It is important to note that there is an additional friction cone which avoids unacceptable acceleration of the retention bearings and may even act as a redundancy, in case of a blockage of the catcher bearing.

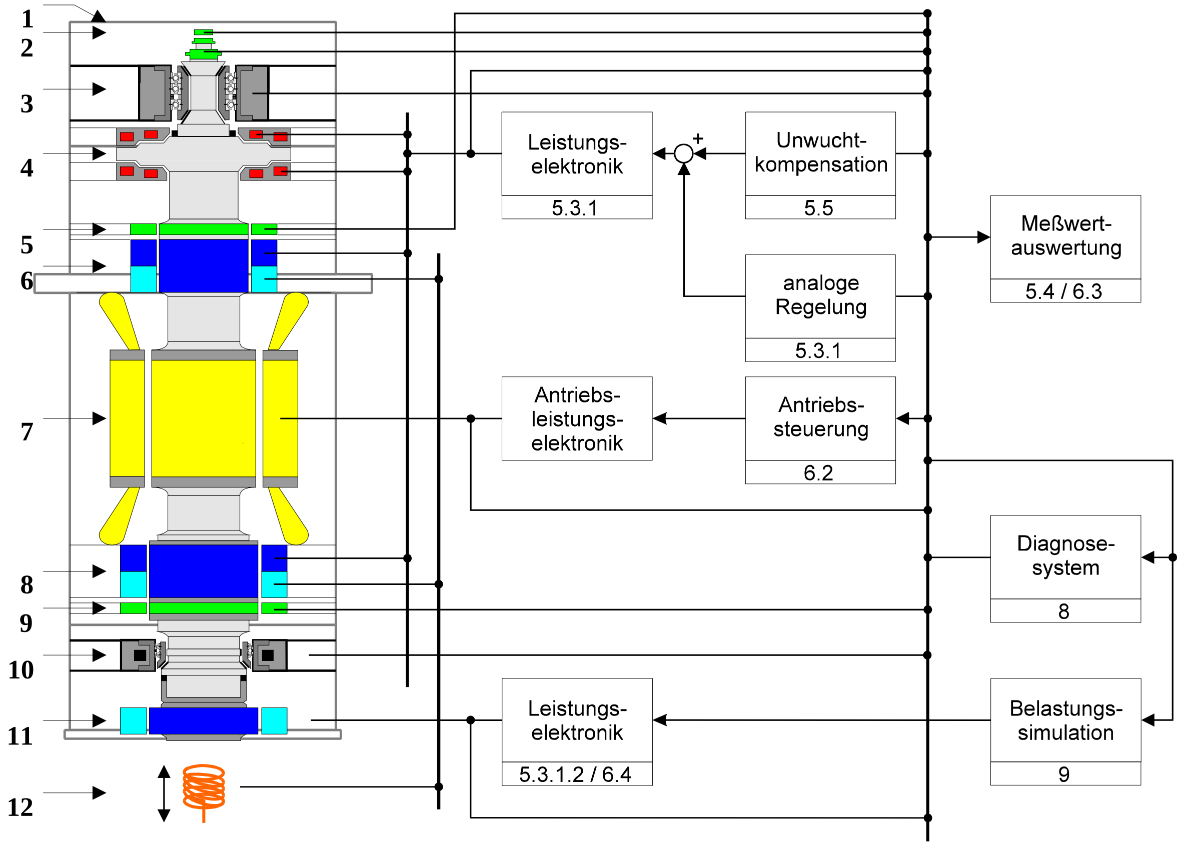
4. Catcher Bearing Test Facility

For a realistic test of the magnetic bearing and the catcher bearings, a special test facility (FLP 500) had been built by ABB and operated at the HRB premises at FZJ. Figure 4.1 shows the first version of FLP as operated in Juelich. Later on, the FLP 500 was transferred to ABB Mannheim for further tests and provided by a concrete cask as a protection against rotor explosion. This facility is now situated at the Technical Highschool in Zittau, Germany.

Figure 4.1: The Catcher Bearing Test Facility (FLP 500) at HRB in Juelich

The design of the FLP 500 is derived from the MALVE 1 prototype with the exception that it is tilted. Thus, the radial retention bearing is at the bottom and the combined axial/radial bearings are on top, as it would have been the case for the main blower. But the overall design of the shaft is near to the auxiliary circulator for decay heat removal. In addition, the FLP 500 possesses a magnetic load simulation equipment for simulation of disturbances.

Figure 4.2 shows a cross section of the FLP 500 including the principle connections to the related electronics. The different components and the similarity to the MALVE 1 design can easily be identified. The FLP 500 contains of a container vessel with a 1320 kg vertical rotor having an integrated asynchronous motor. The rotor is suspended by magnetic bearings as shown in figure 4.3 and stabilised by sensors feeding the electronics of the magnetic bearing. The rotor is provided with an electrical brake for quick stop in case of problems with the bearings. Maximum speed is 7200 rpm.



1 ... Test Vessel; **2** ... Axial Sensor; **3** ... Axial-Radial-Catcher Bearing; **4** ... Axial-Magnetic Bearing; **5** ... Top Radial Sensor; **6** ... Top Radial-Magnetic Bearing; **7** ... Asynchronmotor; **8** ... Bottom Radial-Magnetic Bearing; **9** ... Bottom Radial Sensor; **10** ... Radial Catcher Bearing; **11** ... Magnetic Load Simulation; **12** ... Thermal Heating System

Figure 4.2: Cross section of FLP 500 including Principle of Electronics

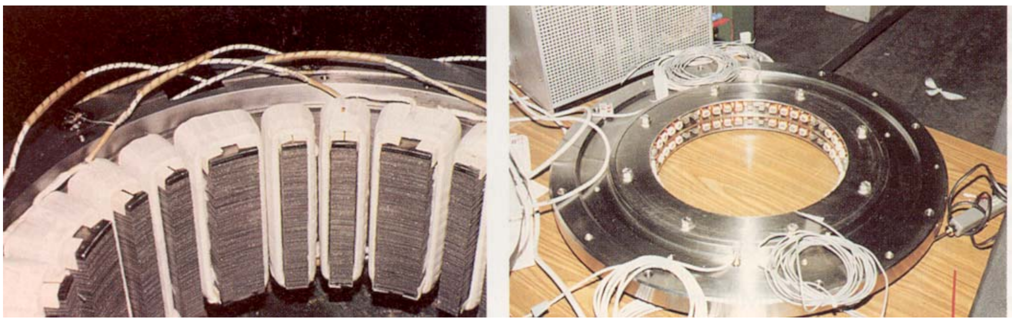


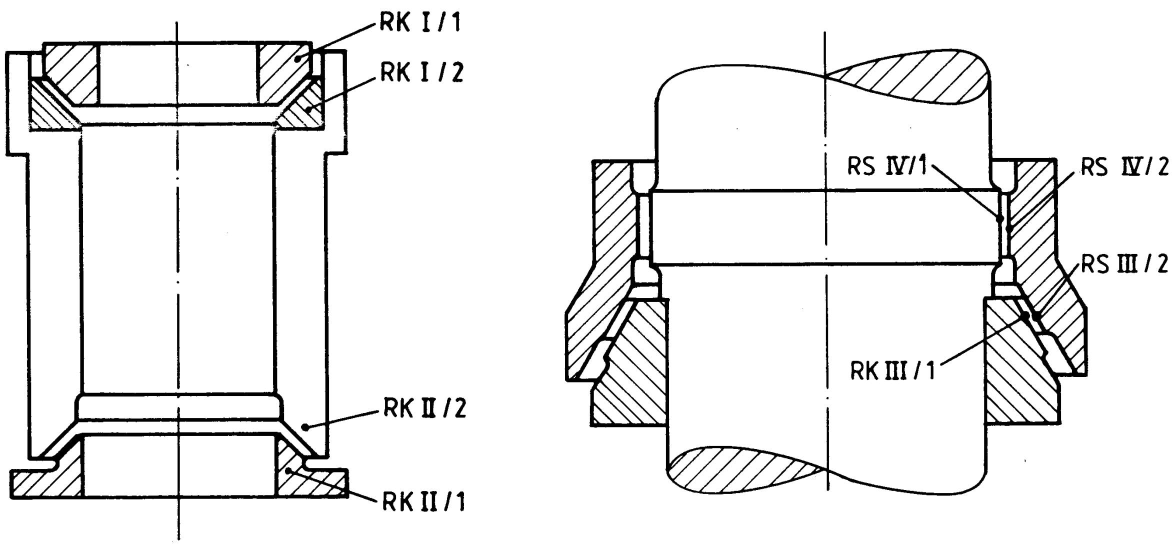
Figure 4.3: Radial Stator of Magnetic Bearing and Sensors (360 mm diameter)

5. Requirements for the Catcher Bearings

The design of the catcher bearings has to cope with the high operational and safety reliability requirements and the specific conditions of the HTR environment with regard to atmosphere and temperatures:

- Pure helium atmosphere with only few ppm of other gases
- No use of oil and grease to avoid impurities in helium
- Temperature about 150°C maximum
- Irradiation resistance up to 10^7 rad
- High peripherical velocities
- Extreme accelerations in case of sudden contact.

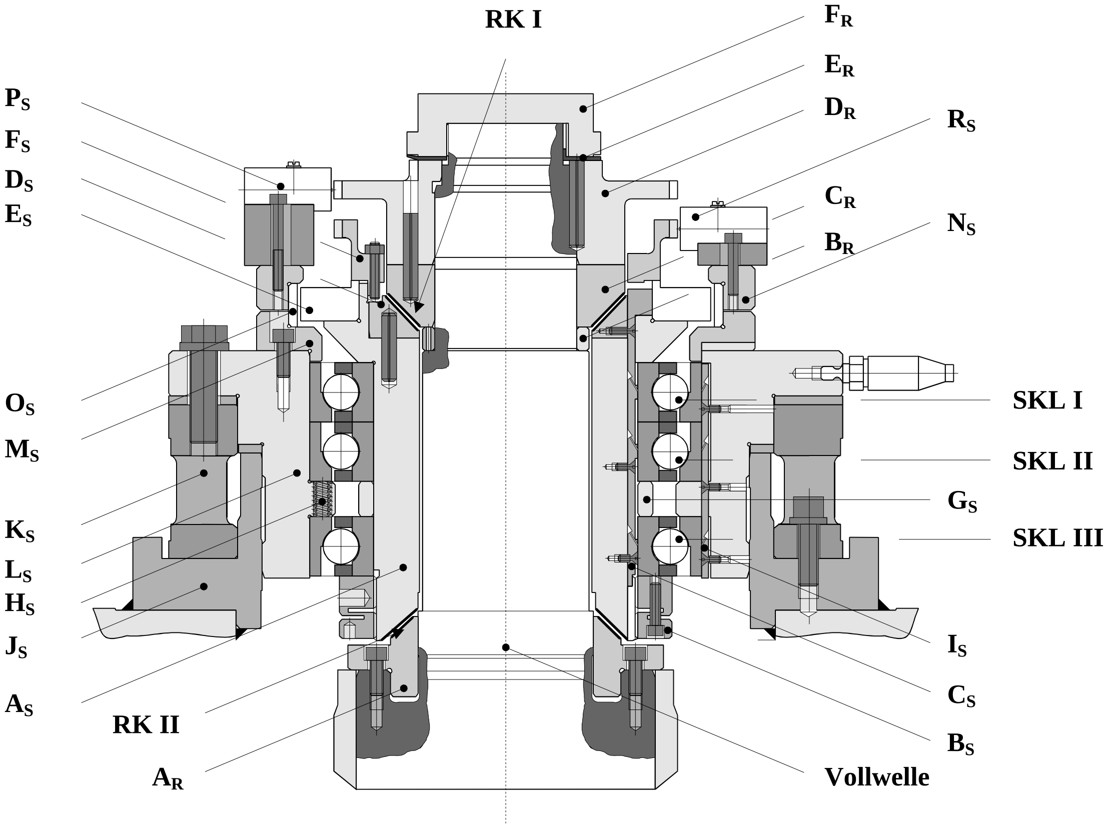
The catcher bearings are not directly connected to the rotor due to a small gap and do not rotate during normal operation of the magnetic bearing. Following an ABB patent, the contact to the rotor is provided by friction cones as principally illustrated in figure 5.1. (for details see position C_R in figure 5.2. and RK III in figure 5.3). Therefore, the catcher bearing has been addressed as a complex **system** and not as a simple retainer bearing only. The cones provide also a redundancy in case of retainer bearing blockage, a 'softer' acceleration of the catcher bearing and some adjustment of eccentricity to reduce vibrations and precession movements of the vertical rotor. The latter function is supported by a spring mechanism.



Axial Radial Catcher Bearing (ARF)　　Radial Catcher Bearing (RF)

Figure 5.1: Principle Arrangement of Friction Cones in Axial and Radial Catcher Bearings

With regard to the radiation field around the catcher bearings, oil or grease lubrication was not taken into consideration because of potential dissociation or hardening of the lubricant. Therefore, dry lubrication had to be developed for bearings and cones. Oil lubrication was only used in the very first test period of FLP 500.



A_R ... Zentrierring, **B_R** ... Distanzring, **C_R** ... Reibring; **D_R** ... Zentrierbüchse, **E_R** ... Sicherungsblech, **F_R** ... Wellenmutter
A_S ... Fanglagerbüchse, **B_S** ... Wellenmutter, **C_S** ... Thermoelementleisten, **D_S** ... Reibring, **E_S** ... Telemetriesender, **F_S** ... Klemmring innen, **G_S** ... Distanzring, **H_S** ... Druckfeder, **I_S** ... Thermoelementleisten, **J_S** ... Trägerring, **K_S** ... Meßring, L_S ... Testbehälter Teil 1, **M_S** ... Druckring, **N_S** ... Klemmring außen, **O_S** ... Telemetrieempfänger, **P_S** ... Drehzahlsensor Welle, **R_S** ... Drehzahlsensor Fanglagerbüchse
RK I/II ... Reibkonus I/II, **SKL I/II/III** ... Schrägkugellager I/II/III

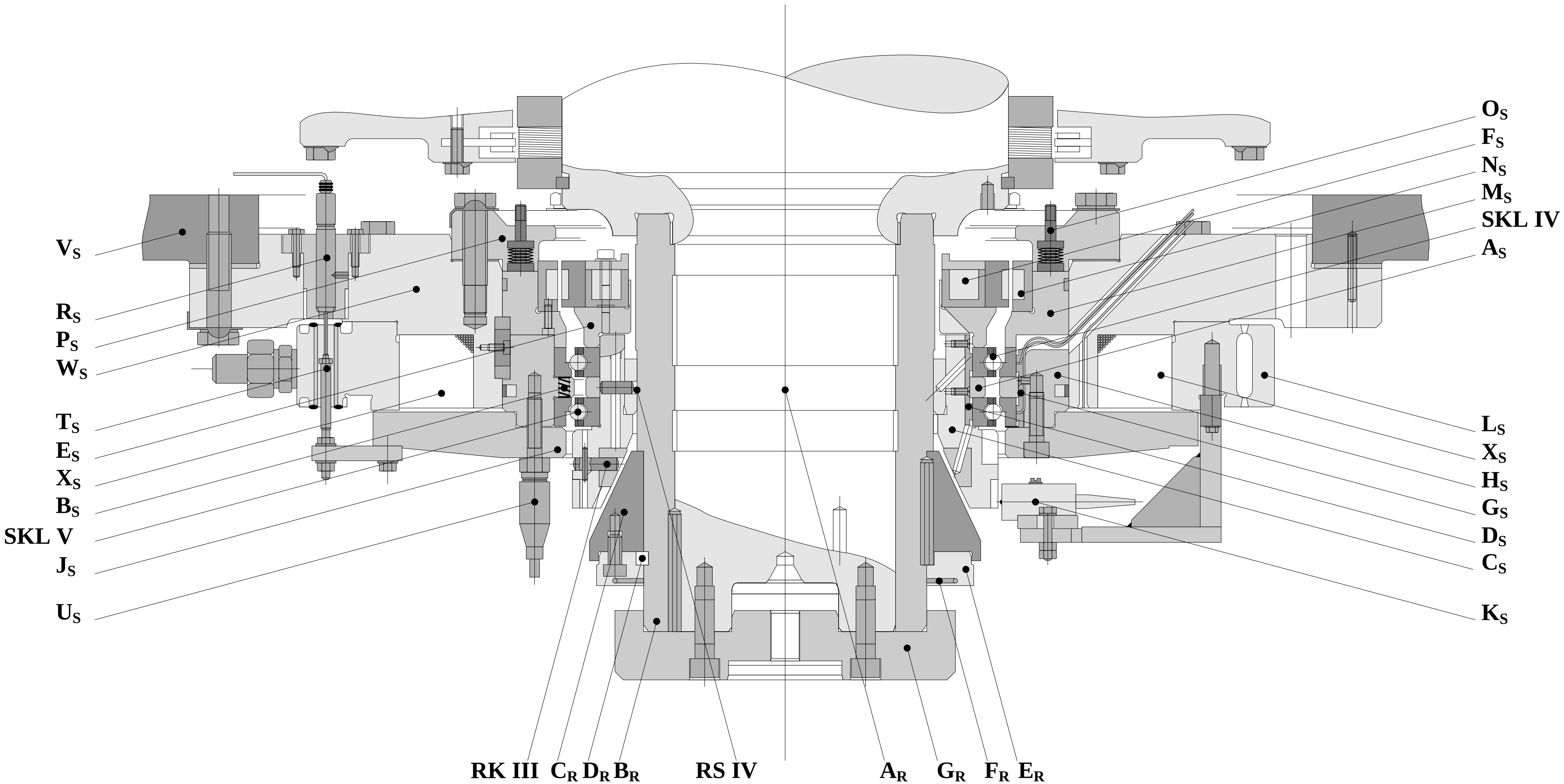
Figure 5.2: Design of the Axial Radial Catcher Bearings including Friction Cone Mechanism

The following mechanical loads for the test of the catcher bearings were specified:

	Axial / Radial Catcher Bearing	Radial Catcher Bearing
Dynamic Axial Load	250 kN	10–30 kN
Static Axial Load	20-50 kN	
Radial Load	< 100 kN	< 100 kN

Table 5.1: Design Data for the Catcher Bearings

When the axial magnetic bearing is switched off the rotor falls down about 1 mm. The acceleration of the catcher bearings to full speed (6000 rpm) needs about 1 second. It was requested that the catcher bearings ‘survive’ several actuations to prevent repair and exchange of catcher bearings after each malfunction of the magnetic bearings. The number of allowable actuations and the temperature rise in the bearings to prevent blockage by expansion of the inner ring were the main objectives of the test programme. The minimum request was 16 actuations to cover the 40 years lifetime of the plant without exchange.



A_R ... Vollwelle; **B_R** ... Wellenbüchse; **C_R** ... Zentrierring; **D_R** ... Sicherungsring 3-teilig; **E_R** ... Verschlußring; **F_R** ... Sicherungsring; **G_R** ... Klammerring
A_S ... Distanzring; **B_S** ... Druckfedern; **C_S** ... Fanglagerbüchse; **D_S** ... Thermoelementleiste; **E_S** ... Druckring innen; **F_S** ... Telemetriesender; **G_S** ... Thermoelementleiste; **H_S** ... Trägerring innen; **J_S** ... Trägerring außen; **K_S** ... Drehzahlaufnehmer; **L_S** ... Hubmagnetkühlring; **M_S** ... Druckring außen; **N_S** ... Telemetrieempfänger; **O_S** ... Federhalterring; **P_S** ... Druckfeder; **R_S** ... Wegaufnehmer; **T_S** ... Wegaufnehmerverlängerung; **U_S** ... Schocksensor; **V_S** ... Testbehälter Teil 3; **W_S** ... Hubmagnet komplett; **X_S** ... Hubmagnet
SKL IV ... Schrägkugellager IV; **SKL V** ... Schrägkugellager V; **RK III** ... Reibkonus III; **RS** IV ... Reibstelle IV
Quelle: GMD5 976 390 /8 c/

Figure 5.3: Radial Catcher Bearing including Friction Cone Mechanism

6. Test results

A large set of measurands was registered at each test to interpret the behaviour of different catcher bearings and friction cones. A typical recording of the acceleration and mechanical forces on the ARF and RF catcher bearing *system* is illustrated in figure 6.1.

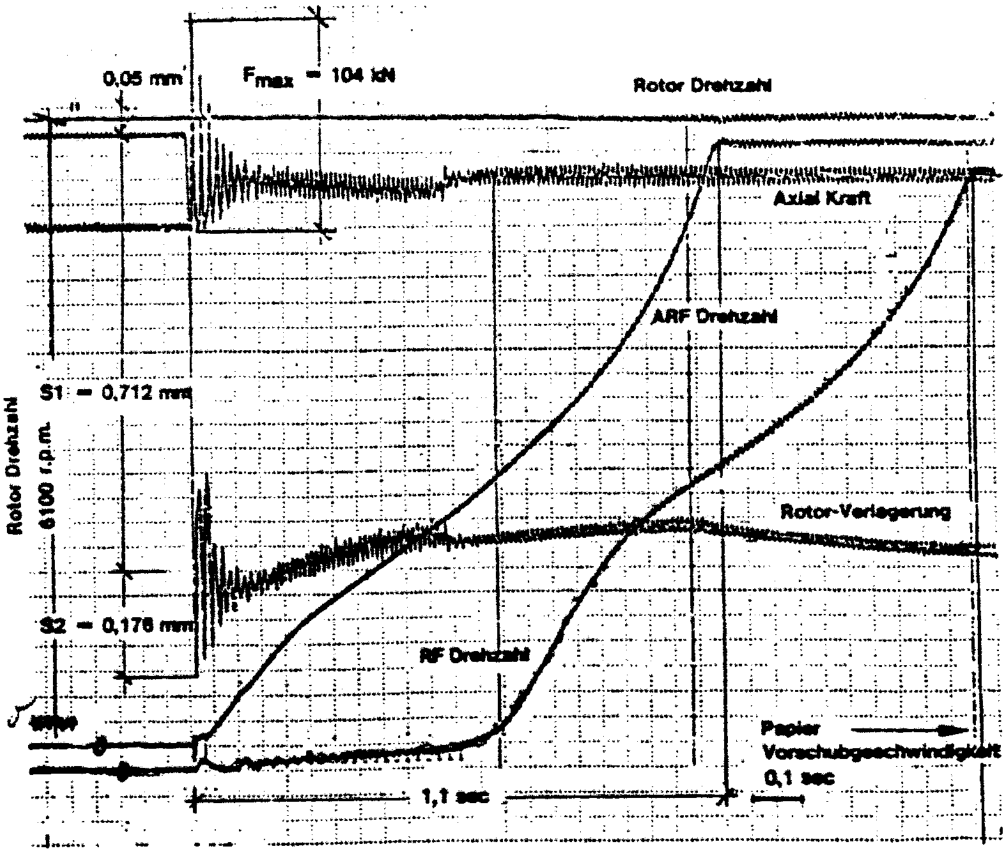
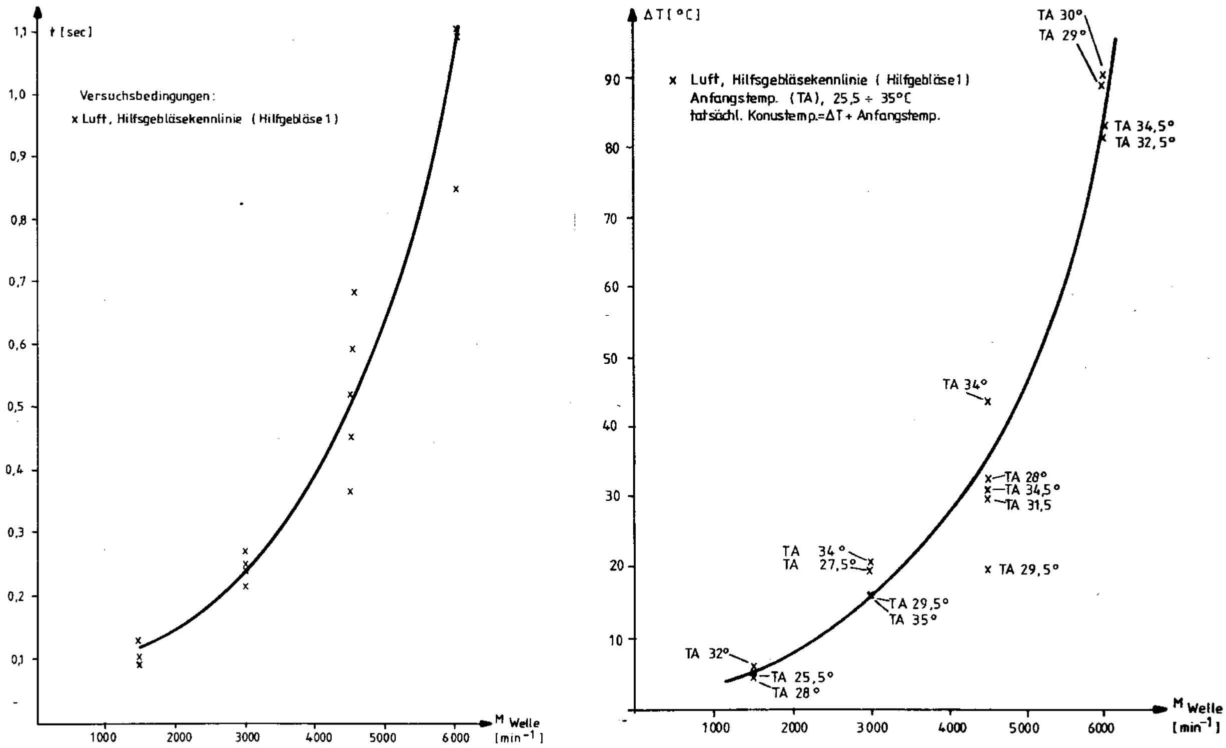


Figure 6.1: Recording of Catcher Bearings starting from 6100 rpm

It can be seen that the forces are in the specified regime and that both catcher bearing systems accelerate to full rotational speed within about 1,1 second. This time and the associated temperature rise in the cones and ball bearings have been measured for different rotational speeds and alternate friction cone materials which have strong influence on the acceleration. Figure 6.2 shows the relationships of such tests for cones operated under air. It can be seen that the temperature in the friction cones remain in tolerable ranges. The cones itself were made of different materials and combinations like bronze, Devametal, sintered metal (with infiltrated dry lubricant) and coated steels. It has to be noted that the friction behaviour under helium is much different and needs special combinations or dry lubrication.

Figure 6.3 shows the temperature rise in the rings of the ball bearings. Depending on the clearance of the bearing play only 20-30°C are allowed to avoid a blockage of the ball bearings. L1, L2 and L3 are the temperature differences for the ARF and L4 / L5 for the RF. These test were made under air.



a: Acceleration of Catcher Bearing

b: Temperature Rise in Friction Cones

Figure 6.2: Acceleration of Catcher Bearings and related Temperature Rise in Friction Cones

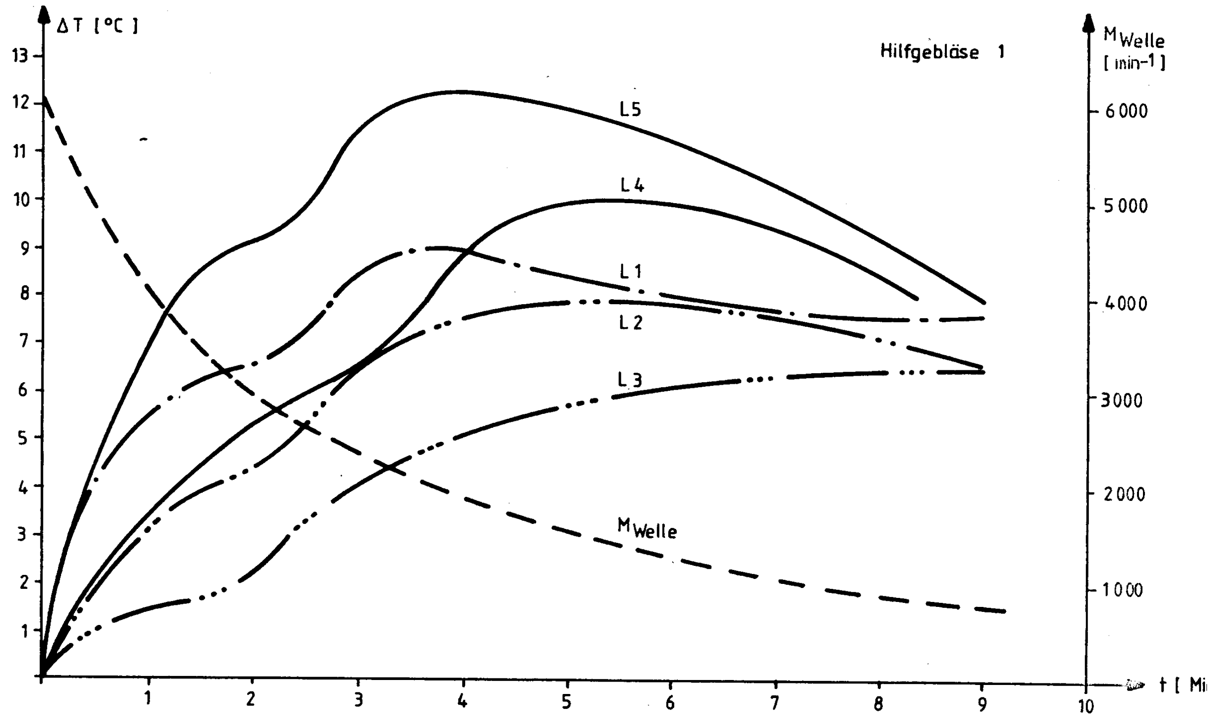


Figure 6.3: Temperature Rise of the Ball Bearing Rings during Coasting of Rotor

Cones and bearings have been checked after test to evaluate their condition. The following figures provide some impression on the wear of the different components

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Figure 6.4: Friction Cone (RK1) after test

The pictures above show that the wear was acceptable (<0,5 mm) after about 70 actuations for a combination of sintered metal including dry lubricant particles against hardened steel.

The next figure shows the condition of the ball bearings after tests. It can be seen that lubricated bearings of classical design (steel balls, steel cage) are still in a perfect status and do not show significant wear. In the case of dry lubricated bearings, a special development was necessary to improve the behaviour by special cages and application of dry lubricant. The bearing below experienced 15 actuations but showed already significant wear.

Figure 6.5: Grease-lubricated (above) and Dry-lubricated Bearing (below) after Test

7. Recommendations for Design of Ball Bearings

For the most critical axial/radial catcher bearing a ball bearing of shoulder type has been selected in combination with the friction cone as explained before. Special attention was put on the following issues:

- Clearance of bearing play
- Osculation and pressure angle
- Cage guidance, cage design and materials
- Surface quality of rolling contacts (rings, cage and balls)
- Lubrication medium, quantity and application
- Heat management
- Damping of the bearing

The clearance had to be significantly increased for dry lubricated bearings as the temperature increase of the inner ring had to be compensated sufficiently. Temperature differences were up to 30°C.

Different types of bearings have been developed and tested:

1. Inner and outer rings made of stainless steel with MoS_2 in-situ coating and steel cage
2. Same as 1 but light-weight cage with silver coating
3. Rings same as 1 but cage made of PTFE + 60% Bz
4. Rings same as 1 but cage made of bronze with PTFE + 60% bushings
5. Rings same as 1 but cage made of bronze with PEEK-CF bushings
6. Rings same as 1 but cage made of bronze with Vespel Sp3 bushings
7. Rings same as 1 but cage made of steel with coating of PTFE + 60% Bz
8. Rings same as 1 but cage made of steel with segmented PTFE + 60% Bz bushings

The versions 1-3 did not reach the targets. They failed mainly during coasting from 6000 rpm. Version 4 reached 13 actuations and showed the principal feasibility of dry lubricated catcher bearings, for the first time.

Versions 5 and 6 were made for testing different gliding materials in the cage bushings but PTFE + 60% bronze performed better. Design 7 only reached 3 coastings but probably due to insufficient coating processes. Variant 8 reached 15 actuations and still showed little wear as shown in figure 6.5. Ceramic balls were also considered to reduce the forces on the cage but cannot be finally evaluated. Further testing of ceramic balls could be of interest.

Higher temperatures at the bearings near to the impeller have to be taken into account. The FLP 500 was prepared for such tests with a heating device. But such experiments have not yet been performed and should be made in the test facility at Zittau.

Permanent magnetic bearings could possibly also be applied either as stand-alone catcher bearings or as supplement bearings to reduce the forces on the catcher bearing.

The combination with friction cones allows for redundancy and safety gain, in case of ball bearing blockage. Gas dynamic forces should be used to reduce the axial loads e.g. compensation of rotor weight via the impeller.

8. References

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