HOCHSCHULE ZITTAU/GÖRLITZ

(FH) - University of Applied Sciences

Ref.: HZG-IPM 610334/3/2.04/F

DELIVERY D28 (Work package 3)

Task 3.2 Recommendations and Statement

Authorised administrative official:

Dr.-Ing. P. Reinhold
(Provost)

Signature

Authorised contact person:

Prof. Dr.-Ing. F. Worlitz
(Project Leader)

F. Worlitz

Signature

Zittau, 12/14/2005

Modifications

Revision	*Date*	*Modifications*
A	12/09/2005	First Issue
B	12/14/2005	Review by partners

EUROPEAN COMMISSION
5th EURATOM FRAMEWORK PROGRAMME 1998-2002
KEY ACTION : NUCLEAR FISSION

HTR-E

High-Temperature Reactor Components and Systems

CONTRACT N°
FIKI-CT-2001-00177

HTR-E Work package 3
Deliverable D28
Recommendations and statements

FRAMATOME ANP SAS, France (coordinator)
University of Applied Sciences Zittau/Goerlitz, Germany (work package leader)

Dissemination level : CO
Document N°: HTR-E-05/11-D-3-3-2
Status : Final
Deliverable N° D28

1 Introduction

This report deals with the recommendations and statement related to the work package 3: Magnetic bearings of HTR-E contract.

These components (large capacity magnetic bearings) are used to support the rotating shafts of turbo-compressors or turbo-machine, which are components in the direct cycle of a modern HTR. This kind of support has been selected for a modern HTR to avoid the risk of leakage and fluid ingress in the primary circuit induced by the concept of mechanical and lubricated bearings (bad experience feedback in US and German former HTRs). So, the magnetic bearings for rotors support are considered as key components with regards to the safety and competitiveness of a modern HTR.

2 Synthesis of WP3 of HTR-E

For the support of modern HTR rotating components, the magnetic bearings are preferred instead of fluid or mechanical bearings because of risks of leaks, wear, jamming of such bearings. In addition, the concept of a large capacity modern HTR (GT-MHR type reactor) considers a single and long shaft for the compressors, the turbine and the electric generator. An important number of magnetic bearings (axial and radial) is necessary to support such a shaft and then the rotor dynamics control of the multi supported shaft is particularly difficult. Active Magnetic Bearings (the stiffness and damping of the bearings is controlled and varying according to the rotor displacements measured by sensors) could fulfil these technical requirements. In addition, the sensor signals of active magnetic bearings can be used for diagnosis algorithms that allow new possibilities of operation monitoring. For starting and shutdown periods auxiliary bearings (mechanical catcher bearings) are used complementary to the magnetic bearings.
But there is no industrial experience of magnetic bearings operating under the HTR typical loads (multi-supported large rotor of a GT-MHR reactor type).
The application of Active Magnetic Bearings for HTR rotating components requires the proof that operating loads are reliable controlled. The knowledge about mechanical loads as well as loads due to thermal effects is important.
The knowledge base of the system design will be generated with dynamic simulation models (MLDyn code), Finite Element analyses (ANSYS code) and experiments for the static and the dynamic behaviour of the magnet supported components using the FLP 500 test facility.

The general objective is to develop a concept proposal for the Active Magnetic Bearing support of the rotating components of future HTR. The proposal includes the Active Magnetic Bearings (with controls, sensors, and power electronics), Catcher Bearings and Diagnosis System. The different tasks performed in this WP are listed and summarized here after.

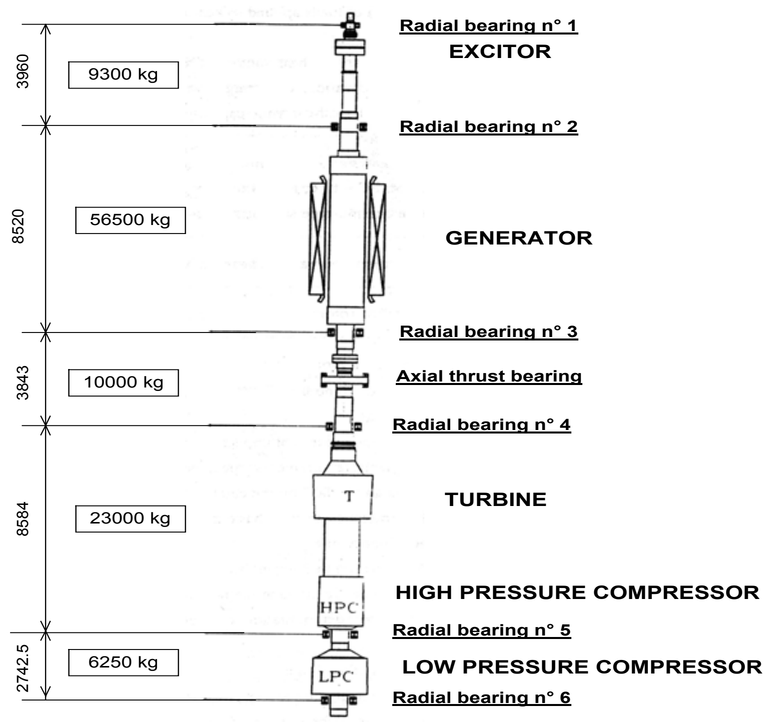
2.1 Task 1: FUNCTIONAL REQUIREMENTS-LOAD ANALYSIS-FEASIBILITY STUDIES

2.1.1 Functional requirements

The basis for the investigations is the definition of the functional requirements under normal and emergency operating conditions for Active Magnetic Bearings and Catcher Bearings.
The functional requirements for the support system of two kinds of turbo-machines are defined in the document HTR-E 02/06 D-3-1-1.
These two machines are:

- the power turbine of a GT-MHR type reactor,
- the high pressure turbo compressor of a PBMR type reactor.

The functional requirements concern the axial and radial active magnetic bearings and the axial and radial catcher bearings.
Hereafter a sketch of the large and single vertical rotor proposed for the GT-MHR with the location of the bearings. This rotor supports all the large rotating components of the direct cycle (turbine, compressors and electric generator).



The loads to be withstood by the bearings for different operating modes are detailed in the following table:

Operating mode	Load numerical value (x 10^4 N)						
	Radial bearings						Axial bearing
	1	2	3	4	5	6	
Nominal, 3000 rpm	0,465	3,72	3,75	1,65	1,47	0,3	45 ↓
Rotational speed up to 3600 rpm	0,67	5,16	5,21	2,38	2,12	0,43	25 ↓
Start up (speeding up)	1,7	11,8	12,0	5,9	5,3	1,08	105 ↓
Scheduled shutdown	1,7	11,8	12,0	5,9	5,3	1,08	105 ↓
Emergency shutdown, when AMBs fail	0,465 [1] 1,7 [2]	3,72 [1] 11,8 [2]	3,75 [1] 12,0 [2]	1,65 [1] 5,9 [2]	1,47 [1] 5,3 [2]	0,3 [1] 1,08 [2]	45 ↓ ... 450 ↓ [1] 105 ↓ [2]
TM seizing (blocking)	0,465	3,72	3,75	12,15	5,0	0,3	45 ↓
External impact (DBE)	1,8	20,2	20,4	9,9	8,82	1,8	19 ↓ ... 131 ↓

Notes : [1] At the moment of loss of power

[2] During TM rotor coastdown

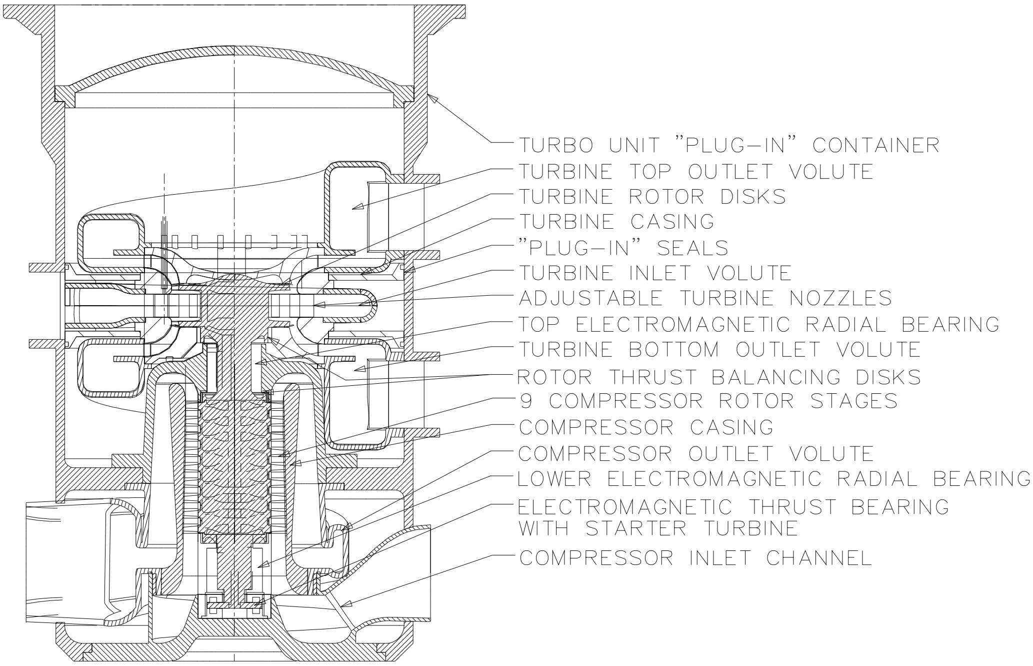
↓ Denote the downward direction of force

On the basis of these loads, the required load capacity of the bearings has been defined by the HTR-E partners.

Bearing type	Required load capacity (x 10^4 N)						
	Radial bearings						Axial bearing
	1	2	3	4	5	6	
AMB	2	12	12	6	6	2	105
CB	2	20	20	10	10	2	450

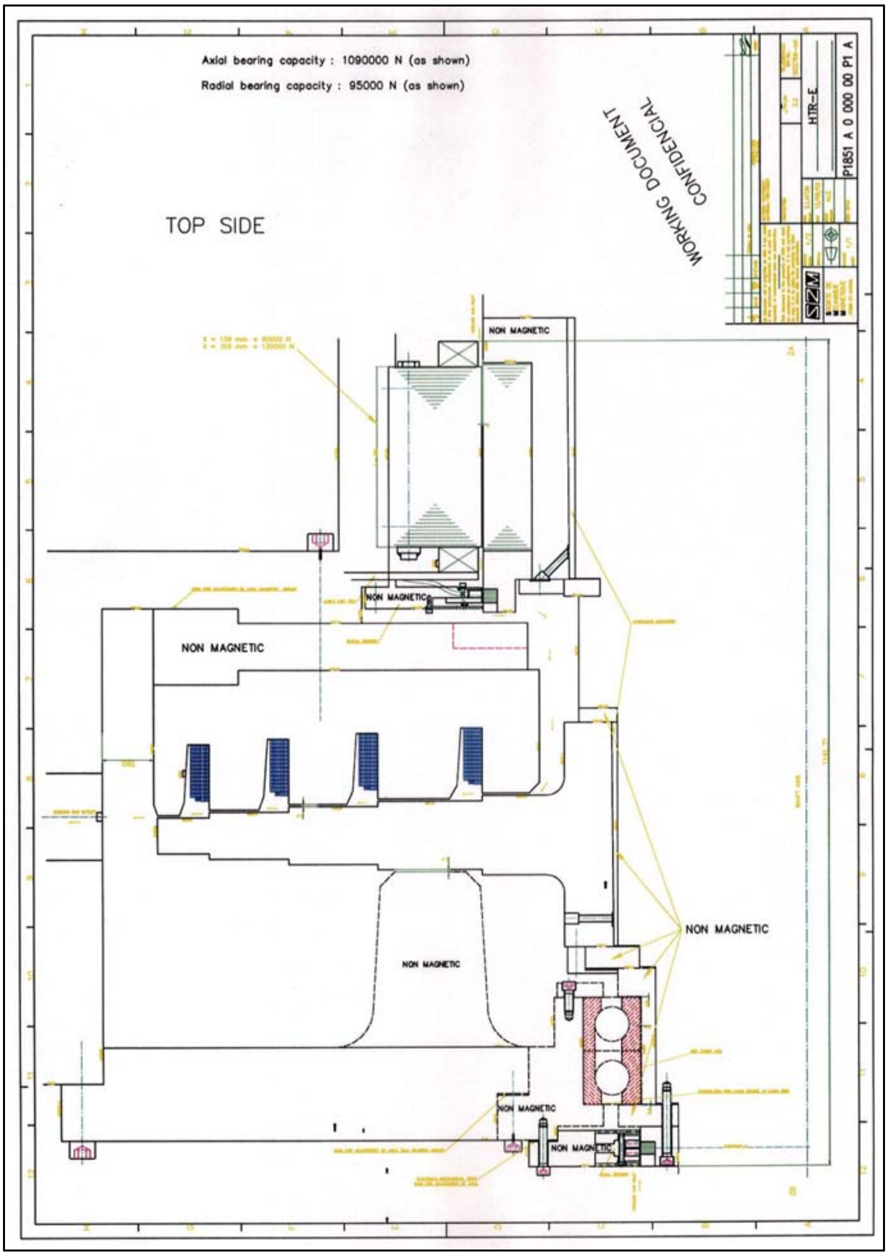
Note that the AMBs by themselves are not sized to withstand the seismic loads and that; in this case, the catcher bearings will react to support a part of these loads.
For the PBMR high pressure turbo compressor it appears that the requirements and loads are not very tricky. The main features for normal operating conditions are summarised below:

- Environment : He
- Radial bearings load (10^4 N) : not available
- Axial bearing load (10^4 N) : 0,7
- Normal rotational speed (rpm) : 15 200
- Medium pressure (MPa) : 7
- Medium temperature (°C): max. 150 °C
- Life span (hr) : min. 53 000
- HPT shaft weight : approximately 700 kg
- The first bending critical frequency of the rotor is expected to be 15% higher than the first over-speed running order.



The HTR-E partners concluded that the support design by active magnetic bearings of such a turbo-machine is achievable by standard bearings without R and D and it was proposed to focus the HTR-E work on the GT-MHR type reactor.

Taking into account these required load capacities, geometrical constraints and other requirements detailed in this HTR-E 02/06 D-3-1-1 report, a conceptual design has been elaborated for the AMBs support of such a machine, see the document HTR-E 02/12 D-3-2-1-1 and the figure hereafter. This conceptual design is suitable for a maximum temperature < 150 °C. Note that the axial magnetic bearing is not sized for 105 tons and that one solution to support the GT-MHR rotor would be to consider two discs with two axial magnetic bearings (S2M proposal).



The last functional specification is related to the requirements for helium circulators (report HTR-E 02/06 D-3-1-1-2). For this kind of 'small' rotating machine, the support design by active magnetic bearings is also achievable by standard bearings without R and D.

2.1.2 Load analysis

The following tasks are performed for the load analysis:

- Analysis of loads at machines which are comparable with HTR rotating components in size, rotational speed levels, unbalance effects, temperature of the medium and environment conditions (theoretical analyses and experiments of single effects at a test facility)
- The load analysis has been performed with dynamic simulation. The simulation tool MLDyn was parameterised with the values given from the requirements HTR-E 02/06 D-3-1-1 and the design study HTR-E 02/12 D-3-2-1-1. With help of the simulation tool, all operating modes (start up, unbalances, speed levels, static and dynamic loads) were investigated for stiff rotors - see also the results in the attachment to the minutes of the 2nd WP3 meeting HTR-E-02/11-M-3-0-2.

- The required modal analyses, harmonic response analyses as well as the frequency response analyses were performed with Finite Element analyses (ANSYS code). The numerical results provide the boundary and loading conditions for the design and the simulation tool (MLDyn).
- Adaptation of a modular simulation tool for real time investigations of the complete system.

2.1.3 Permanent MB feasibility study

An alternative of Active Magnetic Bearings for the rotating components support considering Permanent (Passive) Magnetic Bearings is investigated by a feasibility study. The fail safe characteristics of this system are particularly interesting to reduce the loads to the catcher bearings in accidental conditions (loss of power).

2.1.4 Catcher bearings feasibility study

A specific feasibility study on mechanical catcher bearings is performed in this work program. As part of catcher bearing tests, the Deliverable HTR-E04/10-D-3-1-4-2 covers the past experience from the German HTR R&D Programme. In this deliverable, it is pointed out one important item which is the retainer bearing in the case of AMB technology. The role of this retainer or catcher bearing is to prevent 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 an impeller diameter of 1.25 m. A specific test facility has been built (FLP500 which has been transferred to Zittau University, see picture hereafter) to simulate the conditions during coasting of the blower from 6000 rpm. In addition of these test results, recommendations for design of ball bearings are also given in this Deliverable.

FLP 500 Test Facility

2.2 Task 2: CONCEPT PROPOSAL-MECHANICAL ANALYSES

2.2.1 Concept proposal for bearings and diagnostics

Depending on the special requirements and the results of the load analyses a concept is designed for Active Magnetic Bearings (with controls, sensors, and power electronics) and Catcher Bearings. An important aspect is the fact that sensor signals can be used for diagnosis algorithms. This allows innovations for controlling and monitoring. Three steps are necessary:

- Concept of bearings including the control tasks.
- Development and optimisation of controller algorithms by computer simulation depending on the analysed forces.
- Development of diagnosis algorithms for magnetic bearings, catcher bearings, rotor and test by computer simulation.

The dynamic behaviour (during shut-down, start up, unbalances, and mechanical loads) of the Active Magnetic Bearing system is determined with a simulation tool under online conditions.

2.2.2 Mechanical analyses

With a numerical validation it is to determine whether the proposed magnetic bearing design satisfies the design requirements. The magnetic, thermal and structural behaviour of the magnet supported system for the various load cases are determined by means of transient Finite Element analyses (MSC.Marc code).

2.3 Task 3: EXPERIMENTAL VALIDATION-RECOMMENDATIONS

2.3.1 Experimental validation

With respect to the complexity of the AMBs supported system an experimental validation of algorithms and also the investigation of single effects are necessary. These experiments (FLP 500 test facility of Zittau University) complete the analytical investigations:

- Analysis of static and dynamic loads regarding to the rotational speed and the disturbances during operation
- Validation of simulation tool by comparing simulation results with results from experiment
- Failure and function diagnostics for components (Active Magnetic Bearings, catcher bearings, rotor dynamics, behaviour of the driven machine)

2.3.2 Recommendations and statements

The last task concerns the recommendations and statements including the analysis of analytical and experimental results which is the report at hand. The main Statements will be given in the following chapter.

3 Recommendations on the large capacity magnetic bearings

The statements hereafter include the topics of HTR-E WP3 which are proposed to be further investigated and also the results and tools which are recommended to be used for future works.

Catcher Bearings

It was recommended by S2M to use ceramic ball bearings for the catcher bearings, as they had good experiences with that CBs. The problem, which was mentioned, is the necessary ball size (dependence e.g. on the high dead weight of the rotor; see also subsection "Seismic loadings" of this chapter) what will be at the state of the art a manufacturing problem. Therefore it is necessary to perform experimental investigations in the frame of future works.

Feasibility of the axial AMB

The investigated GT-MHR type reactor is given with a vertical arranged shaft. Therefore the rotors dead weight (105 tons) have to be suspended by the axial AMB. The capacity of a single axial AMB is limited to 1000 kN, a double disk solution was proposed by S2M for reaching a higher load capacity. Otherwise the capacity of the axial AMB would not be sufficient in cases of disturbances to react.

Rotor arrangement of the turbo machine

S2M recommended two vertical shafts with flexible connection (to be developed).
Another recommendation regarding the arrangement of the turbo machine came from the HTR-L partners:
For safety reasons in case of de-blading, a horizontal shaft misaligned with the reactor vessel is recommended for the turbo machine arrangement (missiles oriented far away from the reactor).

Seismic loadings

Seismic loads (occurring during an earthquake) will exceed the load capacity of the radial and axial AMB. The support of the GT-MHR rotor shaft will be transferred from the AMBs to the CBs, whereof the required load capacity for the CBs will be based on the maximum (seismic) loadings (see document N° HTR-E 05/11-D-3-1-2-1-1: Seismic Analysis).
Furthermore it is necessary to have a redundancy for the AMB, each with an independent electrical supply and with UPS in order to avoid leak and radiological release outside the building.

Downscaling

The applicability of the AMBs was proofed in the task "Experimental Validation". For the experiments, performed at the FLP 500 test facility of Zittau University, downscaling conditions were made, based on the requirements of the GT-MHR type reactor. Therefore the loads were scaled down with the factor 10 (according ratio of load capacity of the radial AMBs GT-MHR : FLP 500 = 10 : 1), frequencies of dynamic loads remain the same.
Using downscaling conditions for experiments on test rigs, which are smaller than the original system, is an usual method described by OKBM in ISTC 1261 report.

<u>Tools</u>

MLDyn: MLDyn is a simulation tool which was used to determine the behaviour of the magnetic suspended system as well as for investigations in control algorithms, determination of the influence of dynamic and static loads, single effects, and operational conditions. The validation of MLDyn shows very good accordance between simulation results and measured results from experiment. Therefore it is proposed to be used for pursuing investigations in behaviour analysis and controller prototyping for magnetic suspended HTR-Components.

MLDia: MLDia is a diagnostic tool using the systems inherent signals for extracting features that will be monitored for fault detection. Knowledge-based models, using fuzzy logic, are used to classify faults to determine the kind of fault, where and when the fault occur, what was the reason for the fault and, if necessary, automatically start retaliatory actions.
The models for diagnostics were successfully tested at the FLP 500 test facility and other test rigs. MLDia is recommended to be used for the diagnostics of HTR-Components with AMB support.

ANSYS: For determining the loads which will appear on the AMBs caused by unbalances or occurrence of failures (e.g. de-blading), as well as loads caused by seismic activities, the use of FEM-calculations with ***ANSYS-Code*** has been proofed. Within the HTR-E WP3 such calculations were performed in the tasks “Load Analysis – Modal and Harmonic Analysis”, “Seismic Analysis” and “Magnetic and Mechanical Analysis”.

<u>OKBM</u>

OKBM is an institution organised in Nishni Novgorod, Russia, who also has experience with magnetic suspended TM systems. Their results are specified in the ISTC 1261 report, describing the use of several test rigs. For the close parallels between their investigations and the investigations performed in HTR-E WP3 it would be recommended to have information exchanges for a future work.

<u>Permanent Magnetic Bearings (PMBs)</u>

The feasibility study of PMBs will be the basis for pursuing investigations within RAPHAEL SP-CT. In addition to the active magnetic bearings, a PMB arrangement with a multiple load capacity and higher radial stiffness (compared to the arrangement in the feasibility study – task 2) should be mounted and tested at the FLP 500 test facility. The gained permanent radial stiffness and guidance of the shaft as well as the additional load capacity of the PMBs promise the following features:

- reduced loading on the Catcher Bearings
- thereof the expected lifetime of the CBs may increase
- otherwise the ball sizes of the CBs may become smaller (compare with HTR-E WP3 CB- Concept-Proposal by S2M), what may solve the manufacturing problem (compare statement on CBs in the first subsection of this chapter)

4 Conclusion

The achieved results and the beneficial collaboration within the project provide a clear motivation to continue the related issues in V/HTR-IP.
As part of the Active Magnetic Bearings (AMB), the design studies and tests performed on FLP500 test facility from Zittau University, valid the algorithms and the numerical model. Seismic loads seem difficult to be controlled by an Active Magnetic Bearing, the use of catcher bearing is recommended by switch off the electrical power. The axial Catcher Bearing (CB) stays a very difficult point from design point of view, if an axial shaft is preferable. In case of horizontal shaft the CB issue is solved.
And for PMBs (Permanent Magnetic Bearing) conceptual design for small load capacity have been developed and tested.
The developed and tested diagnostic algorithms are applicable for detecting failures caused by loads, unbalances and also failures in the catcher bearings.