Nuclear Engineering and Design 251 (2012) 344–348

Contents lists available at SciVerse ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Rotor scale model tests for power conversion unit of GT-MHR

C.B. Baxi*, A. Telengator, J. Razvi

General Atomics, P.O. Box 85608, San Diego, CA 92186-5608, USA

ARTICLE INFO

Article history:
Received 22 January 2011
Received in revised form 5 September 2011
Accepted 5 September 2011

ABSTRACT

The gas turbine modular helium reactor (GT-MHR) combines a modular high-temperature gas-cooled reactor (HTGR) nuclear heat source with a closed Brayton gas-turbine cycle power conversion unit (PCU) for thermal to electric energy conversion. The PCU has a vertical orientation and is supported on electromagnetic bearings (EMB).

The rotor scale model (RSM) tests are intended to directly model the control of EMB and rotor dynamic characteristics of the full-scale GT-MHR turbo-machine (TM). The objectives of the RSM tests are to:

- Confirm the EMB control system design for the GT-MHR turbo machine over the full-range of operation.
- Confirm the redundancy and on-line maintainability features that have been specified for the EMBs.
- Provide a benchmark for validation of analytical tools that will be used for independent analyses of the EMB subsystem design.
- Provide experience with the installation, operation and maintenance of EMBs supporting multiple rotors with flexible couplings.

As with the full-scale TM, the RSM incorporates two rotors that are joined by a flexible coupling. Each of the rotors is supported on one axial and two radial EMBs. Additional devices, similar in concept to radial EMBs, are installed to simulate magnetic and/or mechanical forces representing those that would be seen by the exciter, generator, compressors and turbine.

Overall, the lengths of the RSM rotor is about 1/3rd that of the full-scale TM, while the diameters are approximately 1/5th scale. The design and sizing of the rotor is such that the number and values of critical speeds in the RSM are the same as in the full-scale TM. The EMBs are designed such that their response to rotor dynamic forces is representative of the full-scale TM.

The fabrication and assembly of the RSM was completed at the end of 2008. All start up adjustments were finished in December 2009. To-date the generator rotor has been supported in the EMBs and rotated up to 1800 rpm. Final tests are expected to start in the fall of 2011.

1. Introduction

A power-generating unit of the high-temperature helium reactor has a turbo-machine (TM) that is intended for conversion of thermal energy into electrical energy, and helium circulation in the primary circuit (Baxi et al., 2006, 2008). The TM (Fig. 1) consists of a turbo compressor (TC) and a generator. Their rotors are joined with a diaphragm coupling and supported by electromagnetic bearings (EMBs). The TC is enclosed in a metallic shroud to prevent a catastrophic event in case of blade failure. Distinguishing features of the TM design are vertical positioning, the EMB system, a flexible rotor, a helium-cooled generator, significant electric power, the rotation speed of 4400 rpm, the rotor weight 67.7 t, and the rotor length of 29 m. The TM EMB system consists of two axial and four radial EMBs, the EMB control system, and catcher bearings (CBs). The use of EMBs (Schweitzer, 2002; Shi et al., 2004; Bilbow, xxxx; Chiba, xxxx; Schweitzer et al., 1994; Hittner, 2004; Koster et al., 2003; Ion et al., 2004; Guojun et al., 2004; Li et al., 2004; Xingzhong et al., 2004; Kunitomi et al., 2001; Kümmlee et al., 2000; Hsiao and Lee, 1994; Pilat, 2004; Schmied and Pradetto, 1992; Kodochigov et al., 2005a,b; Mitenkov et al., 2005) in the TM makes it possible to: (1) prevent lubricating oil and products of wear and tear from getting into the gas-turbine cycle; (2) reduce bearing operational costs; and (3) enable active control of the rotor dynamics.

2. Rotor scale model

In order to verify the main features of the power conversion unit (PCU), scale tests called rotor scale model (RSM) tests are in progress. The RSM consists of two parts – the generator rotor model

* Corresponding author.
E-mail address: baxicb1130@hotmail.com (C.B. Baxi).

0029-5493/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.nucengdes.2011.09.060

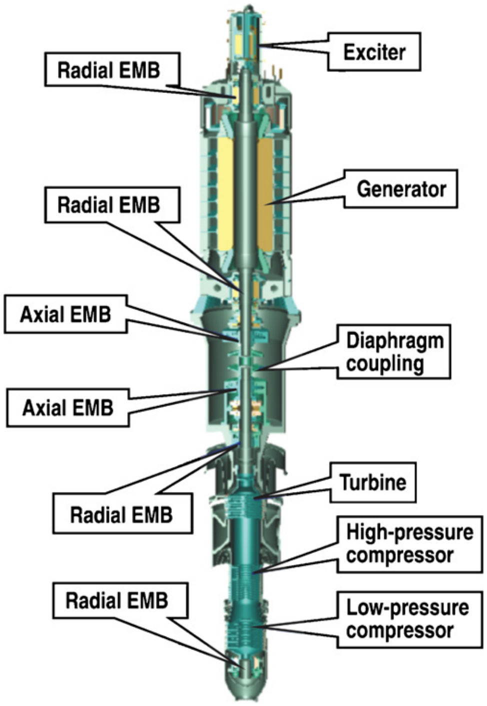

Fig. 1. GT-MHR turbo machine.

and the turbo compressor rotor model that are joined with a flexible or rigid coupling (either may be used in the experiment). Fig. 2 presents a schematic of the generator and the turbo compressor rotor models. Fig. 3 explicitly shows the actual components such as the radial and the axial EMBs, the test facility casing and the shafts. The rotor axis is vertical. The designs of physical model elements, the turbine, compressors, generator and exciter are simplified and represent masses of same moments of inertia, with proper scaling.

In addition, three radial EMBs are installed in RSM. One of the radial bearings is used for simulating the impact of Alford forces on the turbo machine rotor. The other two bearings may be used as additional supports or for creation of additional radial forces.

Electromagnetic sensors of rotor position control are used to continuously measure the gaps between the rotor and the axial and radial EMB electromagnets. Additionally, to control rotor displacement in the horizontal plane at various points along the height, inductive sensors are used.

Four radial and two axial EMBs together with the control system form the electromagnetic suspension system of the rotor model. Each EMB is backed up with a ball bearing type catcher bearing. Bearing cooling is achieved by forced air circulation. RSM electromagnetic suspension system incorporates a multi-channel control system that ensures the required load-bearing capacity of the bearings and creates driving forces sufficient for stabilization.

The generator rotor is driven by two electric motor rotors (5 kW) that were selected so that it will be possible to scale magnetic attraction forces of the full-scale turbo machine main generator and exciter. The motors ensure the model rotor rotation speed can be controlled from 10 to 6000 rpm by means of a frequency converter.

The RSM casing is installed on a vibro-insulating foundation to investigate the impact of various changes in the turbo machine design on the rotor and turbo machine operation. These include: (1) The change in the number of EMBs; (2) location of bearings and stiffness of stator structures, influence of the rotor coupling type (rigid or flexible); (3) deflection of various structure elements from a specified alignment (bearings, generator stators, turbine and compressors); (4) the impact of various force factors on the operation of the rotor and control system including magnetic attraction forces in the generator and exciter, forces of gas-dynamic origin in the turbine and compressors; and (5) verification of calculation procedures of the rotor dynamics based on the obtained experimental data.

Experimental studies of RSM enable us to:

- Investigate the influence of the rotation speed on the operation of the rotor and control system including rotor behavior at several critical speeds and during operation near the critical speeds.
- Investigate a possibility of balancing the rotor in EMB and to damp rotor bending oscillations at critical speeds.

3. Scaling

It is crucial that the scaling factors of the length and the diameter of the RSM are accurate in order to produce corresponding natural frequency characteristics. An example of the scaling analysis for the equation of a beam used to calculate natural frequencies of lateral oscillations and respective critical frequencies of rotor rotation is shown below.

$$\frac{\partial^2}{\partial z^2}\left(EJ\frac{\partial^2 y}{\partial z^2}\right) + \rho S\frac{\partial^2 y}{\partial t^2} = 0, \quad (1)$$

where E is the rotor material elasticity modulus, J is the moment of inertia in the cross-section relative to the central axis, y is the lateral displacement of the given rotor cross-section, z is the length of rotor section from the reference point to the given cross-section, ρ is the rotor material density, S is the rotor cross-sectional area, and t is time.

Applying the similarity and dimensional theories, we obtain:

$$\frac{K_L^4 K_S K_\rho K_\omega^2}{K_E K_J} = 1 \quad \text{or} \quad \frac{K_L^4 K_\rho K_\omega^2}{K_E K_D^2}\cdot\frac{1+c_M^2}{1+c_H^2} = 1, \quad (2)$$

where $K_E, K_J, K_D, K_L, K_y, K_\rho, K_S, K_\omega$ are scaling coefficients, which are ratios of elasticity modulus, inertia moment, diameters D, lengths L, lateral travels, densities, cross-sectional areas, and oscillation frequencies ω of the full-scale rotor over the respective parameters of the rotor scale model; c_M and c_H are the ratio of inner diameter over outer diameter for any cylindrical section of the full-scale rotor and the corresponding section of the rotor scale model.

This scaling analysis provided various parameters, including in particular the two scaling coefficients for the length and the diameter, $K_{LENGTH} = 2.35$ and $K_{DIAM} = 5.52$. In addition to proper scaling the dimensions of the rotor, the structure of the RSM, EMB, and the control system (CS) along with the means of ensuring a redundancy in the CS are identical to those as in the full-scale TM.

4. RSM status as of 2011

As part of start up, the following tests have been conducted:

1. Natural frequencies of RSM casing vibration modes were determined. Tests were performed by simulating vibrations by using “Brüel & Kjær” 4801 vibration exciter in the frequency range of 0–200 Hz.
2. The following parameters were determined for a non-rotating rotor with assigned control system algorithms:

a. Relative position of the geometric and magnetic axes in radial EMBs and gaps in catcher bearings according to signals from displacement sensors.
b. Values of the axes of generator and TC rotor models relative to the central geometrical axis of catcher bearing.
c. Electrical currents in electromagnets.
d. Temperature of windings (coils) of electromagnets.

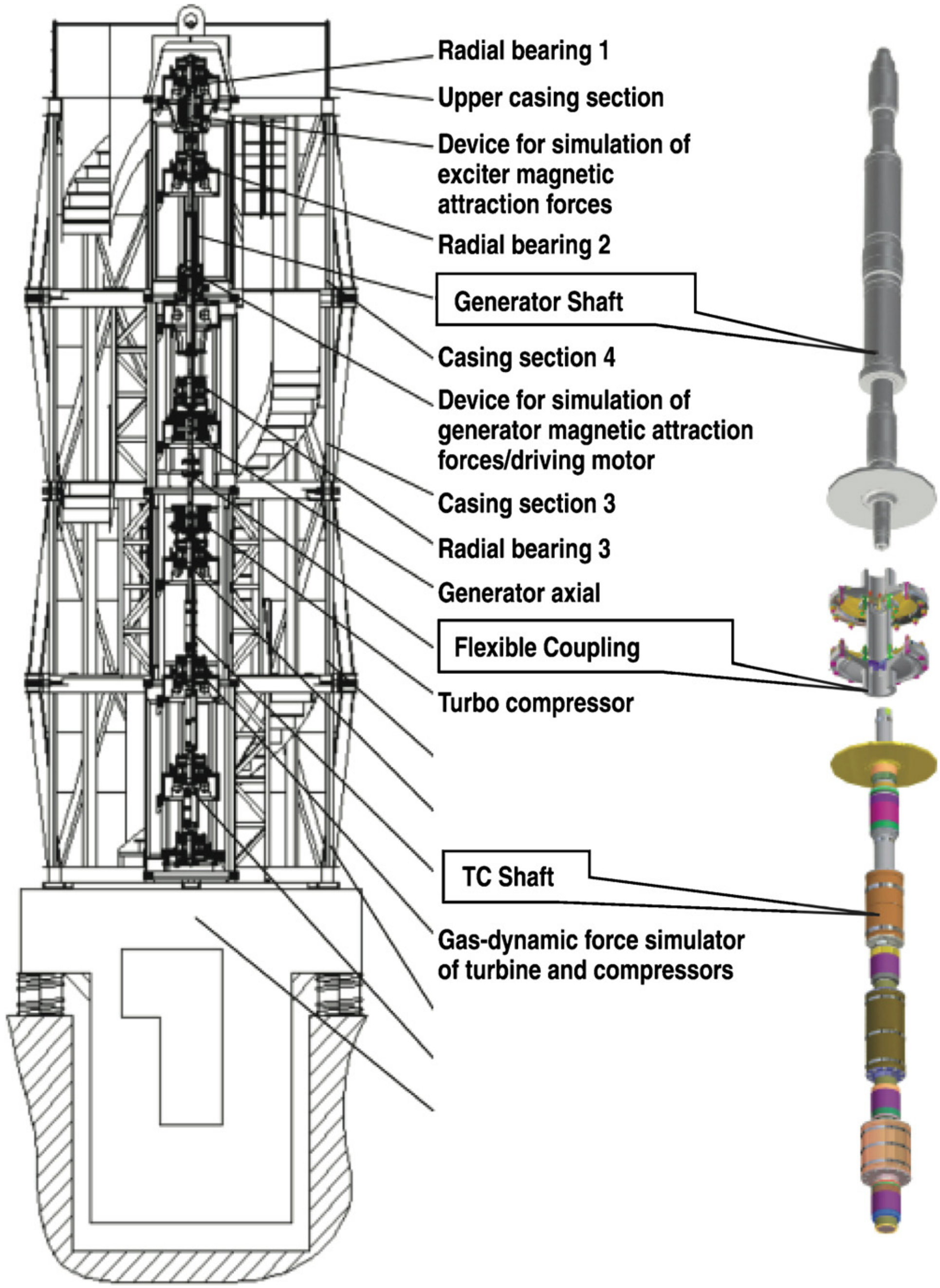

Fig. 2. Rotor scale model.

The generator and the TC rotors were decoupled to start supporting and rotating the generator rotor in EMBs. The difficulties encountered in this process and their resolutions are shown in Table 1.

Other problems encountered were the influence of disturbances on the quality of current control by the relay-operated regulator, failures of power transistors in output stage modules, and position sensors that did not provide the required inductance.

After the EMB and sensors control system was upgraded, the support system was capable of holding the rotor while rotating at a speed not exceeding 1800 rpm. Further upgrades are

Table 1
Difficulties encountered and resolution.

Problem	Effect on RSM tests	Resolution
Characteristics of rotor position sensors do not meet the imposed requirements	IS[a]	Replacement
Characteristics of rotor angular position sensors do not meet the imposed requirements	S[a]	Correct production process
Noise in EMB control system	S[a]	Update EMB control system
Vibration sensors do not give full information on RMS casing displacement	IS[a]	Correct the information-measuring complex software

[a] IS – insignificant; S – significant.

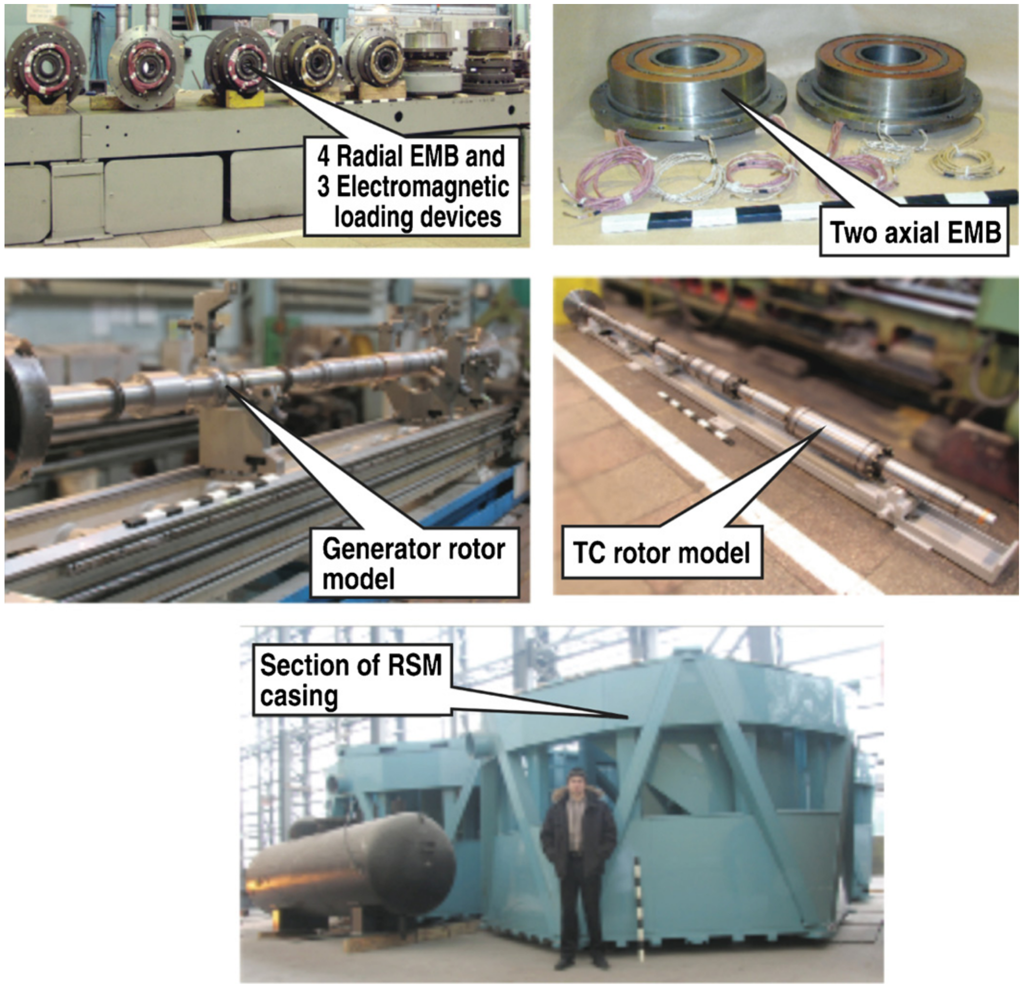

Fig. 3. RSM components.

being conducted to increase stiffness of EMBs and to reduce the oscillation amplitudes.

5. RSM test program

RSM test program includes both the main and the special tests. The goals of the main tests are to:

1. Validate operability of the GT-MHR TM EMB control system to confirm configuration of the GT-MHR PCU.
2. Obtain experimental data for use: (a) during development of the EMB system and rotor for the full-scale TM and (b) during tests of the full-scale TC.
3. Obtain data for verification of rotor dynamics computer codes and EMB control algorithms.

Additional special tests are planned to be conducted in 2012. The goals of these additional tests are to:

1. Obtain additional experimental data on the influence of individual internal and external effects on the dynamics of a flexible rotor with electromagnetic bearings in order to verify the DIROM code and to validate the control algorithm.
2. Determine "margins" of the static load-carrying capacity of EMBs with a stopped rotor.
3. Determine the force moment from skewness of the axial EMB disk relative to the stator.
4. Estimate radial forces in the axial EMB at radial rotor displacement.
5. Estimate actual inertia of EMB CS.
6. Study the influence of additional loading devices used as dampers on rotor dynamics.
7. Continue study of influence of bias (displacement) currents in radial and axial EMB on rotor dynamics.
8. Study influence of tangential forces on rotor dynamics by means of specially provided simulators in transient modes.
9. Determine actual stability boundaries for a flexible rotor with EMBs in transient modes at different parameters of the control system.

6. Safety measures

The rotor in test weighs more than a ton and will rotate at 5200 rpm during the final phase of testing. The stored energy at that speed will be about 2 MJ. The following safety measures have been taken to ensure safety of the equipment and personnel:

1. The rotating parts are enclosed in a steel casing.
2. The whole assembly is located in a concrete structure away from the control room.
3. Access to the experiment is restricted.
4. The test program has been planned so that the maximum speed of 5200 rpm is achieved in steps.

5. A control has been provided to shut down the experiment with one switch.

Also, access is available to the RSM at important locations, through removable windows for repairs or replacements without disassembly of the entire RSM.

7. Conclusions

At present, there is no experience in developing a turbo-machine similar to the GT-MHR TM, which has a long vertical and massive rotor that consists of two flexible rotors joined with a flexible coupling and supported by four radial and two axial EMBs. Thus, the RSM is a unique test facility, which, like the full-scale GT-MHR TM, has two flexible rotors with two bending speeds and a diaphragm coupling, and which enables testing of the vertical flexible rotor with electromagnetic suspension. These investigations will allow the development of a preoperational adjustment; the technology of control law refinement actual characteristics of the rotor, EMB and control system; the technology of rotor balancing in EMB. The tests will also enable obtaining experimental data for development work on EMB system and gaining the EMB system operational experience that will be used during the full-scale TC tests and during the TM standard operation.

Acknowledgements

This work was performed under General Order Agreement No. DE-G103-00SF22008 between the US Department of Energy National Nuclear Security Administration, OKBM and Rosatom of Russia. General Atomics is NNSA's technical support contractor under DE-AC52-07NA27328 for work being performed in Russia. Authors wish to thank P. Karcz and C. Peinado for management support of this work.

References

Baxi, C.B., et al., 2006. Evolution of PCU design of the GT-MHR. In: Proc. International Congress on the Advances in Nuclear Power Plants (ICAPP06), Reno, Nevada.

Baxi, C.B., et al., 2008. Evaluation of alternate power conversion unit designs for the GT-MHR. Nucl. Eng. Des. 238, 2995–3001.

Bilbow, W., xxxx. Electromagnetic Appeal, Engineered Systems. http://www.esmagazine.com/Articles/Feature_Article/9824792b19ba8010VgnVCM100000f932a8c0.

Chiba, A., xxxx. Magnetic bearings and bearingless drives. Newness, Elsevier, Amsterdam, London. http://www.worldcat.org/title/magnetic-bearings-and-bearingless-drives/oclc/57382090.

Guojun, Y., Li, W., Lei, Z., Suyuan, Y., 2004. Preliminary scheme design and analysis of catcher bearing for HTR-10GT. In: Proc. Second International Meeting on High Temperature Reactor Technology, Beijing, China.

Hittner, D., 2004. The European programme of development of HTR/VHTR technology. In: Proc. Second International Meeting on High Temperature Reactor Technology, Beijing, China.

Hsiao, F., Lee, A., 1994. An investigation of the characteristics of electromagnetic bearings using the finite element method. ASME Trans. J. Tribol. 116 (4), 710–719.

Ion, S., et al., 2004. Pebble bed modular reactor – the first generation IV reactor to be constructed. Nucl. Energy 43 (1), 55–62.

Kodochigov, N.G., Belov, S.Ye., Delfontsev, N.S., Tsybirev, S.V., 2005a. Modeling of GT-MHR turbomachine "flexible" rotor with full electromagnetic suspension. In: Proc. Seventh Workshop Mechatronical Systems, Zittau, Germany, pp. 41–48.

Kodochigov, N.G., Vostokov, V.S., Gorbunov, V.S., Khodykin, A.V., 2005b. Analysis of non-linear system describing magnetic suspension in view of cross relations between the magnets. In: Proc. of Seventh Workshop Mechatronical Systems, Zittau, Germany, pp. 49–54.

Koster, A., Matzner, H.D., Nicholsi, D.R., 2003. PBMR design for the future. Nucl. Eng. Des. 222, 231–245.

Kümmlee, H. et al., 2000. Design and experience with a 30,000 HP magnetic bearing supported motor driven turbo-compressor for a speed range of 600 to 6300 rpm. Presented at the TAMU Turbo Show, Austin, TX.

Kunitomi, K., et al., 2001. Design Study on Gas Turbine High Temperature Reactor (GTHTR300). Transactions, SMiRT 16, Washington, DC.

Li, W., Yang, X., Guojun, Y., Lei, Z., Xinxin, W., 2004. Impact analysis on the catcher bearing for the magnetic suspending rotor in HTR-10GT. In: Proc. Second International Meeting on High Temperature Reactor Technology, Beijing, China.

Mitenkov, F.M., et al., 2005. Electromagnetic suspension of vertical turbomachine for nuclear power plant. In: Proc. International Conference "Physics and Control", Saint Petersburg, Russia, pp. 146–151.

Pilat, A., 2004. FEMLab software applied to active magnetic bearing analysis. J. Appl. Math. Comput. Sci. 14 (4), 497–501.

Schmied, J., Pradetto, J.C., 1992. Behaviour of a one ton rotor being dropped into auxiliary bearings. In: Proc. of Third International Symposium on Magnetic Bearings, Alexandria, Virginia.

Schweitzer, G., 2002. Active magnetic bearings – chances and limitations. In: Proc. of the Sixth International IFToMM Conference on Rotor Dynamics, Sydney, Australia.

Schweitzer, G., Bleuler, H., Traxler, A., 1994. Active Magnetic Bearings – Basics, Properties and Applications of Active Magnetic Bearings. vdf Hochschulverlag AG an der ETH Zürlich.

Shi, L., et al., 2004. Design and experiments of the active magnetic bearing system for the HTR-10. In: Proc. Second International Meeting on High Temperature Reactor Technology, Beijing, China.

Xingzhong, D., et al., 2004. Design of the HTR-10 helium circulator with the active magnetic bearings. In: Proc. Second International Meeting on High Temperature Reactor Technology, Beijing, China.