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ROTOR SCALE MODEL TESTS FOR POWER CONVERSION UNIT OF GT-MHR

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ABSTRACT

A power-generating unit with the high-temperature helium reactor (GT-MHR) has a turbomachine (TM) that is intended for both conversion of coolant thermal energy into electric power in the direct gas-turbine cycle, and provision of helium circulation in the primary circuit.

The vertically oriented TM is placed in the central area of the power conversion unit (PCU). TM consists of a turbocompressor (TC) and a generator. Their rotors are joined with a diaphragm coupling and supported by electro-magnetic bearings (EMB).

The complexity and novelty of the task of the full electromagnetic suspension system development requires thorough stepwise experimental work, from small-scale physical models to full-scale specimen. On this purpose, the following is planned within the framework of the GT-MHR Project: investigations of the "flexible" rotor small-scale mockup with electro-magnetic bearings ("Minimockup" test facility); tests of the radial EMB; tests of the position sensors; tests of the TM rotor scale model; tests of the TM catcher bearings (CB) friction pairs; tests of the CB mockups; tests of EMB and CB pilot samples and investigation of the full-scale electromagnetic suspension system as a part of full-scale turbocompressor tests.

The rotor scale model (RSM) tests aim at investigation of dynamics of rotor supported by electromagnetic bearings to validate GT-MHR turbomachine serviceability.

Like the full-scale turbomachine rotor, the RSM consist of two parts: the generator rotor model and the turbocompressor rotor model that are joined with a coupling. Both flexible and rigid coupling options are tested. Each rotor is supported by one axial and two radial EMBs. The rotor is arranged vertically. The RSM rotor length is 10.54 m, and mass is 1171 kg. The designs of physical model elements, namely of the turbine, compressors, generator and exciter, are simplified and performed with account of rigid characteristics, which are identical to those of the full-scale turbomachine elements.

INTRODUCTION

A power-generating unit with the high-temperature helium reactor (Figure 1) has a TM that is intended for both conversion of coolant thermal energy into electric power in the direct gas-turbine cycle, and provision of helium circulation in the primary circuit.

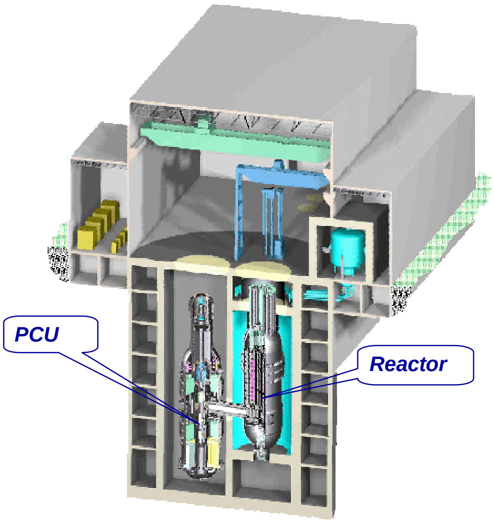


Figure 1 - GT-MHR plant

The TM (Figure 2) is placed in the central area of the PCU and consists of a TC and a generator. Their rotors are joined with a diaphragm coupling and supported by EMBs. Distinguishing features of the TM design are vertical positioning, the EMB system, flexible rotor, helium-cooled generator, significant electric power (287 MW), rotation speed 4400 rpm, rotor weight 67,7 t, rotor length 29 m.

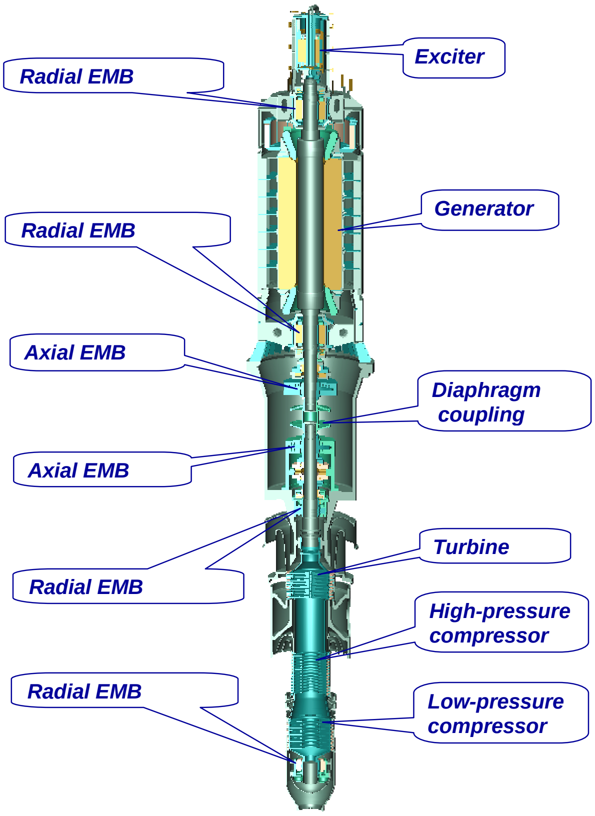


Figure 2 - GT-MHR turbomachine

The TM EMB system consists of two axial and four radial EMBs, the EMB control system, and CBs.

The use of EMBs in the TM makes it possible to:

- prevent lubricating oil and products of wear and tear from getting into the gas-turbine cycle;
- reduce bearing operational costs;
- actively influence the rotor dynamics to lower vibrations and to control rotor position.

Present-day achievements in the area of EMBs provided a well-founded basis for their selection as the TM support.

However, an EMB system relies on external power sources and control system to operate, and as a result, there is always a chance that power supply can be lost, resulting in the loss of all EMB functionality. This is the main problem with the use of any EMB system. Therefore, it is always necessary to include a system of catcher bearings (CBs), that provide safe operation of the TM:

- during a planned switch off of an EMB when the TM rotor is stopped;
- in case of EMB failure during TM operation for rotor "coast down";
- at dynamic loads surpassing EMB load-bearing capacity.

In order to reduce the loads on EMBs and CBs, TC and generator rotors are connected through a diaphragm coupling.

Maximum load-bearing capacity of the state-of-the-art EMBs (S2M, Waukesha Bearings etc.) is 80 kN for the radial and 350 kN for the axial bearings [1-23]. The maximum expected loads on the GT-MHR TM EMBs are 34 and 350 kN respectively.

Experimental study of electromagnet support systems

The complexity and novelty of the task of the full electromagnetic suspension system development requires thorough stepwise experimental work, from small-scale physical models to full-scale specimen. On this purpose, the following is planned within the framework of the GT-MHR Project: investigations of the "flexible" rotor small-scale mockup with electro-magnetic bearings ("Minimockup" test facility); tests of the radial EMBs; tests of the position sensors; tests of the TM rotor scale model; tests of the TM CB friction pairs; definition of gas-static characteristics of the TM CB axial segment; tests of the CB mockups; tests of EMB and CB pilot samples and investigation of the full-scale electromagnetic suspension system as a part of full-scale turbocompressor tests. The logic diagram of GT-MHR TM EMB support system development is presented in Figure 3. The results of these activities will be used for validation of the TM full electromagnetic suspension design and control system, as well as for verification of calculation methodologies.

The following activities have been performed as a part of experimental studies of the EMB system:

- Tests of the small-scale test facility "Minimockup" with a flexible rotor and the full electromagnetic suspension system (Figure 4).

The Minimockup tests were a means of gaining experience in the design and operation of a full electromagnetic suspension system. The Minimockup tests provide the initial basis for development and validation of analytical methods and computer codes that will be used by OKBM for RSM development [20, 21].

The Minimockup consists of a casing and a rotor that is supported on one axial and two radial EMBs. The Minimockup rotor is vertical. In the rotor lower part there is an asynchronous motor that is powered from a frequency converter. The test facility incorporates a control system that consists of power modules, a controller, a measurement data system, a sensor signal converter.

The Minimockup vertical rotor is flexible. The rotor has two critical speeds in the range of rotation speed (0 through 6000 rpm).

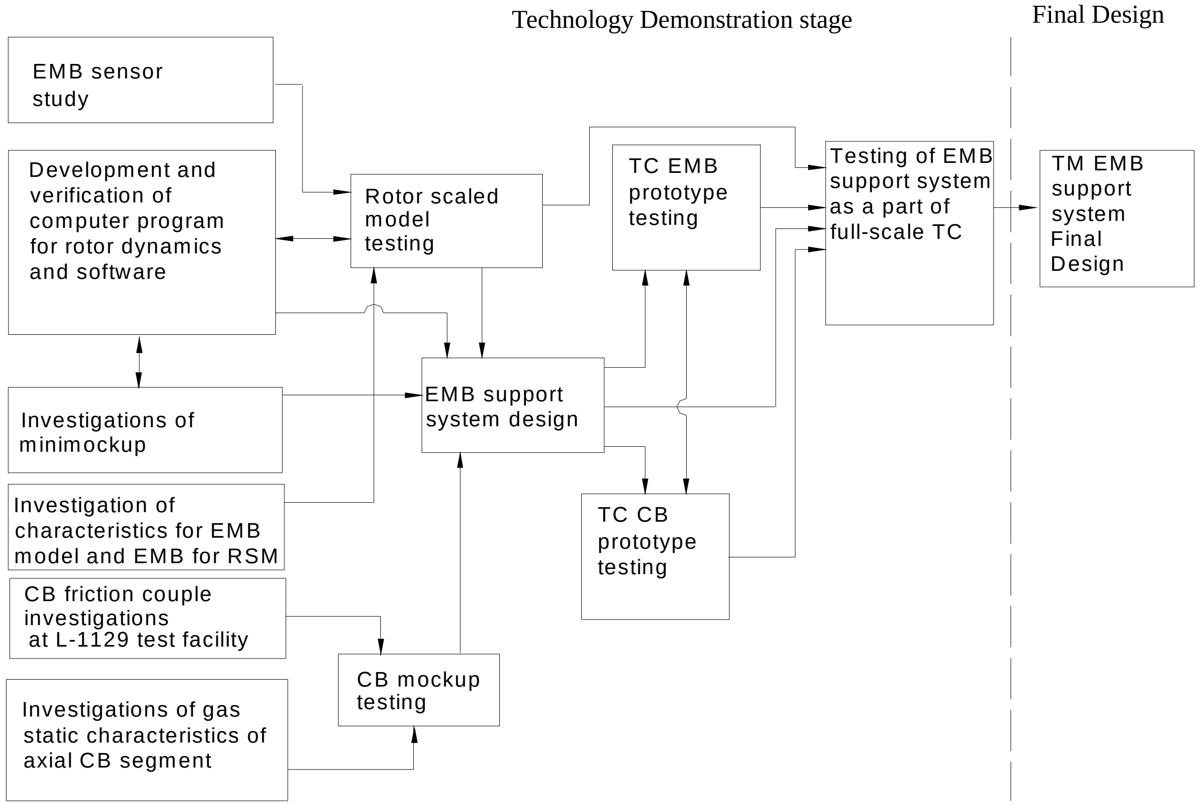


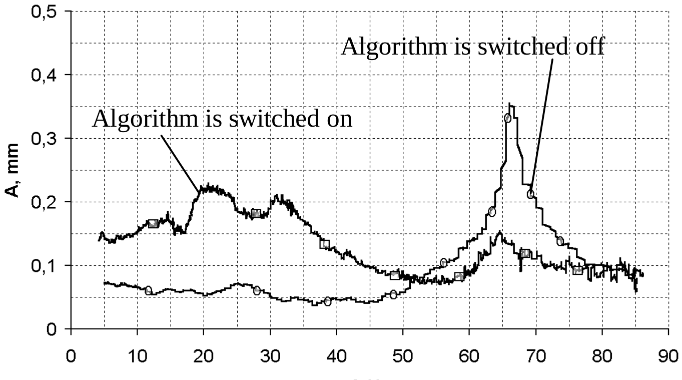
Figure 3 - Electromagnetic Bearings Support System Technology Development Logic Diagram.

Main technical characteristics of Minimockup Test Facility:

- rotor weight …………….…………..…….14,7 kg;
- rotor length ……………………………………0.7 m;
- rotor rotation speed ……..………..…up to 10000 rpm.

Figure 4 – "Minimockup" test facility

Extensive research has been carried out using the Minimockup to characterize the influence of the physical properties of the machine and various parameters related to the control and power electronic amplifier sections. In its original form, the Minimockup has been operated through and above the first bending critical speed. Stability zones have been identified and adaptive control techniques have been explored (Figure 5).



(maximum near 65 Hz – first bending mode)

Figure 5 - Adaptive control example

Now, the Minimockup Test Facility has been upgraded and tests have been performed at the speed to and beyond the fourth critical speed (second bending mode). The upgrade involved modification of the rotor and an increase in load-bearing capacity of the EMBs. Further, it is planned to continue tests at Minimockup Test Facility to study some effects that can happen during TM operation and to finalize various methods of rotor balancing in EMB.

The following results were obtained on the Minimockup Test Facility:

- methods were studied of the flexible rotor stabilization in the vertical electromagnetic suspension system at corresponding to the rotor own rotation speeds;
- elements of methodology of the flexible rotor balancing in the vertical electromagnetic suspension system were mastered, including the virtual methodology (by inclusion of a specially developed algorithm) and physical methodology (by mounting the balancing weights in the correction planes);
- data were obtained for verification of calculating codes that are used for calculations of the TM rotor dynamics in the GT-MHR design.

- Tests of EMB position sensors were conducted. Different alternative designs were studied; sensitivity characteristics were defined depending on physical properties (induction, resistance, magnetic conductivity) and operation parameters (speed, width, gap). The test results became the initial data for development of the bearings and control system. The sensor test facility is shown in Figure 6.

Figure 6 – Test facility for rotor EMB position sensors

- Tests were conducted of the radial EMB model that made possible the experimental defining of characteristics of the radial EMB and load-bearing components of the control system. Further, the test facility (Figure 7) will be used for obtaining experimental characteristics of EMB together with the control system of the turbomachine rotor scale model.

The next stage of the rotor EMB support system experimental studies in progress will be tests of the GT-MHR turbomachine RSM.

Figure 7 - Test facility for Radial EMB model

RSM tests

The RSM consists of two parts (Figure 8) – the generator rotor model and the turbocompressor rotor model that are joined with a flexible or rigid coupling. The rotor axis is placed vertically.

The designs of physical model elements, namely of the turbine, compressors, generator and exciter are simplified and performed with account of rigid characteristics, which are identical to those of the full-scale turbomachine elements.

RSM main technical characteristics:

- rotor total weight ….…..……………...…… 1171 kg;
- rotor total length….………..………………. 10.54 m;
- rotor rotation speed …….….…….… up to 6000 rpm;
- load-bearing capacity of the radial EMB, not less than………………………………………………...… 250 kg;
- load-bearing capacity of the axial EMB, not less than ……………………………………..….... 2000 kg.

The RSM incorporates sensors of rotation speed, rotation angle and vibration.

Electromagnetic sensors of rotor position control are used to continuously measure the gaps between the rotor and the axial and radial EMP electromagnets.

Additionally, to control rotor displacement in the horizontal plane at various points along the height, inductive sensors are supposed to be used.

Four radial and two axial EMBs together with the control system form the electromagnetic suspension system of the rotor model. Each EMB is equipped with a catcher ball bearing.

Bearing cooling is effected by means of forced circulation of air.

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 of the rotor position within the areas of the allowed rotor displacements during the inner disturbances and force impacts in all test modes.

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

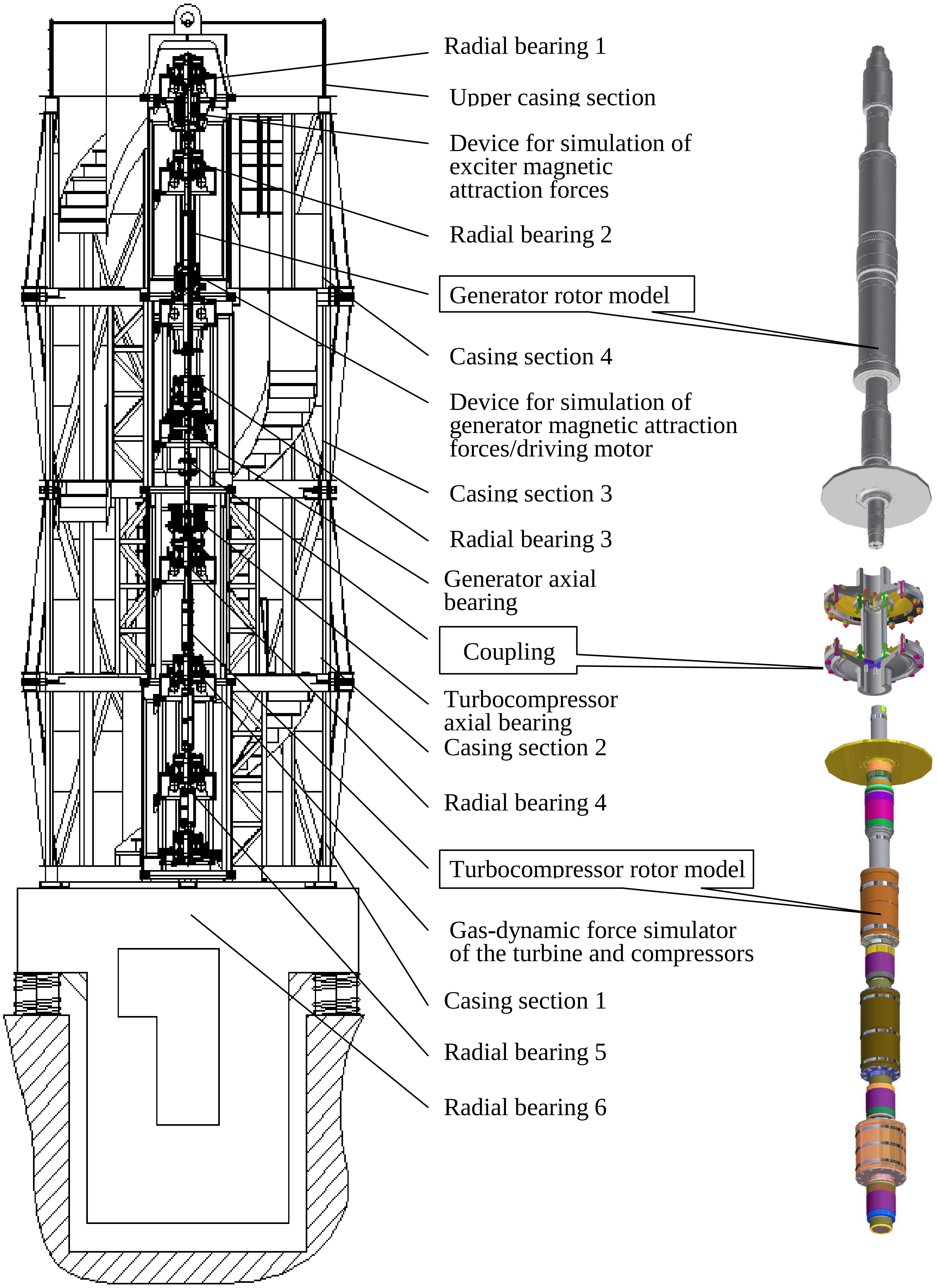


Figure 8 - Rotor Scale Model

The generator rotor model consists of two electric motor rotors that were selected with account of the possibility to scale magnetic attraction forces of the full-scale turbomachine main generator and exciter. The motors ensure the model rotor rotation speed in the range from 10 to 6000 rpm with slide control by means of the frequency converter.

The RSM casing is installed on a vibroinsulating foundation.

Experimental studies of RSM will make possible to:

- investigate rotation speed influence on operation of the rotor and control system including rotor behavior at several critical speeds and during operation at near to critical speeds;
- investigate a possibility to balance the rotor in EMB and damp rotor bending oscillations at critical speeds;
- investigate the impact of different changes in the turbomachine design upon rotor and turbomachine operation including: the change in the number of EMBs, location of bearings and stiffness of stator structures, influence of the rotor coupling type (rigid or flexible), deflection of different structure elements from the specified alignment (bearings, generator stators, turbine and compressors);
- investigate the impact of different force factors upon 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;
- verify calculating procedures of the rotor dynamics basing on the obtained experimental data.

The main task of RSM development is verification of calculating procedures and programs, mastering of software and fundamental design solutions.

The factors influencing the turbomachine were taken into account to the maximum extent during development of RSM.

The scaling factors connect parameters of full-scale turbomachine rotor with corresponding parameters of RSM:

$$\lambda_E = \frac{E_H}{E_M}; \lambda_\rho = \frac{\rho_H}{\rho_M};$$

$$\lambda_d = \frac{d_H}{d_M}; \ \lambda_l = \frac{l_H}{l_M}; \ \lambda_m = \frac{m_H}{m_M} \qquad (1)$$

where λ_E - elastic modulus of the rotor material;

λ_ρ - scaling ratio of rotor material density;

λ_d - scaling ratio of the rotor in relation to the diameter;

λ_l - scaling ratio of the rotor in relation to the length;

λ_m - scaling ratio of weights of any area of the rotor;

E_H; E_M - elastic modulus of the full-scale and model rotors respectively;

ρ_H; ρ_M - density of material of the full-scale and model rotors respectively;

d_H; d_M - diameters of corresponding areas of the full-scale and model rotors respectively;

l_H; l_M - lengths of corresponding areas of the full-scale and model rotors respectively;

m_H; m_M - weights of corresponding areas of the full-scale and model rotors respectively.

Identity of rotation speed characteristics of the full-scale and model rotors is provided by the following correlations between scaling ratios:

$$\frac{\lambda_E \bullet \lambda_d^2}{\lambda_\rho \bullet \lambda_l^4} = 1 \qquad (2)$$

Correlation between diameters and lengths of rotor areas can be defined on condition that the same materials are used for the full-scale and model rotors:

$$\lambda_l = \sqrt{\lambda_d} \qquad (3)$$

The following preliminary values of scaling ratios were accepted:

Diameter - λ_d = 5.52; Length - λ_l = 2.35; Weights - λ_m = 57.8. The rotor model design is simplified. However, model rotor rigid characteristics correspond to those of full-scale rotor. The electromagnetic bearing system, which forms the full electromagnetic suspension, corresponds to that of the full-scale turbomachine in the number, location, rotation speed range and the manner of force interaction with the rotor.

Fabrication of RSM and the test facility will be completed in 2008 (Figure 9 presents a number of RSM components that have been fabricated by 2008). Tests are planned to be started in early 2009.

Conclusion

Nowadays, in the world there is no experience in developing machinery similar to the GT-MHR TM, which have a vertical long and massive rotor that consists of two flexible rotors joined with a flexible coupling and supported by four radial and two axial EMBs. Thus, it is worth mentioning that OKBM is creating 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 makes possible to test the vertical flexible rotor with electromagnetic suspension. These investigations will make possible to master the procedure of preoperational adjustment; the technology of control law refinement with account of factual characteristics of the rotor, EMB and control system; the technology of rotor balancing in EMB; as well as to obtain experimental data for development work on EMB system and to gain EMB system operational experience that will be used during the full-scale TC tests and during TM standard operation.

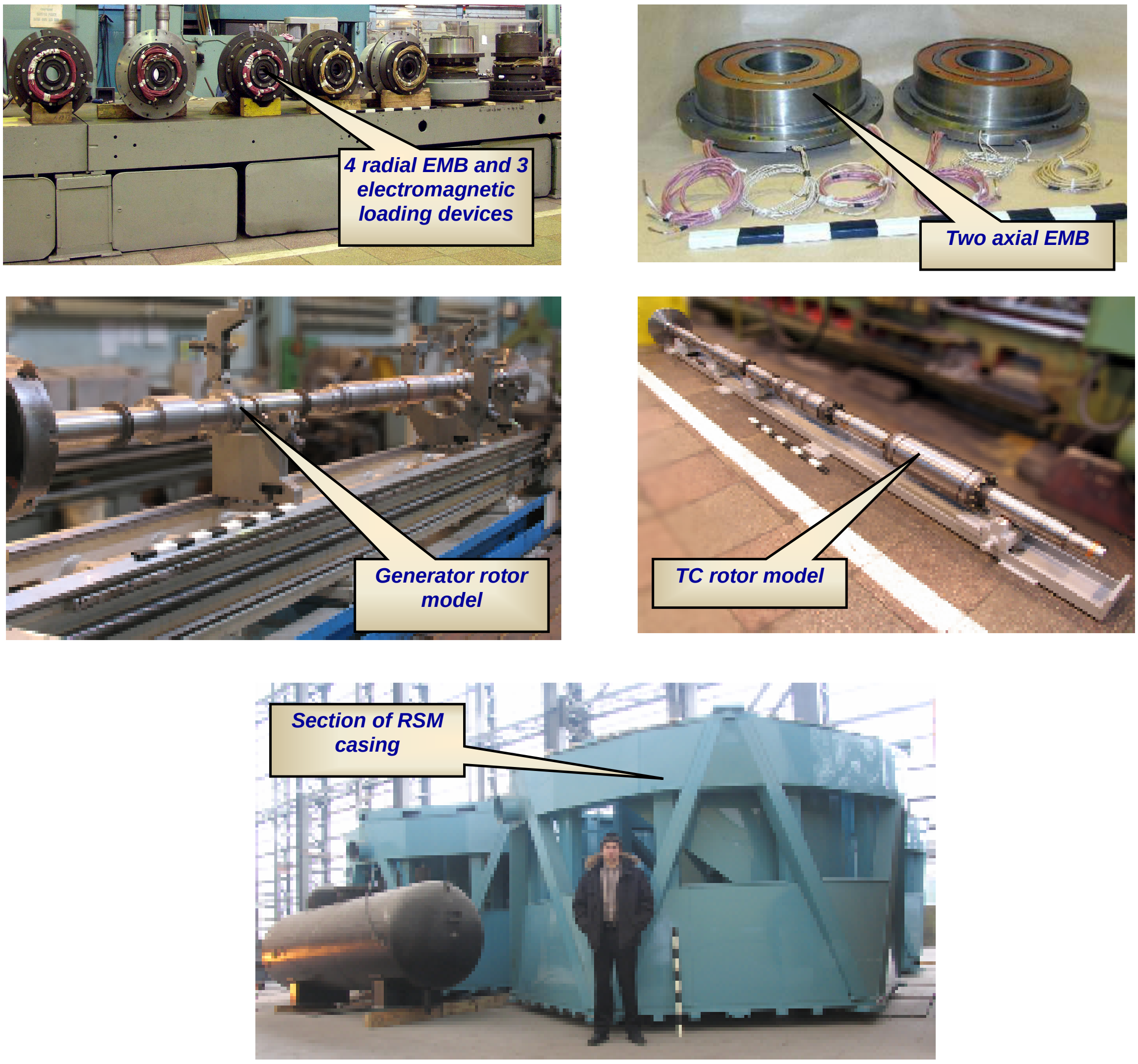


Figure 9 - RSM components

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