ACTIVE MAGNETIC BEARINGS FOR ROTATING MACHINERY IN FUTURE GAS COOLED REACTOR PLANTS

J Alastair Rennie
James Howden & Co. Ltd., Renfrew UK

Colin F McDonald
General Atomics, San Diego, California USA

ABSTRACT

In the past, the bearing options available to circulator designers have been essentially limited to gas and oil lubricated systems. In the case of the former, a technological limitation in size has restricted their use to small auxiliary systems. Oil-lubricated bearings are the mainstay of the industry, and many of the circulators operating in the carbon dioxide cooled reactors in the United Kingdom will see service into the second decade of the next century. However this technology (developed in the 1960's) has been superseded by recent bearing advancements, namely the introduction of active magnetic bearings in heavy duty rotating machinery.

For the next generation of gas-cooled reactors, namely the modular helium reactor (MHR), the long-term goal of a practical lubricant-free system will be realised with the utilisation of magnetic bearings. This paper covers work done to date on magnetic bearings for helium systems and includes design studies for large machines, experimental testing of vertical rotor systems, and the design and fabrication of a high speed, 10 kWe induction motor drive.

The development work done to date is shown to be supportive of vertical rotating machinery needed in future gas cooled reactors, and other potential applications, including the following:-

1) helium turbomachine for the gas turbine plant (GT-MHR)
2) main and secondary system circulators for the future plants involving direct and intermediate helium loops (e.g. high temperature nuclear process heat)
3) shutdown cooling circulator, and
4) rotating machinery in auxiliary systems (e.g. helium purification, gas buffer supply)

The magnetic bearing technology base to facilitate near-term deployment of the MHR is emphasised in this paper.

BACKGROUND

Nuclear reactors which use gas as the primary coolant (rather than water) have been used very effectively to produce power. In the United Kingdom, a significant number of MAGNOX and Advanced Gas-cooled Reactors (AGR's) have been built, both of which use carbon dioxide at high pressure as the primary coolant. A schematic diagram of one such reactor system is shown in Figure 1, highlighting the *main gas circulator* which circulates the CO_2 around the primary loop. These gas circulators are large, with a shaft power of around 6MW, and relatively slow, with a fixed speed around 3000 rpm.

For the MHR, a new, more efficient, more flexible, gas circulator is required, one which meets the sophisticated plant operation requirements as well as providing the reliability expected of such a major piece of the plant.

CONVENTIONAL GAS CIRCULATORS

The gas circulators used in the AGR's are complex machines specifically developed for that particular application [1,2]. However, at the time they were built, there were technical limitations to the design, which imposed limitations on the reactor system. Of particular note, the bearings used were oil lubricated bearings and reliable variable speed, high speed drives were not available for that power.

The oil bearings require complex re-lubrication and sealing systems to control the oil in the circulator compartment, because significant egress of oil would be a problem for the reactor system. The circulator compartment is separated from the reactor primary circuit by a labyrinth seal and buffer gas system. So, together the lubrication system and buffer gas system add significant complexity and costs to the gas circulator system, as well as added problems of disposal of contaminated used oil and filters. The elimination of these systems would be of significant benefit to the end users of the circulators.

MHR MAIN GAS CIRCULATOR

Significant design and development of the main gas circulator has been carried out in support of the MHR steam cycle plant [3,4]. The proposed design was for a modular reactor of around 350 MW thermal with 135 MW electrical (plant efficiency of 38%). For this reactor system, design studies led to a high speed (6000rpm, 6MW) gas circulator, to be installed in the steam generator vessel, with the following features (Figure 2):

1) vertical assembly
2) submerged induction motor drive
3) 2 stage axial flow impeller
4) active magnetic bearings

Apart from the use of magnetic bearings, the circulator concept was virtually the same as the design for the AGR's. Typical design data are presented in Table 1.

In 1993 a decision was made to proceed with a gas turbine modular helium reactor (GT-MHR) for electrical power generation in preference to the steam cycle above. Therefore, work on the steam cycle plant in the USA was discontinued at that time.

It is projected that early in the next century, ever demanding environmental considerations will lead to the utilisation of an advanced MHR for nuclear process heat [5]. In this reactor, an intermediate heat exchanger (IHX) will facilitate the use of pollution-free nuclear generated heat for the production of hydrogen, initially by steam methane reforming, and later by the fossil-free thermo-chemical water splitting process.

The *main circulator* will be a key component in the reactor primary system, to transport the thermal energy, via the IHX to the process system. The features of the *main circulator* for this plant will follow those identified above for the steam cycle plant.

SHUTDOWN COOLING SYSTEM CIRCULATOR

In all of the MHR plant concepts investigated a shutdown cooling system has been included in the design. This system consists of a small gas circulator and heat exchanger installed in the lower plane of the reactor vessel. Details of a representative circulator have been discussed previously [6] with the concepts and features (Figure 3) similar to those of the *main circulator*, namely :

1) vertical assembly
2) submerged induction motor drive
3) centrifugal flow impeller
4) active magnetic bearings

The design philosophy of both the main and shutdown circulators is the same and a similar implementation of the magnetic bearings has been proposed. Typical design data are presented in Table 2.

GAS TURBINE POWER CONVERSION

The GT-MHR is a second-generation nuclear power plant with a meltdown proof reactor and a high efficiency prime-mover based on proven technology. The power conversion system is based on an inter-cooled and recuperated closed Brayton cycle with a projected efficiency of 47% for the initial unit that could be in utility service in the first decade of the next century.

The power conversion system for the GT-MHR is shown on Figure 4, and details of the integration of the components within the vessel have been presented previously [7]. The major component installed on the centre line of the vessel is the vertical single shaft, 286 MWe helium turbine which drives the synchronous generator. The rotating assembly (Figure 5) consists of two compressor sections (separated to facilitate inter-cooling), the turbine, and a submerged helium-cooled generator, and has been discussed previously [8].

The entire rotor (weighing 50 tons) including the generator is supported by an active magnetic bearing system. Magnetic bearings is a key technology for rotating machinery in all closed helium systems [9]. The initial modelling of the rotor system has been based on the utilisation of a five journal bearing system. The thrust bearing (and upper journal bearing) assembly is positioned above the generator for ease of access. A lightweight and rigid rotor construction, resembling aero-engine practice, was chosen to minimise weight and ease critical speed concerns. Rotor dynamic analysis work continues with a goal of reducing the number of bearings.

The magnetic bearing system incorporates considerable redundancy, the primary bearings being backed-up by a second set of bearings powered by an un-interuptable power source. Mechanical anti-friction bearings are also incorporated to prevent rotor damage in the unlikely event that both magnetic fields are lost.

While the rotor is heavier than in applications to date, the thrust unit loads and peripheral velocities are bounded by operating experience. In recent years there has been substantial use of magnetic bearings in industrial applications, and today over eight million hours of operating time has been accumulated on active magnetic bearings Over 150 large turbomachines (e.g. gas compressors, turbines, turboexpanders) have run for more than 1.5 million hours, and the GT-MHR machine will take advantage of this technology base. Tests of the GT-MHR turbomachine bearing system will be undertaken in a representative helium environment, to cover the full spectrum of plant operation (i.e. steady state, transient, start-up, shutdown, and upset events) before fabrication of the complete prototype machine.

AUXILIARY SYSTEMS AND OTHER BLOWERS

James Howden & Co. Ltd. and other Howden Group companies have a number of machines throughout the world operating with magnetic bearings, which provides support for the proposals to use magnetic bearings in the gas cooled reactors. The more recent activities are the retro-fit of magnetic bearings to a Howden fan in the USA [10], and the development of a small high speed blower for auxiliary helium systems [11], (Figures 6 & 7).

The "retro-fit" fan has a shaft weight of some 10 tonnes, runs at 890 rpm and has a shaft power of around 2500 kW. At the opposite end of the scale, the auxiliary system blower has a shaft weight of around 10 kg, runs anywhere between 1000 rpm and 24,000 rpm and has a shaft power of around 10 kW.

MAGNETIC BEARING DEVELOPMENT

Background The application of magnetic bearings to large rotating machinery requires the implementation of an effective catcher bearing system to contain the rotor in the event of failure of the magnetic bearings. The development of magnetic bearings for large gas circulators for the MHR was assisted by the concurrent development of catcher bearings for this environment.

James Howden & Co. Ltd., with Support from The Electric Power Research Institute (EPRI, under contract reference RP2079-16) in the USA embarked on a series of design studies and tests to demonstrate that adequate catcher bearings could be developed for use in the MHR. The work is reported in [12, 13, 14].

Rotor Stability Studies At a very early stage in the conceptual design of vertical shaft gas circulators incorporating active magnetic bearings, it was realised that the rotor could behave in an unstable manner when released without restraint into wide clearance journal bearings following failure of the magnetic bearing system. It is of note that there is evidence in support of this instability happening in real systems [15, 16].

The specific form of instability, brought about by a high speed orbital motion generated in the bottom journal bearing was analysed in a simplistic way, leading to the concern that there was a potential for large forces to be generated. Unless quantified and dealt with, the concern over this form of rotor instability could have remained as an impediment to any final design.

Theoretical modelling and quasi-analog computer simulation were carried out to examine the behaviour of the shaft system. Meanwhile, a quarter scale physical model confirmed the general form of behaviour shown by the computer simulation model. A typical energy plot from the computer model is shown in Figure 8, which was used in the comparison between theory and the scale model. The work concluded that the behaviour of the shaft was dependant on the value of the rolling resistance between the bearing and the shaft. Consequently, the conclusion drawn from the work carried out is that the rotor behaviour in a full size machine can be kept very adequately under control, the primary control device being an engineered rolling resistance within the bearing system.

It is of note that the final computer model has the capability of reproducing the orbit initiation process for a range of selected shaft release conditions and has the capability of reproducing the final steady state orbit speed and radial loads for any given set of system parameters.

Drop Tests The combination of environmental and operating conditions for the catcher bearing are known to be severe, with bearings subjected to excessive loads and speeds in an extremely dry helium atmosphere. Conditions of contact and wear are particularly arduous in this atmosphere and theoretical analysis techniques are not sufficiently robust to model all of the relevant behaviour accurately. The only option available to prove that the catcher bearing system worked satisfactorily was to carry out experimental testing.

A number of studies were carried out for the "thrust catcher bearing" concept, some based on analysis and others on previous experience of wear, contact or operation in a similar environment. The analytical investigations were centred on computing contact loads, frictional coefficients, dynamic response during contact and instability of rubbing surfaces. The investigations on wear, contact and operation looked at the various materials, surface coatings, greases and rubbing surface combinations which could be used effectively in the dry helium environment.

These investigations for the thrust bearing indicated that the more probable solution would be based on an angular contact ball bearing (as opposed to a plain thrust or roller bearing). The complete catcher bearing system would comprise an angular contact bearing supported at the outer ring in a stationary housing. A clutch ring and carrier would be mounted in the bearing inner ring. Upon failure of the magnetic bearing, the shaft would drop onto the stationary clutch ring and accelerate it to shaft speed (in a few milliseconds). The shaft would thereafter be supported by the angular contact ball bearing as it is brought to rest (4 - 30 seconds for normal operation, >30 minutes possibly for concurrent failure of regenerative braking while at atmospheric pressure).

A significant number of options for bearing materials, special coatings, lubricants and rubbing surfaces (clutch) were examined. These ranged from standard or freely available or commonly used to those for very specialised applications. The preference for selection was to obtain the most readily attainable components or processes which would satisfy the needs of the MHR gas circulator. On this basis, two most promising options for each of the bearings, lubricant and rubbing surfaces were selected for testing.

The development testing, when completed, led to the identification of a suitable catcher bearing system, of both geometry and materials, that met an MHR requirement of a minimum of 20 full speed rotor drops without failure. For the selected configuration, 27 rotor drops were completed before a failure mechanism was noticed. With further development, it is projected that the bearing system could be improved to achieve an even greater life for the catcher bearing system.

Signal Noise Tests Development work was proposed to determine the difficulties likely to be encountered in getting control signals from active magnetic bearing position sensors from within the pressure boundary to the control cabinet.

At that time, no experience existed of mounting active magnetic bearings on large, variable speed, electric motors or generators mounted within the reactors primary circuit. The concern arose from experience of bringing out signals from shaft vibration and position transducers in the AGR circulators, where random noise had proved difficult to control. The problem then was overcome by fitting filters to cut off frequencies above 1500 Hz and biasing to remove anomalies from shaft out-of-roundness. It was therefore of concern that an apparently similar system would be used in the control of the magnetic bearings, but one which would not readily lend itself to the use of similar low-pass filters to solve signal noise problems.

The primary task was to assess what magnitude of interference in the signal cables returning to the magnetic bearing control system was tolerable over a wide range of noise frequencies. A scale model bearing, of the type proposed for the MHR circulators, was built into a test rig and subjected to noise interference in the signal cables. Levels of signal noise well in excess of those expected for the gas circulator motor were put into the sensor cables.

The bearing model tests demonstrated that the magnetic bearing control and sensor system was unaffected by having them in close proximity to significant disturbing electrical fields, such as those from large, variable speed electrical drives. However, as with the AGR's, the MHR requires special designs of the electrical penetrations (based on those of the AGR's) to take the signals through the pressure boundary, thereby ensuring adequate shielding and isolation of signals.

SUMMARY AND CONCLUSIONS

The formidable magnetic bearing technology base for conventional industrial rotating machinery has been enhanced by design, analysis and development testing specifically for machines operating in a helium environment. For the next generation of gas-cooled reactors a high degree of confidence exists that the rotating machinery, supported on active magnetic bearing systems, will operate with high reliability and will exhibit near maintenance-free service for the life of the plant.

Table 1. Main Gas Circulator Design Data

Speed	6000 rpm	Power	6MW
Axial Bearing Loading		Radial Bearing Loading	
Normal	Peak	Normal	Peak
4,000 N	29,000 N	25,000 N	72,000 N

Table 2. Shutdown System Circulator Design Data

Speed	4000 rpm	Power	150 kW
Axial Bearing Loading		Radial Bearing Loading	
Normal	Peak	Normal	Peak
2,500 N	10,000 N	3000 N	10,000N

REFERENCES

1 Fraser, W M, "Trends in Design of Blowers for Gas-cooled Reactors", Proceedings of Institution of Mechanical Engineers, Vol. 181, Pt. 31, pp. 102-110, 1966

2 Fraser, W M, "A Review of Submerged Gas Circulators as applied to Advanced Gas-Cooled Reactors", Nuclear Energy, No. 24, pp. 321-326, 1985.

3 Donaldson, J, "Application of Magnetic Bearings to Helium Circulators for High Temperature Gas-cooled Reactors", Paper 879419, Proceedings of 22nd. IECEC, 1987

4 McDonald, C F, et al, "Circulator Design/Technology Evolution for Gas Cooled Reactors", ASME Paper 92-GT-79.

5 McDonald, C F, "Multi-Purpose Nuclear Heat Source for Advanced Gas-Cooled Reactor Plants", Proceedings of 28th IECEC, August 8-13, 1993, Vol. 1, pp. 2.98 - 2.98.

6 McDonald, C F, "Shutdown Cooling Helium Circulator Design Considerations for MHTGR Power Plant", ASME Paper 89-WA/NE-5.

7 McDonald, C F et al, "GT-MHR Gas Turbine Power Conversion System Design and Development", Proceedings of American Power Conference, April 1994, Vol. 56-1, pp. 518-523.

8 McDonald, C F, et al, "Helium Turbomachine Design for GT-MHR Power Plant", Paper to be presented at International Joint Power Generation Conference, October 8-13 1994, Phoenix, Arizona.

9 McDonald, C F, "Active Magnetic Bearings for Gas Turbomachinery in Closed-Cycle Power Plant Systems", ASME paper 88-GT-156.

10 Jones, G, Connelly Jr. and J H, Schmidt, D.W., "Active Magnetic Bearings on a Large Utility Fan", Proceedings of Power-Gen '93 Conference, November 17-19, 1993, Dallas, Texas, USA.

11 Mhango, L M C and Rennie, J A, "Recent Developments and Benefits of High-Speed PWM Inverter-Fed Induction Motor Drive for Gas Filtration in Nuclear Power Plants", 6th International Conference on Electrical Machines and Drives, Oxford, October 1993.

12 Fraser, W M, "Catcher Bearing Development and Test", EPRI Report developed under contract reference RP2079/16, December 1988.

13 Fraser, W M, "Catcher Bearing Development and Test", EPRI Report developed under contract reference RP2079/16, December 1989.

14 Rennie, J A, "Final Report on Thrust Catcher Bearing Tests", EPRI Report developed under contract reference RP2079/16, June 1991.

15 Kirk, R G and Ishii, T, "Transient Rotor Drop Analysis of Rotors Following Magnetic Bearing Power Outage", Virginia Polytechnic Institute and State University, July 1993.

16 EPRI Report, "A Review of the Status of Auxiliary Bearing Development for Magnetic Bearing Installations in Electric Utility Applications", developed under contract reference RP 3319-03.

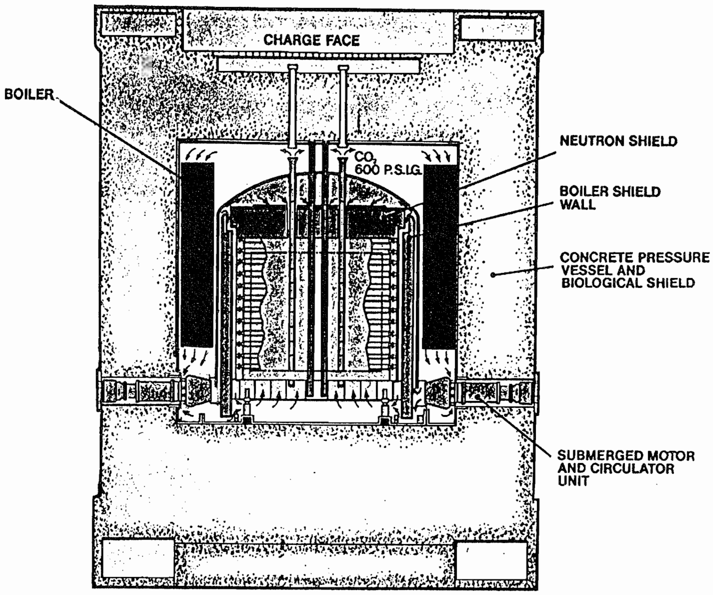

Figure 1 - Schematic Diagram of Gas Cooled Reactor

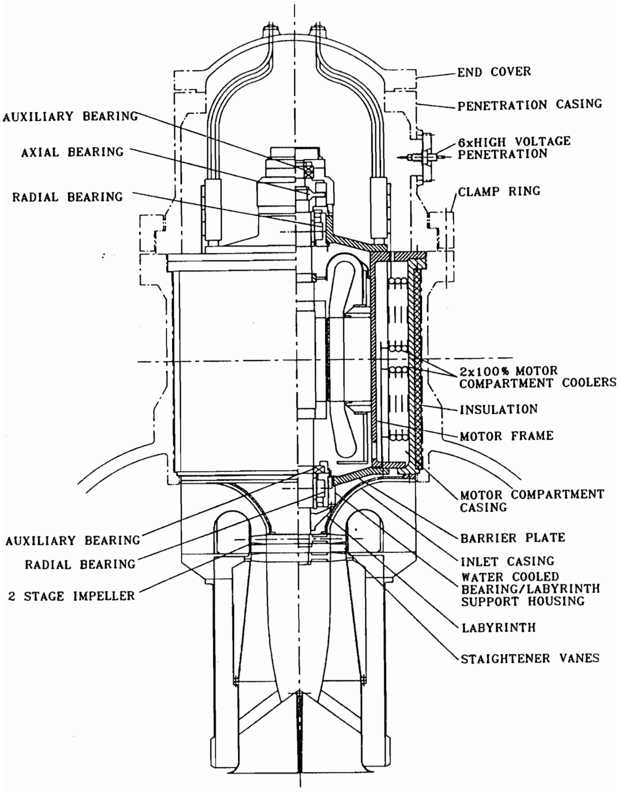

Figure 2 - Layout of Main Gas Circulator

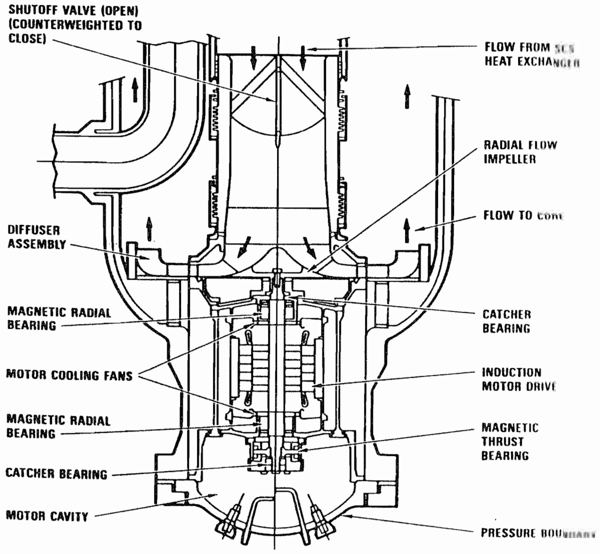

Figure 3 - Layout of Shutdown System Circulator

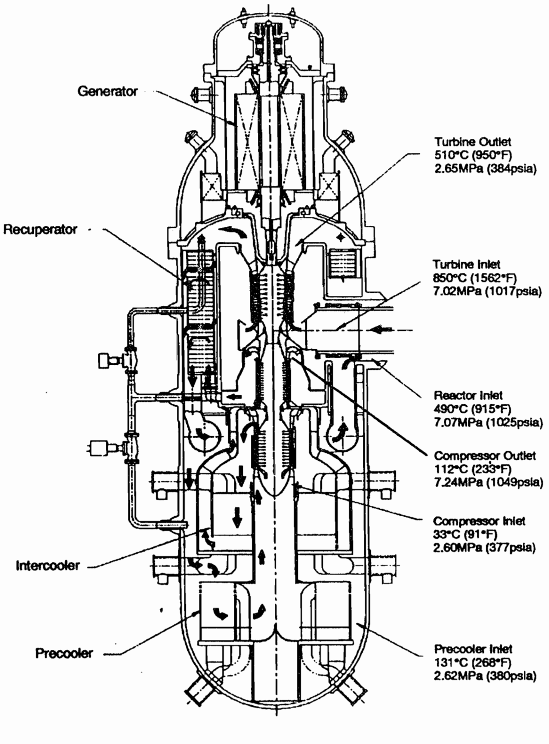

Figure 4 - GT-MHR Power Conversion Set

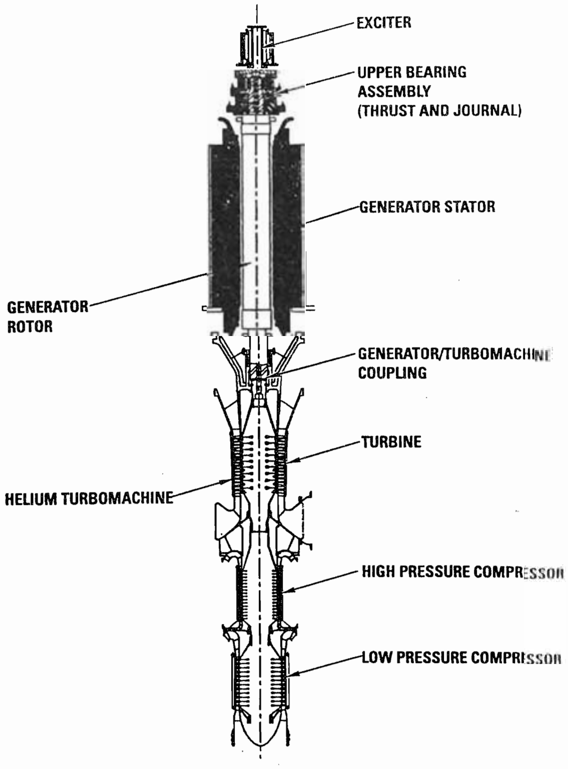

Figure 5 - GT-MHR Rotor Assembly

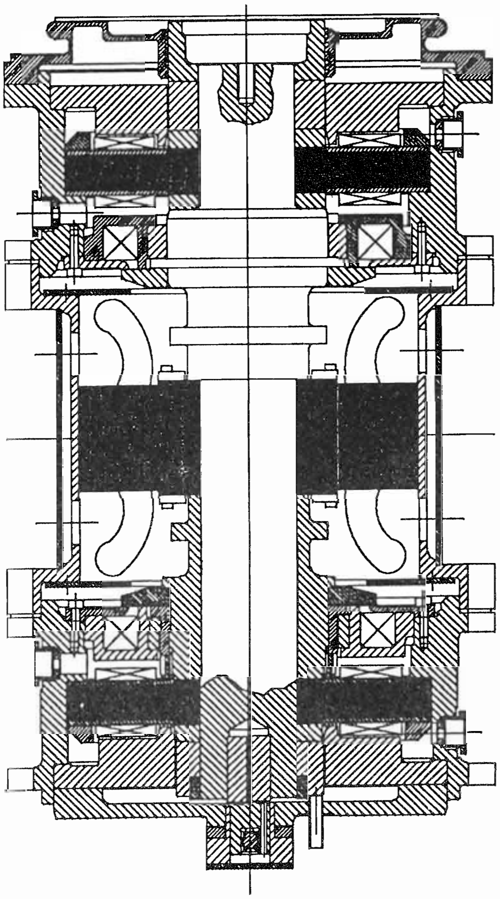

Figure 6 - Section Through Auxiliary Blower

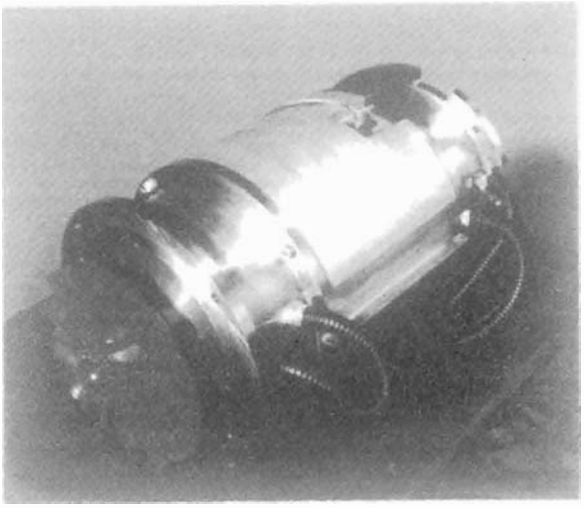

Figure 7 - Auxiliary Blower Photograph

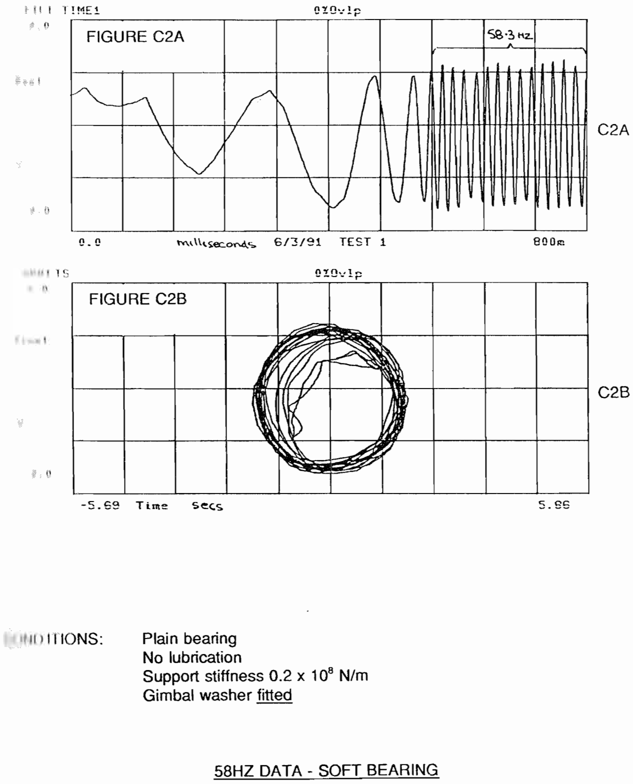

Figure 8 - Bearing Rotor Stability Plot

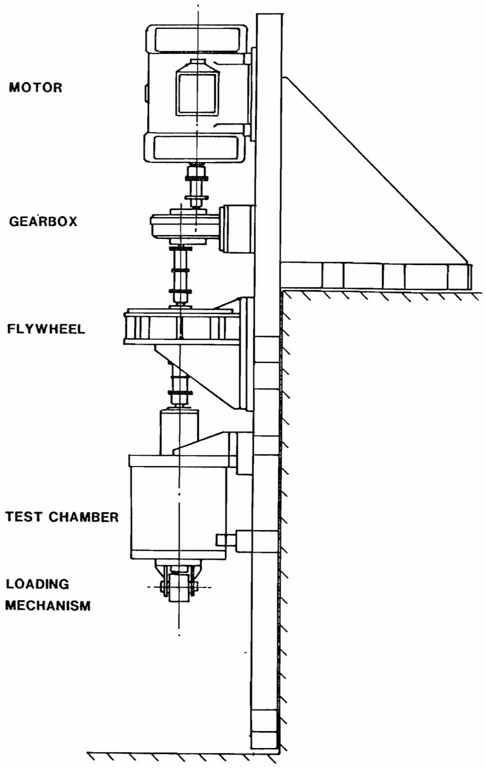

Figure 9 - EPRI Rotor Drop Test Rig