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STATE-OF-THE-ART OF
GAS-BEARING TURBOMACHINERY

by

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TECHNICAL REPORT

No. MTI-65TR5-I

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1. FOREWORD

The current status of gas lubrication is one of transition from research to application. In 1950, activity in gas lubrication was limited to very few universities, research institutes and research departments of industrial companies. In contrast, a world-wide survey conducted by Mechanical Technology Inc., in 1963 (Ref.1), showed that more than 500 organizations were either active in gas lubrication or were assessing the applicability of gas bearings in their products. More recently, in January 1965, the Franklin Institute issued a report (based on answers received to a questionnaire) on the activities in gas bearing research of 74 organizations in this country and in Western and Central Europe, (Ref. 2). A review of this work indicates that, in the majority of cases, it is directed towards development of specific gas bearing supported equipment. Furthermore, there are in current operation a wide variety of such gas bearing supported equipment including gas circulators for reactor loops, inertial guidance instruments, environmental simulation tables, precision spindles and many others. In January 1965, a new milestone was reached, when the first gas bearing supported gas-turbine was run in a closed loop. It achieved self sustaining operation and delivered, to date, surplus power corresponding to 15 KW (Ref. 3). In a test program currently in progress, the power output is being increased to 30 KW.

The rapid growth of gas bearing technology from research to application has been stimulated in large part by the Gas Bearing Technology Program administered by the Office of Naval Research and jointly sponsored by several agencies of the Department of Defense, AEC and NASA. The well-coordinated, technical work conducted under this program by several research groups has served to define the potentials and the problem areas in gas bearings as well as to resolve many of these and to demonstrate the feasibility of gas lubrication for classes of applications. The fact that this program is meeting a real need is evidenced by the volume of independent research and development for specific applications noted in Refs. 1 and 2 which were subsequently undertaken by government agencies and private industry.

A parallel growth in the volume of technical literature in gas bearings has taken place, and its contents have reflected the increasing emphasis on applications. While some of the English language in textbooks on lubrication published between

1949 and 1964 (Refs. 4,5,6 and 7) contained mention of or, in some cases, one or more chapters on gas lubrication, the interest in this subject merited publication in 1960 of a Volume of Symposium proceedings devoted exclusively to the subject (Ref.8). Subsequently, two English language textbooks have been published (Refs. 9 and 10) also exclusively devoted to gas lubrication and a Rumanian textbook on this subject (Ref. 11) is currently being translated into English. This is in addition to an extensive volume of technical papers and to a discussion of the subject in a recent text on Advanced Bearing Technology (Ref. 12), published by NASA.

In general communication between the groups engaged in gas lubrication work has been good. The quarterly progress reports issued by the Office of Naval Research, as well as the periodic survey of the world-wide activity in gas bearings have promoted rapid exchange of data between research and application. It is the intent of this State-of-the-Art to review the current status of gas lubrication from the standpoints of research and applications to rotating machinery. Attempt is also made to forecast the probable future needs and developments in these areas.

2. ADVANTAGES AND PROBLEM AREAS

The growing number of applications of gas bearing is intimately connected with the concept of process fluid lubrication. Under this design concept, the process fluid serves also as the system lubricant. In some cases, operating conditions such as extremes of temperature or a radioactive environment make lubrication with oil (or even with liquid metals) impractical. In other cases, the benefits that can be gained with elimination of an auxiliary lube-oil system and of lube-oil is process-fluid seals (frequently sources of contamination and poor reliability), make process fluid lubrication attractive. Where the process fluid is a gas, the advantages that can be realized from its use as the system lubricant include low and constant friction, as well as the absence of any inherent limitation on environmental temperature or radiation levels. A useful property of gases is that their viscosity (and, hence, their capacity to generate hydrodynamic pressures) increases with temperature, whereas the inverse is true of liquids.

Table 1 lists some of the advantages of gas lubrication, as well as typical areas of applications where these advantages are particularly important. Table 2 shows, for four types of rotating machinery, the particular environmental and operating conditions where gas lubrication is advantageous.

Gas lubricated bearings have, in fact, already been used in many of the applications noted above, such as loop compressors, gyroscopes, precision spindles, memory drums and others. Other applications are now in process of design, manufacture and test, including closed loop gas turbines intended for dynamic power conversion in space vehicles and in mobile power plants. Some of these are reviewed in more detail later in this State-of-the-Art. In most cases, however, the applications were preceded by costly development programs. In the case of high speed rotating machinery, for example, development programs had to be conducted to overcome the following problem areas:

1. Selection of bearing configurations that were stable throughout the operating speed range.
2. Selection of materials, coatings, manufacturing methods and tolerances.

3. Proper coupling of the dynamic characteristics of the bearings (fluid film stiffness and damping) with those of the shaft (mass and stiffness distribution) to keep system critical speeds out of the operating range and to minimize vibration response to unbalance loads.

4. Maintenance of near isothermal conditions in the bearing region, to prevent loss of clearance.

5. Control of the thermal gradients and distortions which produce large misalignment or excessive bearing loading.

6. Integration of all the design elements e.g., aerodynamic, electrical, mechanical and materials.

In addition, poorly defined loads such as aerodynamic thrust loads and large radial loads due to magnetic dissymmetries in motor and generator gaps frequently required extensive re-designs. Much knowledge has been gained in the prior developments, so that the experienced manufacturers of gas bearing supported rotating machinery have devised design and materials selection criteria to cope with the above problem areas. In order to extend the range of applications of gas bearings and to more nearly realize the advantages listed in Table 1, much additional R&D effort is required. Some of the problem areas that must be considered in specific applications are listed in Table 3.

3. CLASSIFICATION

The two broad categories of gas bearings are the self-acting (hydrodynamic) type the externally pressurized (hydrostatic & hybrid) types. In the case of self-acting bearing, the fluid film pressures that serve to separate the journal from the bearing (or the thrust collar from the bearing) are generated by the viscous shear of the gas film. In view of the relatively low viscosities of gases, the load capacity of self-acting bearings is generally limited to several psi. Stability was long a serious problem with self-acting bearings, although it is less serious with certain "inherently" stable types of bearing, such as the tilting pad bearing, provided that it is designed with due regard to the dynamic characteristics of the pads. Care must be exercised in the choice of materials in view of the sliding contacts that occur during starts and stops as well as in event of incidental rubs in operation. Start and stop contacts can be prevented by the use of hydrostatic jacking gas, but at the cost of added complexity.

In the case of externally pressurized bearings, pressurized gas is introduced into the clearance space to achieve separation between the shaft and bearing. Load capacity is governed by the available gas supply pressure and the bearing design. The stability of the bearing is very sensitive to design features such as clearance and restrictor geometry, as well as to the mass of the rotor and the fluid properties. It is generally desirable to avoid recesses or other pockets in the bearing clearance, since these can give rise to pneumatic hammer*. Material selection is less critical than in the case of self-acting bearings, since there is no start-stop contact. Differential thermal expansions must however be avoided, as the performance of the bearing is extremely sensitive to clearance.

Externally pressurized bearings that have sizeable land areas and that operate at sufficiently high speeds that self-acting effects become significant are known as "hybrid" bearings. The characteristics of this type of bearing are therefore dependent on both the externally pressurized gas flow and on the pressures induced by viscous shear in the clearance space. Table 4 is a summary comparison of the various categories of gas bearings.

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* See Terminology, given in Appendix 1.

The above categories of bearings can be manufactured in a wide variety of geometries, to carry radial, axial or combined radial and axial loads. Many of these are similar to the geometries used with liquid lubrication. There have however, been some new geometries that have been developed specially for gas lubrication. One such is the Whipple (helical grooved) bearing which is currently perhaps the most widely used self.acting, gas lubricated, thrust bearing. Since its development for gas lubrication, the Whipple plate has also been successfully used with low viscosity liquid lubricants, such as liquid metals. Tables 5 and 6 show in diagramatic form some of the gas bearing configurations that have been suggested.

4. DESIGN INFORMATION

Design information must consider both steady-state and dynamic conditions. The needed design information and the parameters to be considered in each application are given in Table 7.

In the subsequent sections of this report, design charts from which such data can be obtained for self-acting as well as externally pressurized and hybrid bearings are given.

While the above parameters consider only the fluid flow properties, it is equally important for the designer to consider the material to be employed. The following information must be available to him.

1) Compatability between journal and bearing
2) Metallurgical stability of journal and bearing
3) Coefficient of friction of journal and bearing material
4) Coefficient of thermal expansion
5) Radiation stability
6) Oxidation rate (in presence of oxygen)
7) Thermal conductivity
8) Reaction with environment, (e.g. corrosion due to steam)

Somewhat related to the dynamic performance there is also the problem of starting and stopping a gas lubricated system, particularly if the bearings are of the self-acting type. This problem, aside from posing serious limitations on material choice, is closely related to the system design and requires considerations mostly beyond the scope of the present discussion.

The characteristics of gas lubricated bearings can be seriously altered by environmental effects, including the presence of dust, condensable vapor, and other types of impurities. Proper control of the environment may well determine the useful life of gas lubricated bearings.

Another important area which has started to receive the attention it merits, is the capacity of gas lubricated bearings to sustain vibration and shock loads. This is particularly important in the case of naval and aero-space applications of gas bearing supported machinery. In the case of naval applications, for example, the ship's structure to which the machine would be fastened is subject to appreciable and, at times, quite violent motions as the ship rolls and pitches in the sea. In addition, ship's equipment must be capable of sustaining large shock loads without impairment of operating characteristics. The question must thus be asked as to whether, in general, gas-bearing machinery can survive the dynamic conditions of shipboard environment, and if so, how does one go about designing a gas-bearing system for these conditions.

The extent of work in this area to date has been limited, however one study that was recently conducted (Ref. 13) was quite encouraging. This study consisted of:

(a) Calculation by existing methods, of the response of gas bearing supported machinery to low frequency dynamic conditions and to high impact loads, representative of naval applications.

(b) Subjection of a rotor mounted first in hybrid, gas lubricated journal and thrust bearings and then in self-acting, gas lubricated journal and thrust bearings, to dynamic and shock loads using the procedures devised for vibration and shock testing of lightweight and mediumweight naval equipment.

(c) Comparison of the theoretical predictions and measurements.

(d) Preparation of preliminary design criteria and procedures for the practical application of gas bearings to naval machinery.

Figure 1 shows the rotor, while Figures 2 and 3 show respectively the oscillation-test and the shock test stands. Figure 4 shows the calculated and test data obtained with the hybrid journal bearings, under $\pm 11.5^{\circ}$ oscillations at 62.2 cpm. Figure 5 shows similar data for the hybrid thrust bearing. The data indicated that the bearings were capable of sustaining the motions without contact and that their behavior could be predicted with a fair degree of accuracy. In the high impact tests on the other hand, as shown for example in Figure 6, the rotor and bearings touched (in the case shown, under a hammer drop of 14.1 inches, which produced resonant peaks of approximately 18 g force at the journal bearing housing). Due to the use of highly compatible bearing materials, the bearings survived repeated shock load applications and the resulting contacts without degradation of performance. It is clear nevertheless that much additional R&D work is needed in this area to improve the design procedures for such operation and to develop bearings and bearing materials that are better capable of withstanding shock loads.

Nearly all the gas bearing systems developed to date require that conditions in the region of the bearing (including the journal, bearing and bearing support) be maintained isothermal, to prevent degradation of performance due to clearance changes and distortions. R&D activity is needed to develop gas bearing systems that will compensate automatically for the effects of thermal gradients. This will greatly facilitate the application of gas bearings, for example, in high temperature rotating machinery.

Due to the low damping of gas bearings, gas bearing supported rotors are currently designed to operate below their flexible critical speeds. (This is generally the third critical speed of a rotor supported in two radial, gas-bearings. The first two critical speeds are generally rigid body criticals and they can be safely traversed provided that the shaft is properly balanced). R&D activity to produce design information on means for external damping and, possibly, auxiliary gas bearings that can be introduced and cut out of the system in certain speed range, is necessary. This will increase the usefulness of gas bearings for very high speed rotating machinery.

Finally, R&D work to generate the design information on vapor lubricated and two phase flow bearings is needed for their application, for example in Rankine Cycle turbomachinery (including steam and metal vapor turbines), as well as in auxiliary naval machinery and refrigeration systems.

5. STATUS OF GAS BEARING RESEARCH

A. Analysis and Design

Many of the theoretical problems associated with journal and thrust bearings of either the self-acting, or the externally pressurized and the hybrid types have by now been defined and some have been solved. Analytical results based on the assumption of an isothermal film, have been obtained by several investigators. These have generally been consistent with one another and with experimental data. Table 8 lists the current knowledge and recent advances in gas lubrication analysis and design. As noted, in that table, quantitative design data has been obtained in a number of areas. In subsequent parts of this report, much of this data, that is applicable today to rotating machinery is provided and discussed in greater detail.

B. Materials

Successful use of gas lubricated bearings presupposes that well defined surfaces and dimensional accuracy can be maintained throughout the life of the bearing. These requirements have been obtained in many units operating under moderate conditions. During the early developments of gas bearings, a useful starting point in the selection of materials was the prior experience obtained with: unlubricated sliding contact, boundary lubrication, rubbing face seals and others. While these sources of information are still useful, materials investigations specifically aimed at selection of materials combinations for gas bearings have since been conducted (e.g. Refs. 14,15,16, and 17). A summary of the current State-of-the-Art insofar as materials are concerned is given in Table 9.

The material problems are relatively minor at temperatures up to 300^{o}F, and some combinations are available for use up to 700^{o}F. Above this temperature the problems become numerous.

In general, from the standpoint of compatibility, the following criteria have been found to be most important in the selection of bearing materials:

1. Non-soluble couples
2. Hardness or yield strength
3. Crystal structure

4. Formation of reaction films between the bearing surface and the environment
5. Formation of interaction films between sliding surfaces
6. Materials containing solid lubricants in the structure

However, application of these criteria to a practical operating mechanism requires considerable experience as well as a strong intuitive grasp of the mechanical and chemical problems involved.

C. Environmental Effects

Environment effects may be related to the presence of impurities in the gaseous lubricant or to the chemical reactions between the gas and the bearing materials or to the lack of chemical reaction normally taking place between the ordinary atmosphere and the bearing materials.

In the selection of compatible bearing and shaft materials, consideration must therefore be given to the operating environment of the system. Certain material combinations are known to be effective in an oxidizing environment because of the formation of thin, protective oxide films. In an inert gas environment, these same combinations would be poor choices because these films could not be reformed once they were worn away.

Most of the combinations listed in Table 9 can be used in a variety of environments without sacrificing sliding compatibility effectiveness, although some modifications might be required. For example, the carbon-graphites must be chemically impregnated for use in dry or inert gases since the self-lubricating quality of these materials is dependent on the presence of water vapor. On the other hand, bonded films of solid lubricants, such as MoS_2 and Teflon, and sprayed oxide films are generally effective in both oxidizing and inert atmospheres.

The operating temperature will have a strong influence on the choice of materials. For example, in Table 9, effective temperature ranges are given for each of the material combinations. In some cases, such as the carbon-graphites, the effective range is set by design considerations rather than sliding compatibility. Carbon-graphites can be used up to 1000F but the problem of matching thermal expansion characteristics can be prohibitive. As noted in Table 9, cermets or ceramics appear at present to be preferable for high temperature operation, although much additional R&D work is necessary in this area. Other environments for which R&D work is needed for materials selection include: inert gases, corrosive gases and high levels of radio-activity.

Some environmental effects come about in more devious ways. A prime example is the combined effect of moisture and dust. Moisture condensation in a clean gas film would affect the bearing characteristics but would not otherwise cause drastic consequences. Fine dust particles (relative to the radial clearance) in a dry gas film would have little influence on the bearing characteristics. If both excess moisture and fine dust are present in the gas film, the latter would provide the nuclei to promote condensation, the moistened dust would then swell and stick together and eventually cause seizure of the bearing. Problems of this nature are usually discovered by experience, where-upon R&D effort should provide controlled experimentation in order to identify the cause of difficulty and to devise means of cure.

6. STATUS OF GAS BEARING APPLICATIONS IN ROTATING MACHINERY

As noted earlier in this State-of-the-Art, the number of applications of gas bearings is rapidly increasing. These applications were generally preceded by studies in which the relative merits and drawbacks of lubrication with the process or the ambient gas were compared with those of lubrication with a conventional lube oil system. In a number of cases, gas lubrication was shown to have clear advantages. These cases include: gas compressors and blowers for nuclear and chemo-nuclear loop applications; Brayton Cycle turbomachinery for dynamic power conversion in space vehicles; as well as some environmental simulation tables, precision spindles and instrumentation such as gyroscopes and accelerometers. Here, some of these applications of gas bearings specifically pertaining to motor and turbine driven rotating machinery are noted.

The extent of the applications of gas lubrication to rotating machinery can be gauged from Tables 10 and 11. These list respectively the specifications of typical U.S. and European machines. The information presented is derived from several sources including Refs. 18,19 and 20. Two interesting points emerge from these tables. First, they show that the number of European-built, motor-driven compressors and blowers exceeds the number of such machines built in the United States. The reason for this is that most gas bearing compressors and blowers built to date have been intended for use in reactor, chemo-nuclear and heat transfer loops, where the level of radiation, the high temperatures and the stringent specifications forbidding contamination, have precluded the use of oil bearings. Greater interest in and experimentation with gas cooled reactors has taken place in Europe than in this country. This accounts for the larger number of motor driven gas bearing units produced there. In most cases, however, the U.S. machines are subjected to a more severe environment.

The second point of interest is the greater diversification in the application of gas bearing supported machinery in this country than in Europe. This is due in large measure to the greater emphasis that has been placed here on developing a rational technology in place of cut and try design. Thus, Tables 10 and 11 show that a number of gas turbines and turbine driven units are being developed here, whereas none has so far been produced, to the best of the writers' knowledge, in Europe.

The range of currently built units is indicated in Figs. 7 and 8. Figure 7 shows the range of pressure vs flow characteristics of current gas bearing supported compressors, while Figure 8 shows the weight vs horsepower of the units. Typical U.S. and European built, motor-driven units are shown in Figs. 9 through 14. Figures 15 and 16 shows the first gas bearing supported gas turbine to be developed. This is the unit that was previously referred to in the Foreword to this State-of-the-Art.

7. RECOMMENDATIONS FOR FUTURE RESEARCH AND DEVELOPMENT

Major research in gas bearings is still relatively recent, compared with similar effort in other types of bearings, such as oil lubricated sliding and rolling element bearings. Many areas of gas lubrication continue therefore to demand concentrated effort. Much of this effort continues to be in the areas of analysis and feasibility studies of new concepts and reduction to practice of existing concepts. It is however noteworthy that an increasing percentage of the current research is being directed towards product improvements in areas where gas bearings are already in use.

Tables 10 and 11 showed, for example, the large number of gas bearing applications in rotating machinery. Gas lubrication was shown to be entirely practical in these applications and, in many cases, it was either the only feasible mode of lubrication, or it had substantial advantages over other types. For example, in applications where contamination of the process gas was not permissible, gas bearings proved to be easier to develop and to be much more reliable than zero leakage seals.

Gas bearing research aimed at product improvement in rotating machinery is important, both for the later generations of machines currently running on gas bearings and for new applications. The principal areas where future research work is projected are:

1. Development of gas bearings for non-isothermal environment, i.e.where operation is possible over wide temperature ranges and in the presence of thermal gradients, without need for external provisions, to control the temperature in the bearing region.
2. Development of gas bearing systems for support of flexible rotors, i.e.where adequate damping or where auxiliary bearings are provided that can be introduced into the system in specified speed ranges, in order to support flexible rotors.
3. Development of bearings for two-phase flow systems, e.g.where the lubricant is a wet vapor.

Some of the specific items of future research work, to achieve the above objectives are listed in Table 12.

8. FUTURE APPLICATIONS OF GAS-BEARING TURBO-MACHINERY

The field of gas-bearing applications is unlimited and its possibilities are open to the ingenuity of designers. The important advantages of gas lubrication,some of which were listed in Table 1, warrant the necessary research and development effort to solve the remaining problem areas and to advance new concepts. As evidenced by the increasing number of applications of gas lubrication cited earlier in this State-of-the-Art, there is a growing acceptance of this type of lubrication on the part of producers and designers of compact, high speed rotating machinery. It is therefore expected that, the next several years, research and development in gas lubrication will continue at its present or, more probably, at an accelerated pace.

Specifically in the area of rotating machinery, gas and vapor bearings are expected to be used quite extensively in the following three areas:

1. Compact, Dynamic Power Conversion Systems

   Both the Brayton and Rankine Cycle turbomachinery for dynamic power conversion in space vehicles,in land-based mobile power plants and in undersea power plants can advantageously use process fluid lubrication. For the Brayton Cycle machinery, almost any gas or mixture of gases that are required for the cycle can be used as the bearing lubricant including: helium, nitrogen, air, carbon dioxide, argon, neon, UF6 or others. For Rankine Cycle machinery, lubrication could be accomplished with steam, metal vapor, biphenyl, freon or others. At present, gas lubricated Brayton Cycle turobmachinery is under active development, while a limited amount of research into vapor lubrication for eventual application to Rankine Cycle turbomachinery is in progress.

2. Refrigeration and Cryogenic Systems

   For reasons of long, maintenance-free operating life, there is much current interest in using rotating compressors and expanders instead of reciprocating equipment in cryogenic systems. The high speed, long life, low friction and non-contamination needs of cryogenic turbomachinery make process fluid lubrication the logical choice. Several companies are currently engaged in development of gas-bearing turbomachinery for small cryogenic systems and it is expected that prototypes of this type of equipment will be in operation within the next few years. (It may be noted that even in the case of reciprocating cryogenic equipment, externally pressurized gas lubrication may be used to "float" the piston, thus eliminating wear and leading to much longer operating life than is currently attainable).

3. Locomotion

Increased interest in application of gas lubrication to high speed transportation, e.g. for track lubrication and for some types of jet propulsion is anticipated for reasons for low friction, low vibration and no wear.

On the basis of current work as well as the interest expressed by government agencies and industrial firms in specific new developments, we anticipate that the following milestones in the area of gas-bearing supported rotating-machinery will have been attained by 1970:

1. Production and Utilization of Gas-Bearing Supported Equipment:

a) Compressors for gas and vapor transport in nuclear, chemonuclear, drug and food processing loops.
b) Cryogenic expanders
c) High speed spindles
d) Capstans and tape guides
e) Gyroscopes and accelerometers

2. Developed Prototypes of Gas-Bearing Supported Equipment

a) Turbomachinery for dynamic conversion of solar or nuclear power for space use.
b) Turbomachinery for dynamic power conversion for deep-submergence power plant.
c) Turbomachinery for land based, mobile power plant (e.g. CSG 1)
d) Turbomachinery for low-power, long-life, undersea propulsion.
e) Turbomachinery for torpedo propulsion
f) One or more items of low power (less than 1000 HP) naval turbomachinery.
g) Cryogenic, rotary compressors and expanders for liquid helium systems.
h) Chemical and biological centrifuges

i) Aircraft auxiliary units.

j) High speed, low rating motors and generators

3. Studies of Application of Gas-Bearings to:

a) High speed track transport

b) Jet propulsion

c) Main power generation systems (steam and gas turbines).

APPENDIX 1

TERMINOLOGY

Due to the vast number of independent R&D efforts, together with the rapid progress made in the last few years, there has been some confusion caused by conflicting terminology. The following list is designed to establish a common language.

Self-Acting (or Hydrodynamic) Gas Bearing - One in which the surfaces are separated by gas film pressures generated by the relative motion of the surfaces.

Externally Pressurized (or Hydrostatic) Gas Bearing - One in which the surfaces are separated mainly by the introduction of pressurized gas into the clearance space.

Hybrid Bearings - Bearings which combine the self-acting and externally pressurized features.

Composite Bearings - Bearing geometries which are capable of supporting radial and thrust loads, e.g. spherical, conical, etc.

Steady State Performance of Bearings - Under this condition, the gas film pressure is distributed independent of time. This means a stationary journal axis or thrust collar axis.

Dynamic Performance - Under this condition the axis of the journal or the thrust collar moves so that the local gas film pressure varies with time. Examples of dynamic operation are:

a) start up and shut down transients
b) motion excited by a rotating load
c) motion excited by a reciprocating load
d) bearing instability as described below

Bearing Instability - Dynamic operation of excessive amplitude caused by self-excited time dependent fluid film pressure.

Threshold of Instability - Corresponds to journal speed at which instability is initiated.

Critical Speed - This is a rotating speed of a journal which corresponds to resonance frequency of the system. (The system's critical speeds include rigid body as well as bending or torsional critical speeds.)

Synchronous Whirl - This is a whirling orbital motion of the journal or bearing at a frequency equal to the rotational frequency. The motion of the journal or bearing center is in the same direction as the direction of the rotating member.

An example of the synchronous whirl is the case of unbalanced rotating load. (In the case of vertical plain cylindrical journal bearings, the whirling locus is a circle; in the case of horizontal plain cylindrical journal bearing the whirling locus is an ellipse.)

Synchronous Wobble - This is a wobbling motion of a thrust runner or thrust bearing at a frequency equal to the rotational frequency and in the same direction as the rotating member. An example of the synchronous wobble is the case of an angularly misaligned collar (thrust runner).

Half-Frequency Whirl - A special case of instability generally associated with self-acting journal bearings. This instability occurs when the journal speed reaches a critical value. The journal axis whirls at a frequency of one-half or nearly one-half of the journal speed in the same direction as the journal rotation. The motion of the journal axis can be either conical or translatory.

Resonant Whip - (Often called "Resonant Fluid Film Whirl") A resonant vibration of a journal in a fluid film journal bearing which occurs at approximately twice the actual first system critical and persists at higher speeds. The frequency of vibration is approximately equal to the first system critical regardless of running speed. The motion of the journal axis is in the same direction as the shaft rotation. This condition is caused in part by a flexible rotor. In self-acting gas lubricated systems, typically the rotor is very stiff as compared to the gas film; thus, up to now, this condition has not really been positively identified. A similar condition has, however, been observed with rigid rotor supported on externally pressurized gas dynamic journal bearings.

Pneumatic Hammer - This is a self-excited oscillation in the flow systems of externally pressurized bearing. This oscillation does not necessarily require the relative motion of the bearing surfaces.

APPENDIX 2

In connection with this State-of-the-Art, a survey was made by M.T.I. of organizations in this country that were known to be conducting work in gas bearings. A questionnaire was mailed to these organizations on August 31, 1964 requesting answers to the following questions:

1. List titles of reports, papers, etc., prepared by you or your associates on gas bearings and/or rotor dynamics.

2. List titles of the computer program available within your organization for gas bearings and rotor dynamics. Indicate which program was Government sponsored and the sponsoring agency.

   Description | Remarks

3. Indicate area and sponsor of your present research, e.g., foil bearings, stability of journal bearings, load capacity of Whipple thrust bearings, etc.

   Area | Theoretical Experimental | Sponsor

4. List areas of research, development, etc., which in your opinion deserve immediate attention.

5. List where your organization has applied gas bearings.

The cover letter accompanying the questionnaire stated:

> "As one of the tasks in ONR Contract Nonr 4535, we have been requested to prepare a state-of-the-art on gas bearings. In order to make this report as useful and up-to date as possible, we solicit your assistance in completing the enclosed form. We are writing to you for we recognize that you have contributed to this area".

The replies received are tabulated on the following pages. These demonstrate again the current scope of interest and activity in gas bearings in this country.

Organization Responding - Ampex Corporation, Redwood City, California

Individual(s) Responding - M. Wildmann/W. Gross

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

Gas Film Lubrication, W.A. Gross, John Wiley & Sons, Inc. New York, 1962.

"Gas Bearings, A Survey," W.A. Gross, Wear, 6 (1963) 423-443.

"The Effect of External Pressurization on Self-Acting Foil Bearings," M. Wildmann and A. Wright, Ampex Report, RR 63-6.

"Externally Pressurized Axisymmetrical Foil Bearings," E. Barlow, Ampex Report, RR 63-4.

"An Investigation of Self-Acting Foil Bearings," J.T. Ma, Ampex Report , RR 64-3.

"Axisymmetrical Foil Bearing - Compressible Flow," E. Barlow, Ampex Report, RR 64-6.

"A Survey of Gas-Lubricated Bearing Technology and a Review of Recent Work on Foil Bearings," W.A. Gross.

"The Gas-Lubricated Stepped Thrust Bearing, A Comprehensive Study," M. Wildmann, et.al.

"Grooved Plate Gas Lubricated Thrust Bearings with Special Reference to the Spiral Groove Bearing," M. Wildmann.

Organization's Computer Program

Description	Sponsor

Externally Pressurized Foil Bearing - Approximate Solution

Externally Pressurized Foil Bearing - Numerical Solution

Self-Acting Foil Bearing, Linearized Solution for Large Wrap Angles

Perfectly Flexible Foil - Incompressible Lubricant
Perfectly Flexible Foil - Compressible Lubricant
Finite Thickness Foil - Incompressible Lubricant

Foil Bearing with External Pressurization - Incompressible Lubricant - Numerical Solution.

Zero Width Supply
Finite Width Supply

Foil Bearing with External Pressurization - Approximate Solution

Zero Width Supply
Finite Width Supply

Thrust Bearings

Spiral Groove Thrust Bearings - Solves Whipple's equations to obtain load capacity. Optimization can then be done with same program.

Herringbone with Sinusoidal Gap - Takes first and second order solution and gives pressure and load.

Areas of Present Research

Description	Theory	Experimental	Sponsor
Foil Bearing Studies	X	X	ONR

Recommend Areas of Research and Development

Externally Pressurized Bearings - Stability Criteria

Foil Bearings - Basic Studies
- Application to Rotor Systems

Areas Where Gas Bearings Have Been Applied

High Speed Rotor Supports

Tape Transport: To guide foils and eliminate wear.

Organization Responding - Army Engineer Reactors Group, U.S.
Nuclear Power Field Office, Ft. Belvoir, Virginia

Individual(s) Responding - G.B.Manning/W.M. Crim

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

Final Design Report on the Journal and Thrust Bearings for the CSG-1 Project.
(Prepared by M.T.I. for Army Engineering Reactors Group).

Organization's Computer Programs

Description	Sponsor
Prediction of Natural Frequencies of Systems Having Several Degrees of Freedom (Vibration Analysis)	
Critical Speeds of Flexible Rotors	

Areas of Present Research

Description	Theory	Experimental	Sponsor
(None reported)			

Recommended Areas of Research and Development

The Continuation of the CSG-1 Program.

Areas Where the Gas Bearings Have Been Applied

Clark Bros. CSG-1 Turbocompressor.

Organization Responding - Atomic Energy Commission, Washington, D.C.

Individual(s) Responding - N. Grossman

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

(None reported)

Organization's Computer Programs

Description	Sponsor
(None Reported)	

Areas of Present Research

Description	Theory	Experimental	Sponsor
(None reported)			

Recommended Areas of Research and Development

Material Compatibility

Areas Where Gas Bearings Have Been Applied

Turbocompressors

Organization Responding - Bureau of Naval Weapons, Washington, D.C.

Individual(s) Responding - M. R. Walters

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

(None reported)

Organization's Computer Programs

Description	Sponsor
(None reported)	

Areas of Present Research

Description	Theoretical	Experimental	Sponsor
Develop three (3) models of small 2" diameter gyroscopes with gas rotor bearings. (Development awarded to Honeywell).			Code RREN-4 BuWeapons

Recommended Areas of Research and Development

Lower Cost for Gyroscope Applications

Higher Shock Load Capability

Areas Where Gas Bearings Have Been Applied

Application is Contemplated on a Small Gyro for Shipboard Radar System.

Organization Responding - Department of Commerce, National Bureau of Standards, Boulder, Colorado

Individual(s) Responding - B.W. Birmingham

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"The Application of Gas-Lubricated Bearings to a Miniature Helium Expansion Turbine," B.W. Birmingham, H. Sixsmith and W.A. Wilson, Advances in Cryogenic Engineering, K.D. Timmerhaus, Editor, (Plenum Press, N.Y. 1962).

"Load-Carrying Capacity of Gas-Lubricated Bearings with Inherent Orifice Compensation Using Nitrogen and Helium Gas," H. Sixsmith, W.A. Wilson and B.W. Birmingham, NBS T.N. 115, (August, 1961).

"A Refrigeration System Incorporating a Low Capacity High Speed Gas Bearing Supported Expansion Turbine," D.B. Mann, H. Sixsmith, W.A. Wilson and B.W. Birmingham, Advances in Cryogenic Engineering, K.D. Timmerhaus, Editor, (Plenum Press, N.Y. 1963).

"The Theory of a Stable High-Speed Externally Pressurized Gas-Lubricated Bearing," H. Sixsmith and W.A. Wilson, Journal of Research of the National Bureau of Standards, April-June, 1964.

Organization's Computer Programs

Description	Sponsor
(None reported)	

Areas of Present Research

Description	Theory	Experimental	Sponsor
Program Terminating			

Recommended Areas of Research and Development

(None reported)

Areas Where Gas Bearings Have Been Applied

The National Bureau of Standards has Applied Gas Gas Bearings to a Miniature Expansion Turbine for Cryogenic Temperature Refrigeration.

Organization Responding - Franklin Institute, Philadelphia, Penna.

Individual(s) Responding - H.G. Elrod/W.W. Shugarts

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"The Effect of Speed, Load and Film Thickness on Pressure Distribution in Gas-Lubricated, Tilting-Pad Journal Bearings," E.J. Gunter, Jr., J.G. Hinkle and D.D. Fuller, ASLE Paper No. 64-AM-4B2.

"Steady-State Characteristics of Gas-Lubricated, Self-Acting, Partial-Arc Journal Bearings of Finite Width," V. Castelli, C.H. Stevenson and E.J. Gunter, Jr., Trans. ASLE, 1964.

"The Stability of a Flexible Rotor Subjected to Rotary Damping," E.J. Gunter, Jr., Proceedings of Meeting on Rotating Machinery for Gas-Cooled Reactor Application (Gatlinburg, Tenn. Nov. 4-6, 1963) May 1964, TID - 7690 O.T.S.

"An Investigation of Pressure Distribution in Gas-Lubricated, Tilting-Pad, Journal Bearings for High-Speed Rotors," E.J. Gunter, Jr., J.G. Hinkle and D.D. Fuller, Proceedings of Meeting on Rotating Machinery for Gas-Cooled Reactor Application, (Gatlinburg, Tenn. Nov. 4-6, 1963) May 1964, TID - 7690 O.T.S.

"Theoretical and Experimental Investigation of Gas-Lubricated, Pivoted-Pad, Journal Bearings," E.J. Gunter, Jr., V. Castelli and D.D. Fuller, Trans. ASLE, October 1963.

"Recent Progress on the Development of Gas-Lubricated Bearings for High-Speed Rotating Machinery," E.J. Gunter, Jr., and D.D. Fuller, Proceedings of the USAF Aerospace Fluids and Lubricants Conference (April 16-19, 1963).

"The Theory of Pulsating Flow in Conical Nozzles," H.G. Elrod, Jr., Trans.ASME, Jnl.of Applied Mechanics, March 1963.

"The Application of Gas-Lubricated Bearings to High-Speed Turbomachinery," J.G. Hinkle, E.J. Gunter,Jr., and D.D. Fuller, FIL Report No. Q-A2392-3-13.

"The Application of Gas-Lubricated Bearings to High-Speed Turbomachinery," J.G. Hinkle, E.J. Gunter, Jr., and D.D. Fuller, FIL Report No. Q-A2392-3-12.

"The Application of Gas-Lubricated Bearings to High-Speed Turbomachinery," J.G. Hinkle, E.J. Gunter, Jr., and D.D. Fuller, FIL Report No. Q-A2392-3-11.

"An Outline of a Method for the Investigation of the Stability of Gas-Lubricated, Tilting-Pad Journal Bearings," E.J. Gunter, Jr., and V. Castelli, FIL Report No. I-A2049-21.

"The Application of Gas-Lubricated Bearings to High-Speed Turbomachinery," E.J. Gunter, Jr., J.G. Hinkle and D.D. Fuller, FIL Report No. Q-A2392-3-10.

"The Application of Gas-Lubricated Bearings to High-Speed Turbomachinery," E.J. Gunter, Jr., J.G. Hinkle and D.D. Fuller, FIL Report No. Q-A2392-3-9.

"The Application of Gas-Lubricated Bearings to High-Speed Turbomachinery," J.G.Hinkle, E.J. Gunter, Jr., and D.D. Fuller, FIL Report No. Q-A2392-3-8.

"Steady-State Characteristics of Gas-Lubricated, Self-Acting, Partial-Arc, Journal Bearings of Finite Width," V. Castelli, C.H.Stevenson and E.J.Gunter,Jr., FIL Report No. I-A2049-18.

"Solution of the Stability Problem for 360° Self-Acting, Gas-Lubricated Bearings of Infinite Length," V. Castelli and H.G. Elrod, Jr., FIL Report No. I-A2049-20.

Organization's Computer Program

Description	Sponsor
Dynamics of Tilting-Pad Bearing Shaft Systems Numerically solves the time-transient Reynolds equation for a system of two tilting-pad journal bearings and shaft. For successive discrete time intervals, shoe pressure distributions are calculated and resulting forces are applied to the shaft and shoes permitting their respective motions to be calculated. Analysis includes two degrees of freedom (pitch and roll) for each of 3 shoes at each journal location. In addition, at least one shoe (and possibly 3) for each bearing will be spring mounted. The shaft is allowed four degrees of freedom. This work is in process.	NASA (through the Pratt and Whitney Aircraft Corp.)
Hybrid Gas Journal Bearings Numerically solves the steady-state Reynolds equation of tilting-pad and 360° bearings with any number of axial grooves and/or up to 6 pressurized recesses allowing for variable clearances in the circumferential; and axial directions. This work is in process.	NASA (through Pratt and Whitney Aircraft Corp.)

Areas of Present Research

Description	Theoretical	Experimental	Sponsor
Entrance Effects in Externally Pressurized Bearings	X	X	ONR
Bearing Materials Evaluation		X	ONR
Bearing Stability	X	X	ONR
Tilting-Pad Journal and Thrust Bearings	X	X	ONR, AEC
Stability Analysis of Tilting-Pad Bearings	X	X	AROD
Application of Tilting-Pad Bearings to Turbomachinery	X		(NASA) Pratt and Whitney
Comparison of Bearing Stiffness Analyses	X		ONR
Design Information for Tilting-Pad Thrust Bearings	X		ONR

Recommended Areas of Research and Development

Translating Theoretical Information into Design Information (Design Manuals).

Materials Evaluation

Performance Characteristics of Specific Externally-Pressurized Bearing Configurations.

Pneumatic-Hammer Instability of Externally-Pressurized Journal and Thrust Bearings.

Use of Porous Material in Externally-Pressurized Bearings.

Viscous Drag-Induced "Thrusting" and Turbine Torque Effects.

Areas Where Gas Bearings Have Been Applied

Laboratory Test Apparatus

Tonometer (Medical Instrument)

Tension Test Machine for Testing Paper

Turbomachinery

Gyroscope (Spin Axis)

Gyro Rate Table

High-Speed Centrifuge

Space Simulator Table

High-Speed Memory Disc

Organization Responding - General Electric Company, Advanced Technology Laboratories, Schenectady, New York

Individual(s) Responding - G. R. Fox

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"The Externally Pressurized, Porous Wall, Gas-Lubricated Journal Bearing, I" H.J. Sneck and K.T. Yen, ASLE Trans., vol. 7, No. 3, July, 1964, pp. 288-298.

"The Application of Experimental Mobility Methods to the Vibration Analysis of Rotor-Bearing Systems," J.M. McGrew and H.E. Marx, General Electric Co. Report.

"The Externally Pressurized, Porous Wall, Gas-Lubricated Journal Bearing, II," H.J. Sneck and R.C. Elwell, October 8, 1964, Paper Submitted to ASLE for 1965 Annual Meeting.

"Analysis of the Short Gas Lubricated Journal Bearing," H.J. Sneck, General Electric Company Report 63GL116, August 12, 1963.

"Low Viscosity Bearing Stability Investigation," J.D. McHugh, Report No. NASA-CR-54039.

Organization's Computer Program

Description	Sponsor
Critical Speed Program MMD009 - Prohl Method. Gyroscopic Effects on Disks can be considered, but Transverse Moments of Inertia about an Axis through a Section Diameter cannot. Gives Rigid Body and Bending Critical Speeds.	General Electric Co.
L15701 Eigenvalue Program - Allows for Rotational and Transverse Moments of Inertia and Bearing Stiffnesses.	General Electric Co.

Areas of Present Research

Description	Theoretical	Experimental	Sponsor
Low Viscosity Bearing Stability	X	X	NASA-Lewis Research Center
Closed Cycle Cryogenic Refrigerator Gas Bearing Development		X	G. E. Co.

Recommended Areas of Research and Development

High Speed Rotor Stability

Design of Tilting-Pad Journal Bearings

Stability of Externally Pressurized Bearings

Turbulence Effects in High Speed Bearings

Areas Where Gas Bearings Have Been Applied

Closed Cycle Helium Compressors

Missile Arming and Fuzing Devices

Miniature Cryogenic Turboexpanders

Dynamometers for FHP Motors & Other Test Devices

Impulse Type Air Turbine

Missile Attitude Control Test Tables

Organization Responding - Honeywell, Inc. Aeronautical Division, Minneapolis, Minn.

Individual(s) Responding - L. Rood

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"Dynamic Behavior of Self-Acting Gas Lubricated Thrust Bearings," L. H. Rood and G.T. Erickson.

"The Application of Gas Bearing Spin Motors to Miniature Gyros," R.G. Baldwin and S.J. Korzenowski.

Organization's Computer Program

Description	Sponsor
Gas Bearing Analysis Program	Honeywell Inc.

Areas of Present Research

Description	Theoretical	Experimental	Sponsor
Internal Development Program			

Recommended Areas of Research and Development

Cost

Capabilities

Areas Where Gas Bearings Have Been Applied

Gyros

Instruments

Controls

Organization Responding - I.B.M. Research Laboratories, San Jose, California

Individual(s) Responding - W. Langlois

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"Small Transient and Periodic Squeeze Motions in Parallel Gas Films," W.A. Michael, IBM Research Report, RJ-197, September 25, 1963.

Organization's Computer Program

Description	Sponsor

Areas of Present Research

Description	Theoretical	Experimental	Sponsor

Recommended Areas of Research and Development

Foil Bearing Research and Development

Foundations of Non-Newtonian Lubrication Theory

Squeeze Bearing Development

Areas Where Gas Bearings Have Been Applied

Computer Memories

Organization Responding - I.B.M. Thomas J. Watson, Research Center, Yorktown Heights, New York

Individual(s) Responding - L. Licht

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"Effect of Misalignment on a Circular, Externally-Pressurized Gas-Lubricated Bearing," L. Licht and R. Kaul, Trans. ASME, Journal of Applied Mechanics. March, 1964.

"Dynamics of Externally-Pressurized Sliders with Incompressible and Compressible Films," L. Licht and J.W. Cooley, Trans. ASME, Journal of Basic Engineering, June, 1964.

Organization's Computer's Program

Description	Sponsor
A Number of Computer Programs Available	

Areas of Present Research

Description	Theoretical	Experimental	Sponsor
Foils Bearings	X	X	I.B.M.
Air-Lubrication of Tapes, Flexible Strips, Discs. etc.			

Recommended Areas of Research and Development

Theoretical and Experimental:

Formulation of 3-Dimensional Problems of Elastohydrodynamic Lubrication Involving Plate, or Shell-Like, Thin, Flexible Surfaces. Solutions of Such Problems in Ascending Order of Difficulty. Corresponding experiments.

Problems Involing Transients and Flutter in Elasto-Hydrodynamic Lubrication.

Thin Film Gas Lubrication

Areas Where Gas Bearings Have Been Applied

Support of Magnetic Heads, Mounting of Drums, Transducers for Optical Read-Out.

Support of and Guidance of Flexible Recording Media.

Organization Responding - ITT Federal Laboratories, San Fernando, California

Individual(s) Responding - G.B. Speen

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"Gas Bearings in Precision Instruments," G.B. Speen, Electro-Mechanical Design, April, 1964, pp. 40-43.

"Gas-Supported Dual Element Gyroscopic for Space Use," G.B. Speen, Proceedings of Fourth Joint Automatic Control Conference (ISA), June 1963.

"Dual Element Gas Gyro Minimized Drift," G.B. Speen, Space/Aeronautics, December, 1963.

"The Application of Gas-Lubricated Bearings in Precision Instruments," G.B. Speen, ASME Spring Lubrication Symposium, June, 1963.

"Isoelasticity in Gas-Lubricated Support Systems," G.B. Speen and R.C. Turnblade, Lubrication Engineering, Nov. 1963.

Organization's Computer Programs

Description	Sponsor
Spherical Bearings - Externally Pressurized	Company sponsored

Areas of Present Research

Description	Theoretical	Experimental	Sponsor
Spherical Bearings	X	X	Company
Segment Bearings	X	X	Company

Shock Tolerance
Vibration Tolerance
Stability
Turbine Torques

Recommended Areas of Research and Development

Properties of Gas Bearings Under External Excitations

Areas Where Gas Bearings Have Been Currently Applied

Gyroscopes

Accelerometers

Inertial Platforms

Generators

Rotating Equipment

Compressors

Organization Responding - Lear Siegler, Inc. Instrument Division, Grand Rapids, Michigan

Individual(s) Responding - K. Liebler

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"Hemispherical Squeeze Film Bearings," K. Liebler, ONR Conference in Cleveland, Ohio, May 1, 1964.

"Squeeze Film Suspended Inertial Sensors," L.F. Warnock, Symposium on Unconventional Inertial Sensors, Oct. 19, 1964.

Organization's Computer Programs

Description	Sponsor
Several Rudimentary Computer Design Programs	Company Funded

Areas of Present Research

Description	Theoretical	Experimental	Sponsor
Hydrodynamic Gas Bearings Including both Journal and Thrust Bearings.		X	Company Funded
Investigation of Squeeze Film Bearings			

Recommended Areas of Research and Development

Areas Where Gas Bearings Have Been Applied

Accelerometers

Organization Responding - Litton Systems, Inc., Guidance & Control Systems Div., Woodland Hills, California.

Individual(s) Responding - J. S. Ausman

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"The Fluid Dynamic Theory of Gas-Lubricated Bearings," Trans. ASME, vol.79, August, 1957, pp. 1218-1223.

"Finite Gas-Lubricated Journal Bearing," The Institute of Mechanical Engineers, Proceedings of the Conference on Lubrication and Wear, 1957.

"How to Design Hydrodynamic Gas Bearings," Product Engineering, November 25, 1957, pp. 103-106.

"Torque Produced by Misalignment of Hydrodynamic Gas-Lubricated Journal Bearings," Journal of Basic Engineering, vol. 82, ser. D, No. 2, June, 1960, pp. 335-341.

"Theory & Design of Self-Acting, Gas-Lubricated Journal Bearings, Including Misalignment Effects," First International Symposium on Gas-Lubricated Bearings held in Washington, D.C., Oct. 26-28, 1959, pp. 161-192.

"An Improved Analytical Solution for Self-Acting Gas Lubricated Journal Bearings of Finite Length," Journal of Basic Engineering, vol. 83, Ser.D, No.2, June, 1961, pp. 188-194.

"An Approximate Analytical Solution for Self-Acting Gas Lubricated of Stepped Sector Thrust Bearings," ASLE Trans. vol. 4, No. 2, November, 1961, pp.304-313.

"Linearized PH Stability Theory for Translatory Half-Speed Whirl of Long Self-Acting Gas - Lubricated Journal Bearings," ASME Paper 62-WA-185, presented at ASME Winter Annual Meeting, Nov. 1962.

"On the Behavior of Gas-Lubricated Journal Bearings Subjected to Sinusoidally Time-Varying Loads," Presented at 1964 International Lubrication Conference.

"Gas-Lubricated Bearings," Chapter 5 in Advanced Bearing Technology, by E.E. Bisson and W.J. Anderson, NASA-SP 38, 1964.

Organization's Computer Programs

Description

Journal Bearing Stability (Infinitely Long Bearing)	Numerical Computations of Approximate Analytical Solutions to Reynolds Equation and Equation of Journal Motion.
Journal Bearing (Infinite Length) Steady State Response to Sinusoidal Loading.	No Numerical Integration

Areas of Present Research

Description	Theoretical	Experimental	Sponsor

Areas Where Gas Bearings Have Been Applied

Gyroscope Spin Bearings and Drum Memory Spin Bearings.

Organization Responding - M.I.T. Instrumentation Laboratory, Cambridge, Mass.

Individual(s) Responding - M.S. Sapuppo

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

Reports are Confidential

Organization's Computer Programs

Description	Sponsor
Radial Stiffness of Journal with Rayleigh Steps	Air Force BSD
Dimensional Tolerance Effect on Journal and Thrust Bearings	Air Force BSD

Areas of Present Research

Description	Theoretical	Experimental	Sponsor
Journal with Rayleigh Steps and Whipple Grooved Thrust Plates			
Static and Dynamic Radial Support	X	X	Air Force BSD
Static and Dynamic Axial Support	X	X	Air Force BSD
Static Precessional Support	X	X	Air Force BSD

Recommended Areas of Research and Development

Manufacture and Testing of Gas Bearings Having Axial and Radial Gaps less than 50 Microinches

Areas Where Gas Bearings Have Been Applied

As the Stable Angular Momentum Source for Use in the Pendulous Integrating Gyro Accelerometer.

Organization Responding - M.I.T.- Dept. of Mechanical Engineering, Cambridge, Mass.

Individual(s) Responding - H. H. Richardson

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"Plane Vibration of the Inherently Compensated Gas Journal Bearing - Analysis and Comparison with Experiment," P.J. Mullan and H.H. Richardson, ASLE Paper 64-AM-4B3.

"A Preliminary Study of Whirl Instability for Pressurized Gas Bearings," R.H. Larson and H.H. Richardson, Trans. ASME, Journal of Basic Engineering, vol. 84, ser.D. No.4, December 1962.

"Static and Dynamic Characteristics of Compensated Gas Bearings," H.H. Richardson, Trans. ASME, vol. 80, pp. 1503-1509, 1958.

"Design Study of a Hydrostatic Gas Bearing with Inherent Orifice Compensation," S.K. Grinnell and H.H. Richardson, Trans. ASME, vol.79, 1957, pp. 11-22.

"Flow of a Compressible Fluid in a Thin Passage," S.K. Grinnell, Trans. ASME, vol. 78, pp. 765-772, 1956.

Organization's Computer Programs

Description	Sponsor
Plane Vibration and Steady Rotation of Pressurized Journal Bearings: Lumped and Distributed Parameter Perturbation Analyses.	
Axial Vibration and Thrust Bearings as above.	

Areas of Present Research

Description	Theoretical	Experimental	Sponsor
Pressurized Thrust Bearing Dynamics	X	X	Air Force
Pressurized Journal Bearing Dynamics	X	X	Air Force

Recommended Areas of Research and Development

Bearing Behavior at Large Eccentricity Ratios Including Stability.

Interaction of Multi-Rotor, Multi-Bearing Shaft Systems.

In General, Generation of Design Data and Curves, Verified by Experiment, Which can be readily used by Designers at least for Feasibility Studies.

Areas Where Gas Bearings Have Been Applied

Instrumentation for Extreme Environments; Accelerometers and Rate Gyroscopes.

Pneumatic Positive Displacement Motors.

Research Apparatus; Torque Dynamometers, Low Friction Guides, Control Value Supports, Centrifugal Test Equipment.

Pneumatic Control Components Such as Flapper-Value Amplifiers, Compensation Networks, Transformers, etc.

Organization Responding - Mechanical Technology Incorporated, Latham, New York

Individual(s) Responding - E. B. Arwas

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"The Infinitely Long, Partial-Arc, Self-Acting Bearing - A Method of Solution for Full Range of the Compressibility Number," C.H.T.Pan, R.J.Wernick, H.S.Cheng and L. Ting, MTI 64TR50.

"The Static and Dynamic Characteristics of the Spiral Grooved Thrust Bearing," S.B. Malanoski and C.H.T. Pan, MTI Report 64TR11, (published also as ASME Paper 64-LUB-9).

"Characteristics of Herringbone-Grooved Gas Lubricated Journal Bearings," J.H. Vohr and C.W. Chow, MTI Report 64TR15 (published also as ASME Paper 64-LUB-5).

"Research on Gas Lubrication at High Temperature and Low Flow Rates," M.W. Eusepi, J. Meacher and P. Lewis, MTI Report 64TR35, (Fourth Quarterly Progress Report).

"Research on Gas Lubrication at High Temperature and Low Flow Rates," M.W. Eusepi, and P. Lewis, MTI Report 64TR53, (Fifth Quarterly Progress Report).

"Stability Analysis of Gas-Lubricated, Self-Acting, Plain, Cylindrical, Journal Bearings of Finite Length, Using Galerkin's Method," H.S. Cheng and C.H.T.Pan, ASME Paper No. 64-LubS-5.

"Linearized PH Stablity Theory for Finite Length, Self-Acting Gas-Lubricated, Plain Journal Bearings,"C.W. Ng, ASME Paper 64-LUB-28.

"The Stability of an Elastic Rotor in Journal Bearing with Flexible Damped Supports," J.W. Lund, Submitted for Publication by ASME.

"A Theoretical Analysis of Whirl Instability and Pneumatic Hammer for a Rigid Rotor in Pressurized Gas Journal Bearings," J.W. Lund, Submitted for Publication by ASME.

"The Selection and Evaluation of Materials and Lubricant Films for Gas-Lubricated Gyro Bearings," S.F. Murray and M.B. Peterson, MTI Report 64TR1.

"Thermal Considerations of the Clark Brothers Model CSG-1 Rotor and Bearings," J. W. Bjerklie, MTI Report 64TR48.

"Analysis of Spiral Grooved, Gas-Lubricated Spherical Thrust Bearings," C.H.T. Pan, MTI Report 64TR55.

"Evaluation of Bearing Material Combination of NASA Turbine Compressor," S.F. Murray, MTI Report 64TR56.

"Spectral Analysis of Gas Bearing Systems for Stability Studies," C.H.T. Pan, MTI Report 64TR58.

"Phase I - Final Report Bearing Analysis and Preliminary Design Studies," C.H.T. Pan, MTI Report 64TR66.

"Grooved Bearings End Effect," H. Poritsky, MTI Report 64TR26.

"Gas-Lubricated Spiral-Grooved Conical Bearing," C. Chow, MTI Report 64TR27.

Organization's Computer Programs

Description	Sponsor
A large number of computer programs have been prepared, some for research investigations and others for design calculations of gas bearing performance and of rotor dynamics. Some of the design programs are listed below.	
Critical speeds and rotor response of elastic rotors in flexible bearings and pedestals. (These programs are based on the Holzer and Myklestad-Prohl analyses. Both the bearings and the pedestals are introduced as sets of stiffness and damping coefficients. Gyroscopic effects are included. Single shaft rotors or multi-shaft rotors connected by spline couplings can be treated).	Internal
Dynamic response of a vertical rigid rotor supported by an eccentrically attached flexible shaft and running in elastically mounted, viscously damped bearings.	AEC
Balancing of rotors. (The circumferential and axial locations of mechanical unbalances are calculated from response magnitudes and phase angles measured in several planes along the rotor).	Internal
Static and dynamic characteristics of self-acting journal bearings (several programs have been prepared using linearized Ph, Galerkin and finite difference treatments).	ONR
Characteristics of plain and grooved spherical and conical bearings (several programs were prepared, principally under commercial sponsorship for design calculations with specific geometries).	Various
Herringbone grooved journal bearings (calculates the steady state performance and instability threshold of this type of bearing).	ONR
Stiffness and flow of externally pressurized and hybrid journal and thrust bearings.	NASA
Stiffness and flow of externally pressurized pads.	Air Force
Squeeze film bearings (initial programs were asymptotic solutions for load capacity and stiffness of thrust bearings. Later programs were for: (a) edge corrections for thrust bearings, (b) power loss calculations, (c) asymptotic solution for journal bearings, including non-uniform excursion modes, (d) design of iso-elastic bearings).	Internal (initial programs) NASA (later programs)
Design program for helical grooved thrust bearings, including compressibility and variable Λ effects.	Internal
Design program for tilting pad journal bearings (the pad data is stored in computer memory. The program calculates the design information for composite bearing characteristics such as pivot film thickness, power loss, stiffness, pad resonances, pivot stresses and others, for the specific bearing geometries, gas viscosities, load and speed ranges of interest).	Internal

Areas of Present Research

Description	Theoretical	Experimental	Sponsor
Dynamic Analysis of Spiral Grooved Journal and Thrust Bearings	X	X	M.I.T.
Application of Galerkin's Method to Partial Arc Bearings	X		O.N.R.
Generalized Stability Analysis	X		O.N.R.
Air Hammer and Hybrid Instability	X		A.S.D.
Generalized Design Data on the Externally Pressurized Gas Bearing	X		O.N.R.
Analysis of the Combined Journal-Thrust, Externally Pressurized Gas Bearing	X		N.A.S.A.
Representation of the Pressure Distribution Around Gas Bearing Feeder Holes	X	X	N.A.S.A.
Fractional Frequency Whirl and Resonant Whip	X	X	Internal
Response of Gas Bearing Supported Rotors to Dynamical Forces	X		O.N.R.
Threshold of Pneumatic Hammer	X		N.A.S.A.
High Temperature Externally Pressurized Gas Bearings	X	X	A.S.D.
Capability of Gas Bearing Supported Rotors to Sustain Dynamic and Shock Loads	X	X	O.N.R.
Gas Bearing Materials (S.F. Murray)		X	Internal
Squeeze Film Bearings		X	N.A.S.A.
Dynamic Analysis of Tilting Pads	X		Internal
Foil Bearings	X	X	Internal
Development of Gas Bearings and Rotor Dynamics Analysis for Brayton Cycle Turbomachinery	X	X	N.A.S.A. thru Pratt & Whitney Aircraft

Recommended Areas of Research and Development

In the Area of Turbomachinery, the following Developments are needed:

Gas bearings capable of operation in a non-isothermal environment, i.e. over wide temperature ranges and in the presence of steady state and transient thermal gradients, without need for external cooling or heating provisions.

Gas bearings for support of flexible rotors.

Bearings for operation with two-phase flow, e.g. vapor lubricated bearings.

Areas Where Gas Bearings Have Been Applied

Applications:

- Compressors
- Blowers
- Fans
- Gas Turbines
- Gyroscopes (in conjunction with other organizations)
- Dental Drills (in conjunction with other organizations)

Organization Responding - NASA - George C. Marshall Space Flight Center
Huntsville, Alabama

Individual(s) Responding - P. H. Broussard

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"Static Load and Flow Equations for a Double Acting, Journal Fed Externally-Pressurized Thrust Bearing," P.H. Broussard, J. Burch and E. Martz, published in Astrionics Research and Development Report No.2 at George C. Marshall Space Flight Center in Huntsville.

Several Working Papers on Division and Laboratory Level on Gas Bearings and Related Topics.

Organization's Computer Program

Description	Sponsor
Double Acting Thrust Bearings (No.2)	N.A.S.A.

Areas of Present Research

Description	Theoretical	Experimental	Sponsor
Squeeze Film Bearings	X	X	N.A.S.A.
Externally Pressurized Gas Bearings	X	X	N.A.S.A.
Hydrodynamic Bearings	X	X	N.A.S.A.

Recommended Areas of Research and Development

Efficient Practical Application of Squeeze Film Principle

Areas Where Gas Bearings Have Been Applied

Gimbal Bearings for Gyroscope Spin Motors

Externally Pressurized for Gyroscopes

Torque Measuring Device

Support for Stabilized Platform Checkout

Satellite Simulator

Gas Transfer Coupling

Moment of Inertia Measuring Device

Center of Gravity Indicator

Load Support for Horizontal Shake Table

Jig Supports Used during Final Mating of Large Missile Sections

Hydrodynamic Bearings

Bearings for Gyroscope Spin Motors

Bearings for Gas Pump

Squeeze Film Bearings

Gimbal Bearings for Gyroscopes (presently in R&D)

Organization Responding - NASA - Lewis Research Center, Cleveland Ohio

Individual(s) Responding - G. K. Fischer

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"Some Instabilities and Operating Characteristics of High-Speed Gas-Lubricated Journal Bearings," G.K. Fischer, J.L. Cherubim and D.D. Fuller, ASME Paper 58-A-231.

"Some Static and Dynamic Characteristics of High-Speed Shaft Systems Operating with Gas-Lubricated Bearings," G. K. Fischer, J.L. Cherubim and O. Decker, First International Symposium on Gas Lubricated Bearings, O.N.R., ACR-49.

"Experiments with Rotating, Ten Inch Diameter Externally-Pressurized Air Thrust Bearings," Z.N. Nemeth and W.J. Anderson, First International Symposium on Gas Lubricated Bearings, O.N.R., ACR-49.

Organization's Computer Program

Description	Sponsor

Areas of Present Research

Description	Theoretical	Experimental	Sponsor
Dynamic Characteristics of Gas Bearings	NASA	NASA	N.A.S.A.
General Stability Theory as Applied to Rotating Systems	FIL	NASA	N.A.S.A.
Radial Flow Turbo-Compressor on Gas Bearings - Brayton Cycle Contract No. NAS3-2778.	AiRe-search	AiRe-search	N.A.S.A.
Axial Flow Turbo-Compressor on Gas Bearings - Brayton Cycle Contract No. Nas3-4179.	P&W MTI-FIL	P&W	N.A.S.A.
Turbo-Alternator on Gas Bearings - Brayton Cycle Contract No. NAS3-6013	P&W MTI-FIL	P&W	N.A.S.A.
Brushless Rotating Electrical Generator for Space Power Systems - Brayton Cycle Contract No. NAS3-2783	Lear Siegler MTI		N.A.S.A.

Recommended Areas of Research and Development

Study and Experimental Definition of Characteristics of Motors and Alternators for Space Application as They Affect Gas Bearing Design With Regard to Interactions and Net Effects of Load and Stability.

Study and Experimental Investigation of Pivot Material and Design for High Temperature (1000°F) Tilting Pad Bearings for 10-20,000 hours, Life, Transport, Launch, Boost and Temperature Cycling Conditions based on Present State of the Art.

Recommended Areas of Research and Development (cont'd)

Study of Tilting Pad Pivot Motion with a Basic Experimental Investigation on Nature of Pivot Wear in Inert Gases at High Temperature (1000^{o}F) for 10-20,000 hours Life at Turbomachinery Speeds with Material Tests.

Journal and Bearing Material Survey of Literature and Experimental Investigation with Special reference to Operation in Inert Gases at High Temperature (1000^{o}F) for 10-20,000 hours, Transport, Launch, Boost, Multiple Restart Capability and Temperature Cycling during Ground Tests.

Thrust Bearing Design Investigation with Hydrodynamic starting for Auxiliary Pressure Supply at Low Ambient Pressure, High Temperature and High Speeds. This is to include Comparative Performance of Different Designs for Load, Stability, Misalignment, Interactions with System and Net Effects.

Design Study of High Temperature Mounting Configuration for Fixed and Tilting Pad Journal and Thrust Bearings to Accommodate High-Speed High-Temperature Turbomachinery with no cooling requirements including Mechanical Compensation Devices for Thermal and Centrifugal Distortions.

High Temperature Machinery Design Studies and Experiment for Brayton Cycle Axial and Radial Flow Turbomachinery, Alternators and Electric Motors with no Cooling Requirements. Specific Design Consideration is necessary for Manufacturing Procedures, Materials, Thermal Isolation and Design Configuration.

Study of Effects of Rotating, Pulsating and Shock Loads on Fixed and Tilting Pad Journal and Thrust Bearings with Special Reference to the Number of Sectors or Pads Affecting Stability and Load Capacity.

An Analytic and Experimental Study of Operation at or near System Criticals with Special Reference to Self-Acting Thrust and Radial Bearings.

Hybrid Bearing Design Criteria Study including Orifice Entrance Effects for Optimum Conditions for Load Stability, Power Loss and Clearance at Low Supply and Ambient Pressures.

Pneumatic Hammer Detail Design Criteria Study and Experimental Investigation at Low Supply and Ambient Pressures with Special Reference to Hydrostatic Starting and Hybrid Bearings.

Organization Responding - Oak Ridge National Laboratory, Oak Ridge, Tenn.

Individual(s) Responding - D. L. Gray

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"Operating Characteristics of Gas-Bearing Compressors Built by Bristol Siddeley Engines Ltd.," USAEC Report, TID-7631, April 2-4, 1962.

"Tests Using Hydrostatic Gas Bearings," USAEC Report, TID-7690, November 4-6,1963.

Organization's Computer Programs

Description	Sponsor
Gas Lubricated Journal Bearings - Pressure Distribution in Finite, Plain Cylindrical Journal Bearings.	A.E.C.

Areas of Present Research

Description	Theoretical	Experimental	Sponsor

Recommended Areas of Research and Development

Development of Gas Lubricated Bearings for Use in Compressors with Motor Ratings to 200 hp.

Areas Where Gas Bearings Have Been Applied

Oak Ridge National Laboratory has Purchased Three Gas Bearing Compressors for Use in In-Pile Loop Service.

Organization Responding - Rocketdyne, Canoga Park, California

Individual(s) Responding - R. Spies

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"Lateral Vibration of Rotor Supported by Bearings Having Arbitrary Force Characteristics - Part I - Analysis," F. Shen, in preparation for ASME.

Organization's Computer Program

Description	Sponsor
IBM 7094 Computer Program for a Major Part of the mentioned report's analysis.	

Areas of Present Research

Description	Theoretical	Experimental	Sponsor
Stability of L.M. Journal Bearings	X	X	R.T.D.
Stability of Hybrid Bearings	X	X	R.T.D.

Recommended Areas of Research and Development

Stability of Turbulent Bearings

Areas Where Gas Bearings Have Been Applied

Support Bearings for Liquid Metal Lubricated Test Rig

Organization Responding - Thompson Ramo Wooldridge Inc., Cleveland, Ohio

Individual(s) Responding - O. Decker

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"Some Static and Dynamic Characteristics of High Speed Shaft Systems Operating with Gas Lubricated Bearings," G. Fischer, J.L. Cherubim and O. Decker.

"Gas Bearing Development at Stratos," O. Decker and J. Yampolski.

"The Application of Air Lubricated Bearing to the TVXL 170 Turbo-Expander," O. Decker.

"Gas Bearing Designs for Helium Circulators," O. Decker.

"Development of Gas Bearings for a High Temperature, Vacuum Radiation Cooled Motor," Somogyi.

"The Development and Application of Gas Lubricated Tilting Pad Bearings to Brayton Cycle Turbomachinery," O. Decker, Dedelow and Cooley.

"A Simplified Technology for the Analysis of Preloaded Tilting Pad Bearings," O. Decker, Somogyi and Dedelow.

"Critical Speed Calculation Methods including Bearing Stiffness," Gall.

Organization's Computer Program

Description	Sponsor
Spiral Groove Thrust Bearings - Based on Whipple Tech.	T.R.W.
Critical Speeds & Vibrational Characteristics of Shafts on Flexible Supports - Based on Modified Prohl & Myklestad Method.	T.R.W.
Hybrid Bearing Analysis Technique - Based on Laminar and Incompressible Flow.	A.E.C.

Areas of Present Research

Description	Theoretical	Experimental	Sponsor
Gas Lubricated Tilting Pad Bearings	X	X	T.R.W.
Gas Lubricated Hybrid Bearings	X	X	T.R.W.

Recommended Areas of Research and Development

Tilting Pad Gas Bearings

Extend Analytical Techniques and Computer Programs to Generate Design Curves for Larger Range of Λ (up to 20) and B/L Ratios (from 0.5 to 3.0) and include Influence of Low Ambient Pressure ($P_a < 5$ psia).

Verify experimentally.

Analytically, establish Optimum Pad Numbers (Three, Four or More)

Experimentally establish Optimum Pivot Configuration, Material for High Temperature, Zero G Operation and Suitable Schemes for Providing Proper Preload.

Extend Analysis to include Reynolds No. > 2000.

Recommended Areas of Research and Development (cont'd)

Hybrid Gas Bearings

Establish Useful Analytical Techniques to include the Influence of Rotation.

Establish Influence of a Variety of Supply Pad Configurations.

Include Influence of Non-Laminar Flow in Bearing Clearance Space.

Experimentally Verify the above Analytical Predictions.

Establish Useful Analytical Techniques to Predict Regions of Pneumatic Instability.

Establish Parameters which Influence Whirl Ratios Greater than 2 (i.e. Fractional Frequencies $< 1/2$).

Areas Where Gas Bearings Have Been Applied

High Temperature ($1000^{\circ}F$) Vacuum Radiation Cooled Motor (self-acting gas bearings).

High Speed Turbo-Supercharger (hybrid gas bearings).

Turboalternator for Space Power Machinery (tilting pad gas bearings).

Organization Responding - Union College, Schenectady, New York

Individual(s) Responding - J. Modrey

List of Papers and Reports on Gas Bearings and/or Rotor Dynamics

"Green's Functions for Journal Bearings," ONR Report, August, 1964.

"The Probability of Intermittent Contact of Externally Pressurized Gas Bearings Excited by Stochastically Defined Forcing of the Bearing Supports," ONR Report, August, 1962.

Organization's Computer Programs

Description	Sponsor

Areas of Present Research and Development

Description	Theoretical	Experimentally	Sponsor
Adjustable Orifice for Externally Pressurized Bearings (Flake Valve)		X	

Recommended Areas of Research and Development

Data on Actual Discharge Coefficients of Feeders for Hydrostatic Bearings.

Simple but Reliable Design Data on the Non-Laminar Zone Directly Downstream of the Orifice of Hydrostatic Bearings.

Feedback Orifice Control for Hydrostatic Bearings.

Make a Statistical Survey of the Actual Clearance Characteristics of Production Bearings. Express this Clearance in Probabilistic Terms Rather than $h = 1 + \epsilon \cos \theta$. Solve the Reynolds' Equation in Terms of the Stochastically Defined Clearance and Express the Resulting Capacity in Probabilistic Terms. It may turn out that Variations in h^3 from $(1 + \epsilon \cos \theta)^3$ Account for Larger Real Errors than our Present Attempts at Rigorous Analysis Justifies.

Areas Where Gas Bearings Have Been Applied

TABLE 1

ADVANTAGES AND TYPICAL AREAS OF APPLICATIONS OF GAS BEARINGS

	Advantages	Typical Areas of Applications
1.	Thermal Stability at high and low temperatures.	High Speed Turbomachinery High Speed Motors and Generators Aircraft Accessory Equipment Naval Accessory Equipment Cryogenic Equipment
2.	Resistance to Radiation	Nuclear Loop Machinery Space Machinery
3.	No Contamination	Closed Loop Systems Processing & Conveying of Chemicals, Food and Drugs.
4.	Low and Constant Friction	Instruments (e.g. gyroscopes & accelerometers) Control Equipment Dynamometers
5.	Close Position Control	Computers Instruments Precision Spindles Precision Manufacturing Equipment
6.	Long, Maintenance Free, Life	Instruments Nuclear Loop Machinery Space Machinery Naval Machinery

TABLE 2

ENVIRONMENT AND OPERATING CONDITIONS OF TYPICAL, GAS LUBRICATED ROTATING MACHINERY

Environment and Operating Conditions	Where Machines are Used: Fans and Circulators	Compressors	Turbines	Motors and Generators
Environment:				
Radioactive	Nuclear Loops	Isotopic and nuclear power conversion.		
High Purity	Nuclear and Chemo-Nuclear Loops	Isotopic, nuclear and solar power conversion. Brayton and Rankine Cycle Machinery		
		Chemical, Food, Drugs, Refrigeration		Chemical, Food, Drugs, Refrigeration
High Temperature	Nuclear Loops	Brayton and Rankine Cycle Machinery		
		Nuclear and Chemo-Nuclear Loops		
Low Temperature		Cryogenic Compressors	Cryogenic Expanders	Cryogenic Generators
Operation:				
Long Life	All areas, but particularly for inaccessible machinery, e.g., high radiation, space and undersea machinery.			
Low Friction	All, but particularly controls, instruments and dynamometers.			
Low Noise	All, but particularly fans, compressors, turbines, motors and generators.			

TABLE 3

SOME PROBLEM AREAS WHICH MUST BE CONSIDERED IN THE APPLICATION OF GAS BEARINGS TO ROTATING MACHINERY

ITEM	PROBLEM AREAS
Self-acting* (Hydrodynamic)	Instability (Fluid Whirl, Resonant Whip) Dynamic Performance, (Critcal Speeds, Synchronous Whirl, Response to External Vibration) Performance under Misalignment Materials (Compatibility, Fretting, Coefficient of Friction, Stability) Non-isothermal operation (designs to prevent or compensate for distortions and clearance changes)
Hybrid (Externally) Pressurized Bearing with Rotation)	Instability (Fluid, Whirl, Resonant Whip, Pneumatic Hammer) Dynamic Performance (Critical Speeds, Synchronous Whirl, Shock, Acceleration, Response to External Vibration) Performance under Misalignment Lockup Pressurized Flow Requirements Materials (Erosion, Fretting, Stability) Non-isothermal operation (designs to prevent or compensate for distortions and clearance changes without large in flow).
Electric Motors	Magnetic Dissymmetry Electric Resonances Compatibility of Materials with Gases and Vapors Unavailability of Motors with High Power, High Speed, and Light Weight Unavailability of Motors with High Temperature Insulation.
Reliability	Effect of Time on Performance (wear under starts, stops and incidental rubs)

* See Terminology in Appendix 1.

TABLE 4

COMPARISON OF SELF ACTING AND EXTERNALLY PRESSURIZED GAS BEARINGS

Bearing System	Load-carrying capacity	Operating requirements: Max. stable speed	Starting torque	Mtls. Comp.	Auxiliary Equipment.
Externally pressurized (hydrostatic)	Depends on supply pressure & bearing geometry.	Very high	Very low	Minin. problem	Separate compressor or other continuous high pressure supply
Self-acting (hydrodynamic with dry starting)	Limited by speed, bearing geometry and fluid properties	Depends mainly on bearing and rotor geometry, fluid properties	Depends on choice of materials as limited by fluid properties	Carefully select materials for minimum wear during starting and stopping	
Self-acting with hydrostatic start- and stoping	Limited by speed, bearing geometry, and fluid properties	Depends mainly on bearing and rotor geometry, fluid properties	Very low	Minim. problem	Reservoir of fluid for starting, stopping
Hybrid (combined externally pressurized and self-ac. ing)	Depends on supply pressure, bearing geometry, speed, and fluid properties	Depends mainly on bearing and rotor geometry, fluid properties	Very low	Minim. problem	Separate compressor or other continuous high-pressure supply

TABLE 5

GAS LUBRICATED JOURNAL BEARINGS

- Self Acting
  - Cylindrical
    - Ungrooved
    - Grooved
  - Segmented Bearing
    - Elliptical
    - Multi-lobe
    - Step
    - Tapered Land
    - Pivoted Pad
  - Partial
    - Fixed Pad
    - Pivoted Pad
    - Flexurally Mounted Pad
  - Foil
- Squeeze Film
  - Cylindrical
  - Conical
  - Spherical
- Externally Pressurized and Hybrid
  - Single Plane Feeding / Multiplane Feeding
    - Point Admission / Pocket Admission
      - Orifice Compensation
      - Capillary Compensation
      - Porous Plug Compensation
      - Other Methods

TABLE 6

GAS LUBRICATED THRUST BEARINGS

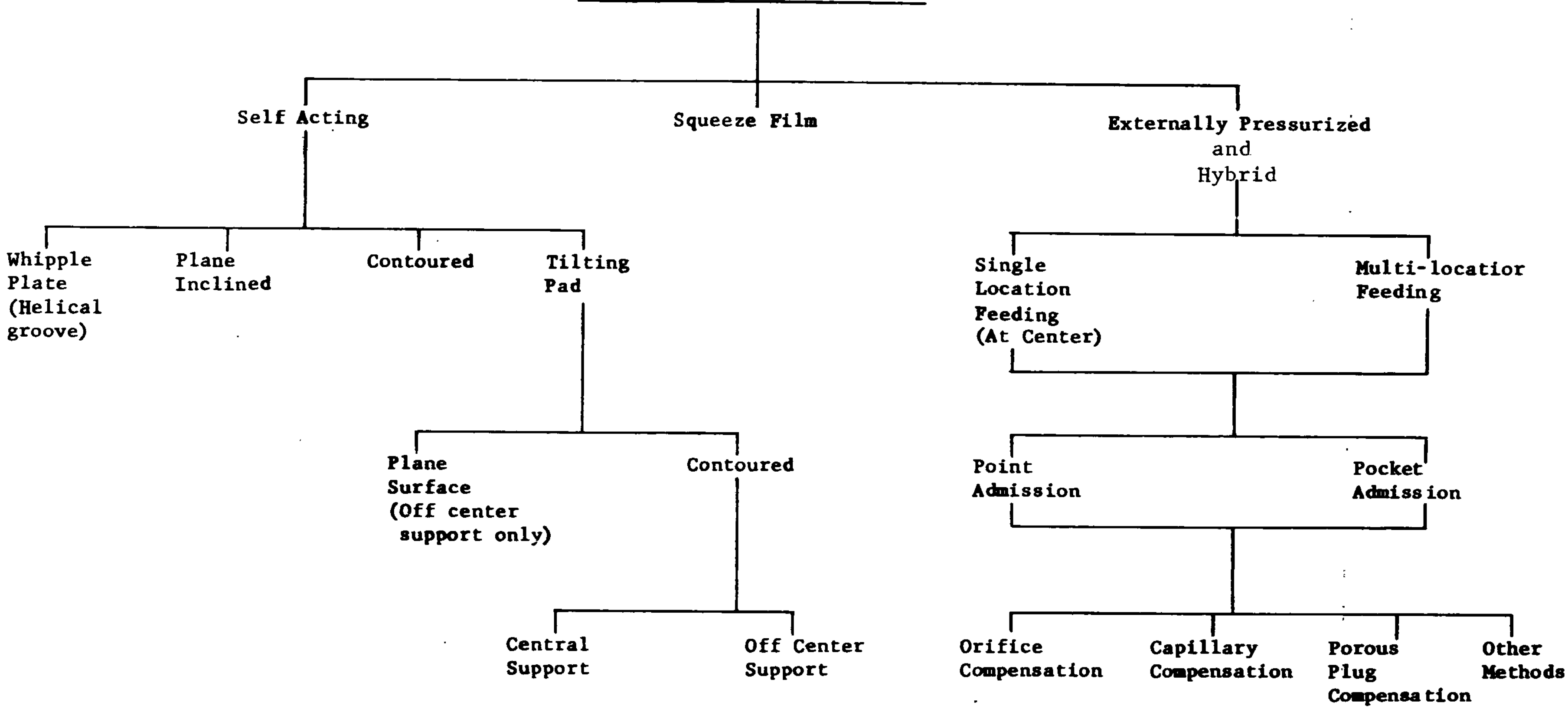

TABLE 7

REQUIRED DESIGN INFORMATION

Steady State Performance

Type	Design Data Required	Design Specifications
Self-Acting	Load carrying capacity Bearing or journal friction Attitude angle Minimum film thickness	Bearing geometry (including tolerance effects) Speed Fluid characteristics Ambient pressure
Externally Pressurized	Load carrying capacity Bearing or journal friction Attitude Angle Minimum film thickness Supply flow requirement	Bearing geometry (including tolerance effects) Speed Fluid characteristics Ambient pressure Supply pressure External flow resistance

Dynamic Performance Information

Type	Design Data Required	Design Specifications
Self-Acting	Region of stable operation Stiffness characteristics Damping characteristics Other film force characteristics (Bearing influences on rotor criticals)	Bearing geometry (including tolerance effects) Speed Fluid characteristics Ambient pressure Rotor flexibility Time varying loads
Externally Pressurized	Region of stable operation Stiffness characteristics Damping characteristics Other film force characteristics	Bearing geometry (including tolerance effects) Speed Fluid characteristics Ambient pressure Rotor flexibility Time varying loads Supply pressure External flow impedance

TABLE 8

SUMMARY OF STATUS OF GAS BEARING ANALYSIS AND DESIGN WORK

I. CURRENT KNOWLEDGE

OPERATION	BEARING GEOMETRY
A. Steady-State Operation	
1. Self Acting Journal Bearings	Plain Cylindrical partial arcs (principally 80° and 95° arcs) (1) Pivot mounted partial arc (1) Spherical (1) (2) Herringbone grooved (1) (2)
2. Self Acting Thrust Bearing	Flat Surface pads (1) Crowned pads Step bearings (1) (2) Helical and Herringbone grooved plates (1) (2)
3. Self Acting Composite Bearings	Spiral grooved conical (2) Spiral grooved spherical (2)
4. Externally Pressurized	Plain cylindrical, discretely fed (1) Plain cylindrical, slot fed (1) Plain cylindrical, pocket fed
5. Externally Pressurized Thrust Bearings (hybrid)	Annular, discretely fed (1) Annular, pocket fed
6. Externally Pressurized Composite Bearings	Spherical (2)
B. Dynamic Operation: Stability and Small Amplitude Oscillation about Steady State	
1. Self Acting Journal Bearings	Plain cylindrical (1) Partial arc Pivot mounted partial arc Herringbone grooved (2) Resiliently mounted plain cylindrical (2)
2. Self Acting Thrust Bearings	Spiral and Herringbone grooved plates (2)
3. Self Acting Composite Bearings	Spiral grooved conical (2) Spiral grooved spherical (2)

(1) Comprehensive design curves have been compiled
(2) Limited to small displacements from centered position

TABLE 8 (Continued)

OPERATION	BEARING GEOMETRY
4. Externally Pressurized Journal Bearings (hybrid)[(3)]	Restrictor compensated plain cylindrical[(1)] Inherently compensated plain cylindrical[(1)]
5. Externally Pressurized Thrust Bearings (hybrid)[(3)]	Restrictor compensated annular plates[(1)] Inherently compensated annular plates[(1)]
C. Dynamic Operation: Large Amplitude Motions	
1. Self Acting Journal Bearings	Plain cylindrical Pivoted partial arc

II RECENT ADVANCES

Foil Bearings - This is the name assigned to the support of very flexible elements on a thin gas-lubricant films. Gas-Lubrication is practiced for tape transport and support of magnetic tapes and tape guides in order to prevent wear and to insure close position control. Both self acting and externally pressurized gas films have been used for this purpose. Recently, interest has been expressed in using foil type bearing surfaces to support turbomachinery rotors, although such applications are still in the preliminary analytical and test stages.

Squeeze-Film Bearings - Under high frequency vibratory motion, positive pressures are generated in thin gas films that can support sizeable loads. Development work is in process to apply this type of gas bearing to gyroscopes, accelerometers and other instruments. Future applications may include jacking of self acting bearings as well as support of some turbomachinery rotors.

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(1) Comprehensive design curves have been compiled.
(3) Quasi-static treatment of restrictor flow was used.

TABLE 9

GAS BEARING MATERIAL COMBINATIONS AVAILABLE FOR USE AT VARIOUS TEMPERATURES IN AN OXIDIZING ATMOSPHERE

Temp. Range	Bearing Materials	Shaft Materials	Problem Areas	State of the Art
Cryogenic	Fused Teflon film on metal substrate	Fused Teflon film on metal substrate	Wear life of Teflon film under start-stop conditions not known. Durability of film during high speed rubs not known.	Basic friction and wear tests indicate feasibility of obtaining at least 100 starts and stops at low stresses 2-3 psi.
-65 to 300F	Carbon-graphites.	Hard chrome plate. Nitrided steels. Hardened steel.	Temperature limitation due to design considerations, such as designing for differential thermal expansion. Bearing may score shaft due to high speed rub.	Proven to be capable of more than 1000 starts and stops at stresses up to 4 psi.
-65 to 500	Du bonded to metallic substrate.	Hard chrome plate. Nitrided surfaces. Hardened steel (40 R_c+). Electrolysed steel.	DU has relatively poor resistance to starts and stops at stress levels > 2 psi.	DU has excellent resistance to damage during high speed rubs.
	Resin-bonded solid lubricants bonded to metallic substrate.		Resin-bonded films require careful preparation and run-in.	Resin-bonded films are capable of 1000 starts and stops at stress levels up to 3 psi but wear rapidly during high speed rubs.
-65 to 900F	Plasma sprayed metal-bonded carbide coating*	Plasma sprayed Al_2O_3 coating*	Poor for high speed rubs.	Excellent start-stop behavior. Negligible wear after 1000 starts and stops at 4 psi stress.
	Plasma sprayed chrome oxide*	Plasma sprayed chrome oxide*	Non-conductive nature of coating makes grooving and elec- measurements difficult.	Excellent start-stop behavior at 4 psi. Very promising for resistance to damage during high speed rubs.
Above 900F	Cermets or ceramics	Cermets or ceramics	No experience available.	Very limited

* Must be used on oxidation - resistant substrate metal to prevent spalling of coating.

TABLE 10

SPECIFICATIONS OF TYPICAL U.S. MACHINES

Machine type	Design is by:	Status	Bearing Design: Type	Bearing Design: Gas Used	Performance (actual or predicted): Speed, rpm	Drive, hp	at inlet: flow, cfm	at inlet: T, °F	at inlet: P, psi	Head, ft.	Coeff. Q/ND^3	(1-stage) Ψ
Motor Driven Compressors, Blowers and Fans												
1 Regenerative	MTI	delivered	self-acting	He	12,000	8	6.1	100	492	6,600	.00603	2.820
2 Centrifugal	MTI	delivered	self-acting	He	12,000	75	972	600	500	7,560	.09230	0.710
3 Modified Centrifugal	MTI	delivered	self-acting	He	18,000	10	58.5	1000	500	11,250	.00625	0.657
4 Two-stage Centrifugal	MTI	delivered	self-acting	--	10,800	35	400	--	--	6,120	.06940	0.540
5 Regenerative	MTI	delivered	self-acting	Air	3,600	0.125	9	70	14.7	638	.01545	2.210
6 Two-stage Regenerative	MTI	designed	self-acting	Air	12,000	10	37.4	200	15	12,450	.01759	1.610
7 Two-stage Centrifugal	MTI	designed	self-acting	Mix	52,500	59 (aero)	336	70	14.5	63,500	.05340	0.632
8 Axial	MTI	prelimi-nary design	self-acting	Air	30,700	250 (aero)	8,430	90	14.5	10,365	.93600	0.270
9 Axial	MTI	prelimi-nary design	self-acting	Air	18,280	250 (aero)	12,880	90	14.5	6,770	.84800	0.270
10 Viscous (Double-sided)	MTI	Prelimi-nary design	self-acting	Air	24,000	--	0.55	150	20	15,270	.00018	1.25
11 Regenerative	MTI	in con-struction	self-acting	Corr. Mol. wt. 4-40	4,000 to 18,000	12	3 to 40	200 to 800	15 to 1000	500 to 1,000	.04	4.0
12 Centrifugal	GE	delivered	ext.-press.	He	24,000	10	57.4	180	215	9,200	.01477	0.688
13 Centrifugal	GE	delivered	ext.-press.	N_2	24,000	10	47.4	180	215	3,350	.04113	0.518
Turbines												
14 Re-entry impulse	MTI	in con-struction	self-acting	Air	11,500	2 (aero)	--	100	26.7	--	--	--
15 Axial	MTI	designed	self-acting	Mix	52,500	59 (aero)	--	1450	48	--	--	--
16 Axial	MTI	in con-struction	ext.-press.	N_2	100,000	20 (aero)	--	1950	100	--	--	--
17 Radial	Sund-strand	completed	self-acting	H_2-O_2	48,000	7 (aero)	--	300	100	--	--	--
18 Radial (Exhaust Temp. -435 F)	NBS	completed	self-acting	Air	600,000	--	--	100	--	--	--	--
Turbocompressors and Turboalternators for Power Conversion												
19 Axial Turb. Radial Comp.	MTI	on test	self-acting	N_2	24,000	115 (aero)	1500	T-1400 C- 100	15	29,000	.11	1.4
20 Axial	P&W MTI	in design	self-acting	Air	50,000	--	--	T-1400 C- 100	6.1 to 12	--	--	--
21 Radial	AiRe-search	in design	self-acting	Air	38,000	--	--	--	--	--	--	--
22 Axial Turb. Homopolar Alternator	P&W MTI GE	in design	self-acting	Air	12,000	--	--	--	6.1 to 12	--	--	--
Electrical												
23 Motor-Generator	MTI	proposed	self-acting	He	3,600	10 KW	--	--	--	--	--	--
Test Rotors and Simulators												
24 Vertical Multi-stage	MTI	delivered	self-acting	--	10,800	40	--	--	--	--	--	--
25 Turbocompressor	MTI	completed	ext.-press.	N_2	35,000	35	--	--	--	--	--	--
26 Vertical and Horizontal, shock and vibration loading	MTI	completed	self-acting and ext.-press.	Air	10,000	--	--	--	--	--	--	--
27 Horizontal	FIL	completed	self-acting	Air	24,000	--	--	--	--	--	--	--
28 Horizontal	FIL	completed	self-acting	Air	18,000	--	--	--	--	--	--	--
29 Horizontal	FIL	completed	ext.-press.	Air	18,000	--	--	--	--	--	--	--
30 Horizontal High Temp. (1950 F)	MTI	in test	ext.-press.	N_2	100,000	--	--	--	--	--	--	--
31 Horizontal	MTI	completed	ext.-press.	Air	60,000	--	--	--	--	--	--	--
32 Horizontal	MTI	completed	self-acting	Air	24,000	--	--	--	--	--	--	--
33 Vertical and Horizontal	MTI, P&W	in design	self-acting	Air	60,000	--	--	--	--	--	--	--
34 Vertical and Horizontal	MTI	in design	self-acting	Air	14,000	--	--	--	--	--	--	--
35 Vertical and Horizontal	AiRe-search	in test	self-acting	Air	45,000	--	--	--	--	--	--	--
Turbine Driven Pumps and Blowers												
36 Feedwater Pump	GE, MTI	designed	ext.-press.	Steam	--	--	--	--	--	--	--	--
37 Forced Draft Blower	MTI	Prelimi-nary design	ext.-press.	Steam	12,500	800 (aero)	30,000	70	14.7	830	--	--

Definitions of Q/ND^3 and Ψ are given in Fig. 7.

TABLE 11

SPECIFICATIONS OF TYPICAL EUROPEAN MACHINES

Machine type	Design is by:	Status	Bearing design Type	gas used	Performance (actual or predicted) Speed, rpm	drive hp	flow, cfm	T, °F	P, psi	head ft
Motor Driven Compressors and Blowers										
1 Centrifugal	Bristol-Siddeley	delivered	self-act.	CO_2	13,700	20	17	575	294	5000
2 Centrifugal	Bristol-Siddeley	was tested	self-act.	CO_2	5,100 to 13,200	35	0.4 to 4	2.51 to 1140	340 to 837	200 to 4300
3 Centrifugal	Bristol-Siddeley	delivered	self-act.	CO_2	2,850	5	14	154	260	500
4 Centrifugal	Bristol-Siddeley	delivered	self-act.	CO_2	16,500	28	14	154	285	3200
5 Centrifugal	Bristol-Siddeley	delivered	self-act.	CO_2	13,000	10	45	693	265	2400
6 Centrifugal	Bristol-Siddeley	delivered	self-act.	CO_2	9,000	10	140	242	165	1900
7 Centrifugal	Bristol-Siddeley	delivered	self-act.	CO_2	11,000	15	110	780	213	2300
8 Centrifugal	Bristol-Siddeley	delivered	self-act.	CO_2	12,500	102	110	832	465	6600
9 Centrifugal	Bristol-Siddeley	delivered	self-act.	CO_2	11,140	26	230	306	278	3400
10 Centrifugal	Bristol-Siddeley	delivered	self-act.	He	20,000	5	16	152	15	20,000
11 Centrifugal	Bristol-Siddeley	delivered	self-act.	He	15,000	17	240	90	406	5,000
12 Centrifugal	Bristol-Siddeley	delivered	self.act.	He	14,800	80	160	632	310	4,200
13. Centrifugal	Bristol-Siddeley	delivered	self-act.	A	13,700	4	100	117	13.62	4,700
14. Centrifugal	Société Rateau	delivered	self-act.	He	11,500	120		716	284	
15. Centrifugal	Société Rateau	in const.	self-act.	He	12,000	100		716	284	
16. Centrifugal	Société Rateau	delivered	self-act.	CO_2	11,500	50		842	354	
17. Centrifugal	Société Rateau	in const.	self-act.	CO_2	11,500	50		842	312	
18. Centrifugal	Société Rateau	in test	self-act.	CO_2	18,000	30		680	850	
19. Centrifugal	Société Rateau	in test	self-act.	He	23,200	10		662	284	
20. Centrifugal	Société Rateau	in test	self-act.	He	23,200	20		122	425	
21. Centrifugal	Société Rateau	in const.	self-act.	CO_2	11,500	250		572	1000	
22. Centrifugal	Société Rateau	delivered	self-act.	He	20,200	3		100	483	
23. Centrifugal	Société Rateau	in test	self-act.	CO_2	11,500	20		752	710	
24. Centrifugal	Société Rateau	in test	self-act.	CO_2	15,000	70		752	850	
25. Centrifugal	Société Rateau	in test	self-act.	He	11,500	60		212	284	
26. Centrifugal	Société Rateau	delivered	self-act.	He	24,500	10		662	354	
27. Centrifugal	Société Rateau	delivered	self-act.	CO_2	12,000	150		932	710	
28. Centrifugal	Société Rateau	delivered	self-act.	UF_6						
29. Centrifugal	Société Rateau	in const.	self-act.	CO_2	12,000	250		842	710	
30. Centrifugal	Société Rateau	in const.	self-act.	Air & He	24,000	20		200	1000	
31. Centrifugal	Brown Boveri	delivered	self.act.	He	11,400	95		662	289	

TABLE 12

SOME RECOMMENDED FUTURE WORK IN GAS BEARINGS

AREA	ITEMS
Analysis and Design	1. Dynamic response or the stability of flexurally mounted bearings (self acting and hybrid)
	2. Vibration and shock load capacity of gas bearing films (self acting & hybrid)
	3. Elastohydrodynamic gas lubrication
	4. Dynamic analysis of foil bearings
	5. Statics and Dynamics of Squeeze film bearings.
	6. Restrictor Flow under dynamic conditions
	7. Development of active restrictor systems
	8. Pneumatic hammer of hybrid bearings
	9. Statics and Dynamics of the hydrostatically supported hybrid bearings.
	10. Dynamic analysis of externally damped bearings.
	11. Two-phase flow in bearing and restrictor passages
Materials	1. Friction and wear in oxidizing, reducing and inert atmospheres
	2. Mechanical behavior of surface films.
	3. Development of high temperature surface films
	4. Dimensional stabilty of bearing and flexure materials at elevated temperatures.
	5. Errosion of bearing and restrictor passages due to impingment of liquid particles in wet vapor streams.
Instrumentation	1. Development of permanent, low cost, film thickness monitoring transducers

TABLE 12 (Continued)

AREA	ITEMS
Instrumentation	2. Development of optical or other transducers with very high frequency response, for film thickness measurement.
Applications to Rotating Machinery	1. Application Studies of gas bearings for various systems, including: (a) Nuclear and chemonuclear loop machinery (b) Brayton Cycle Turbomachinery (c) Naval Turbomachinery (d) Cryogenic Turbomachinery (e) Compressors and blowers (f) High speed motor-generator sets (g) Turbines and turbine drives (h) Aircraft jet engines (i) Aircraft accessory systems (j) Ultra-High speed centrifuges (k) Rankine Cycle turbomachinery (steam and metal vapor turbines) (l) Refrigeration systems
	2. Experimental verification of gas bearing performance in selected systems, using dynamic simulators.

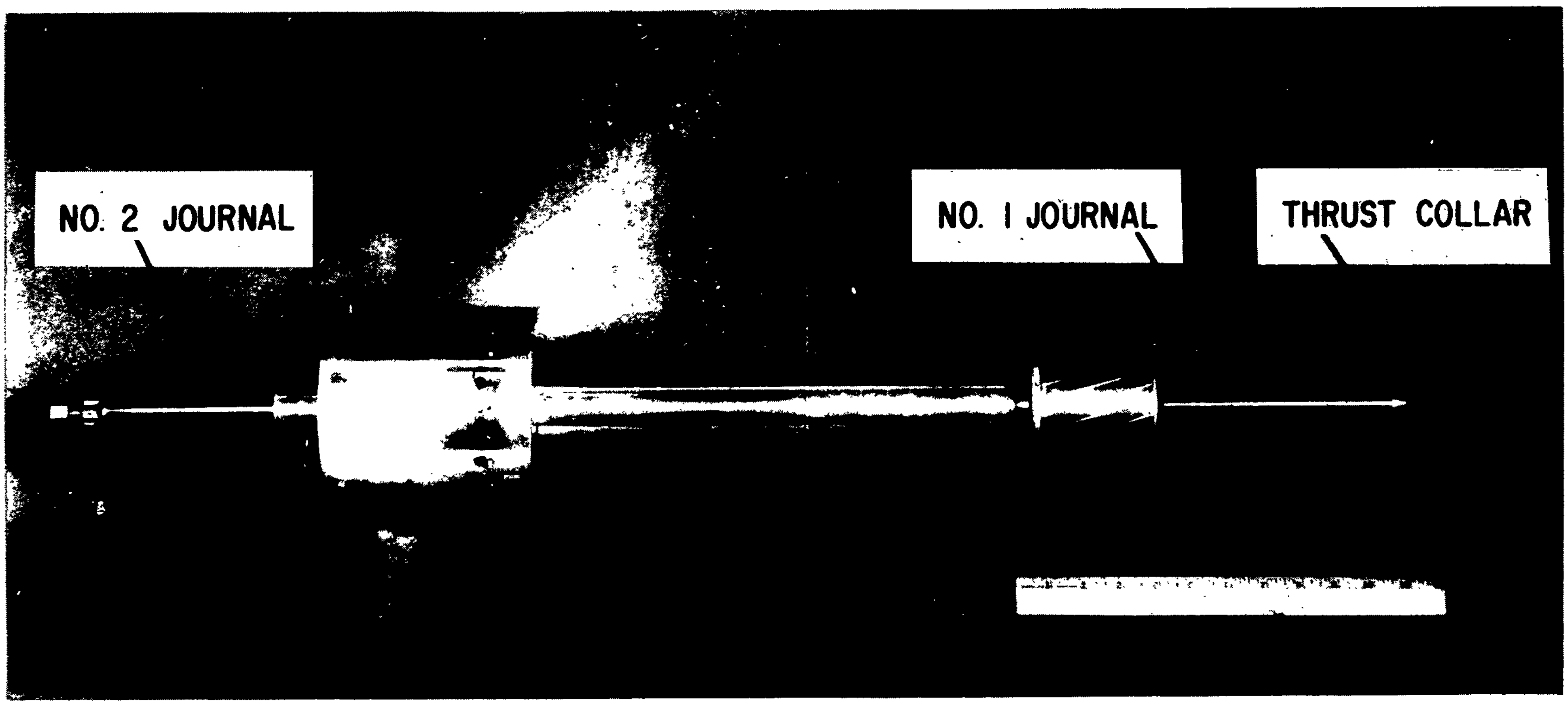

Fig. 1 Shaft Assembly of Gas-Bearing Test Machine

Fig. 2 Test Machine Mounted on Oscillation Test Stand

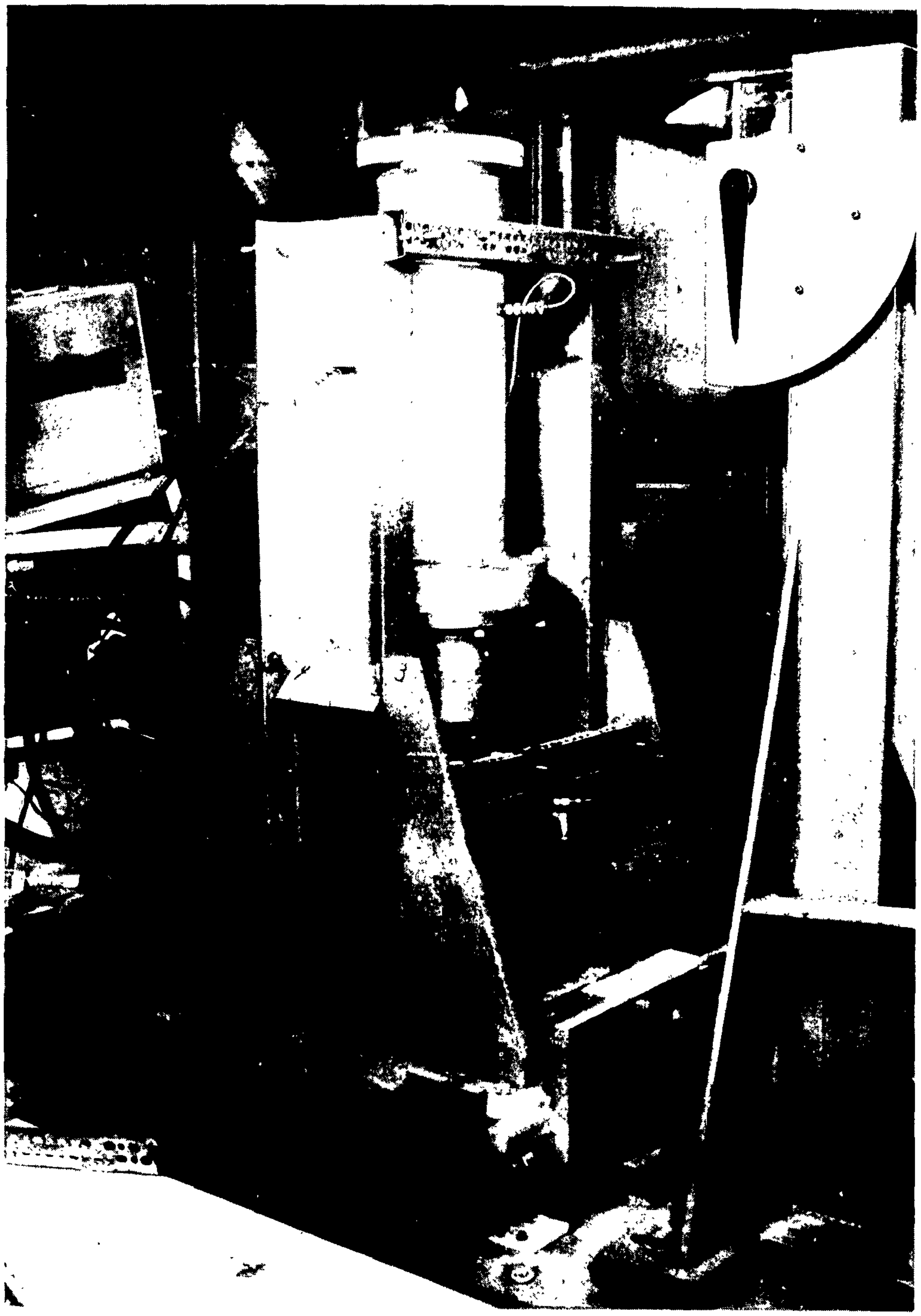

Fig. 3 Test Machine Mounted on Shock Test Stand

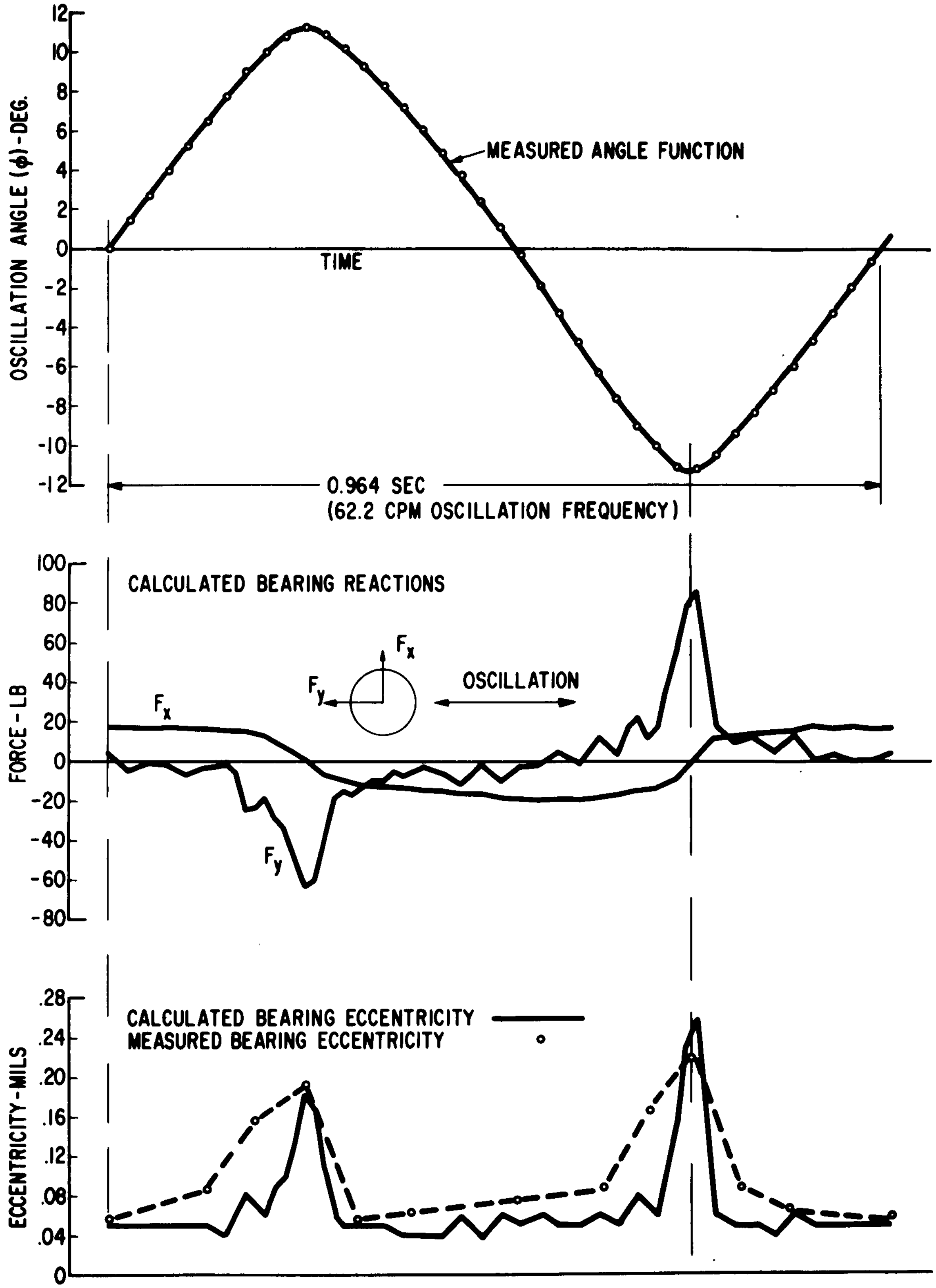

Fig. 4 Comparison of Measured and Calculated Response For Upper Hydrostatic Journal Bearing During Frame Oscillation

Journal bearing supply pressure: 75 psig
θ: 0.0 degrees

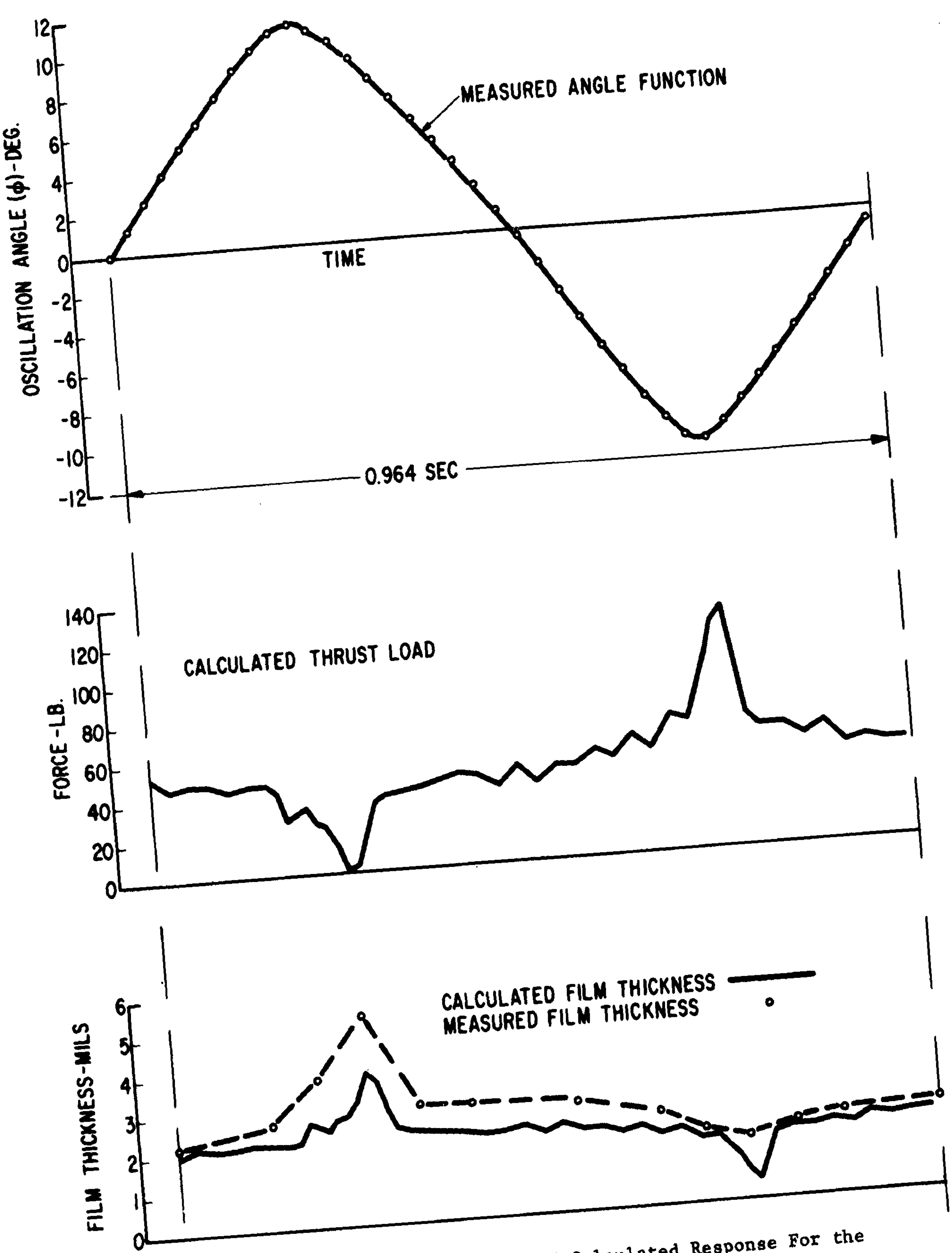

Fig. 5 Comparison of Measured and Calculated Response For the Hydrostatic Thrust Bearing During Frame Oscillation

Thrust bearing supply pressure: 50 psig

θ: 30.0 degrees

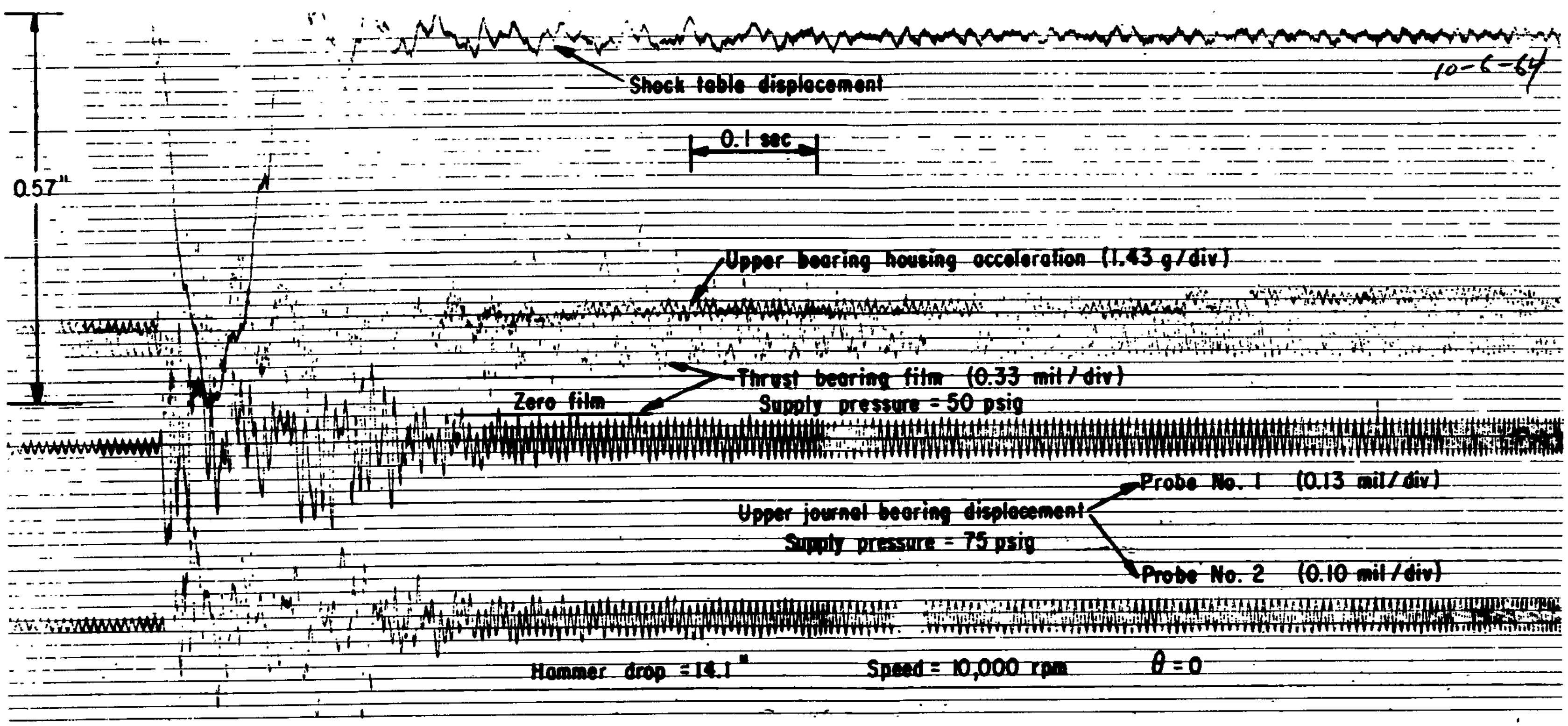

Fig. 6 Dynamic Responses Due to Frame Impact — Hydrostatic Bearing System

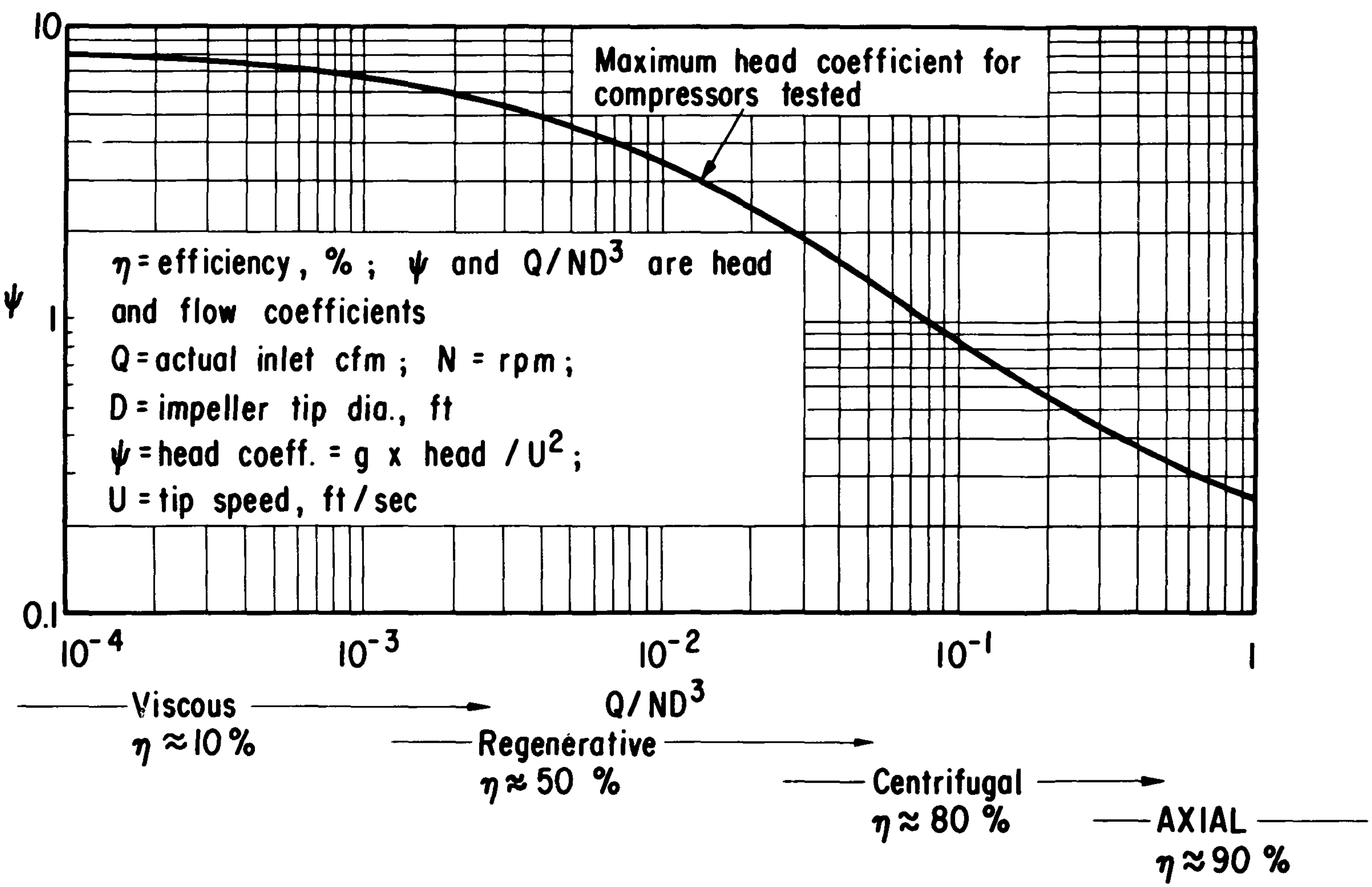

Fig. 7 Range of Head Coefficients per Stage of Current Gas-Bearing Supported Compressors.

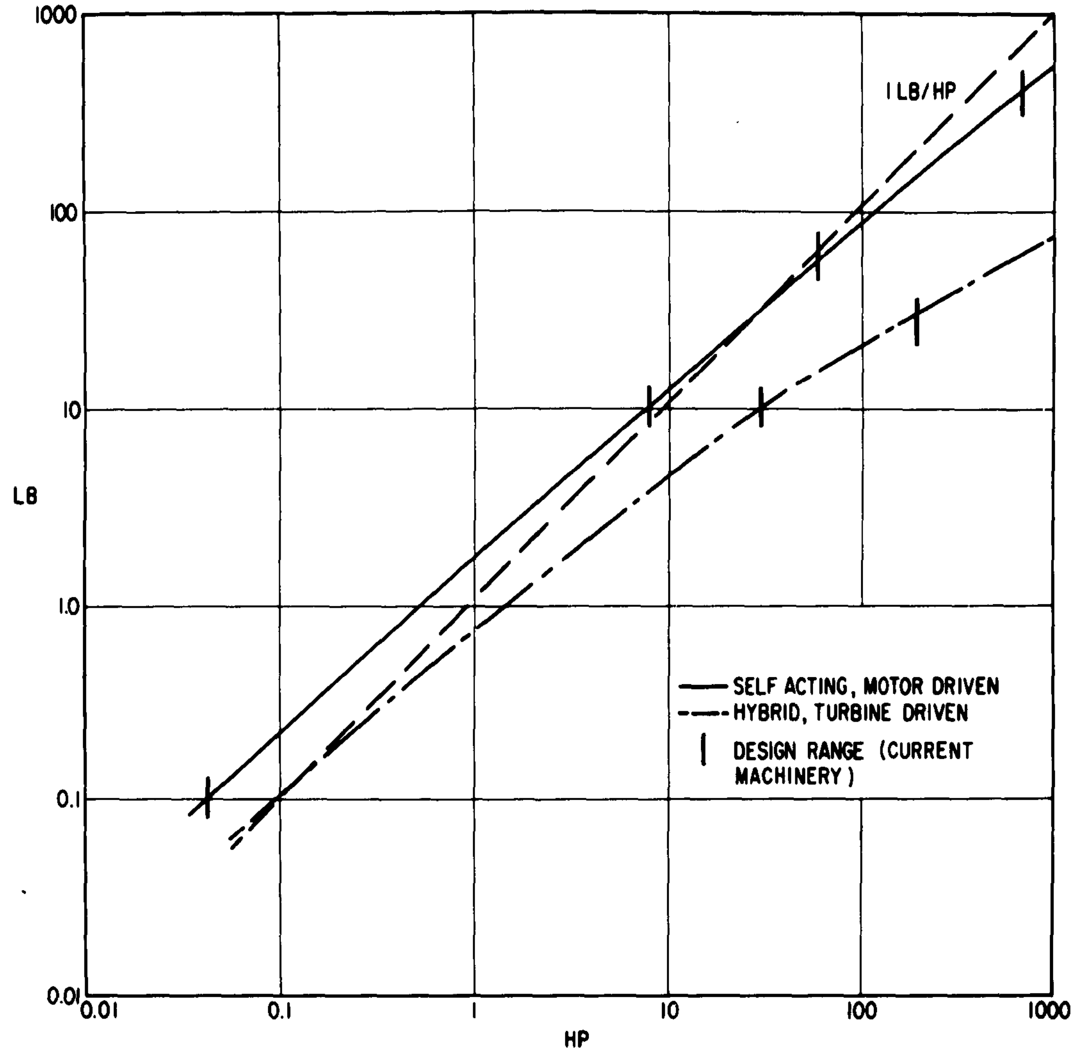

Fig. 8 Weight versus Power Rating of Current Gas-Bearing Supported Rotating Machinery

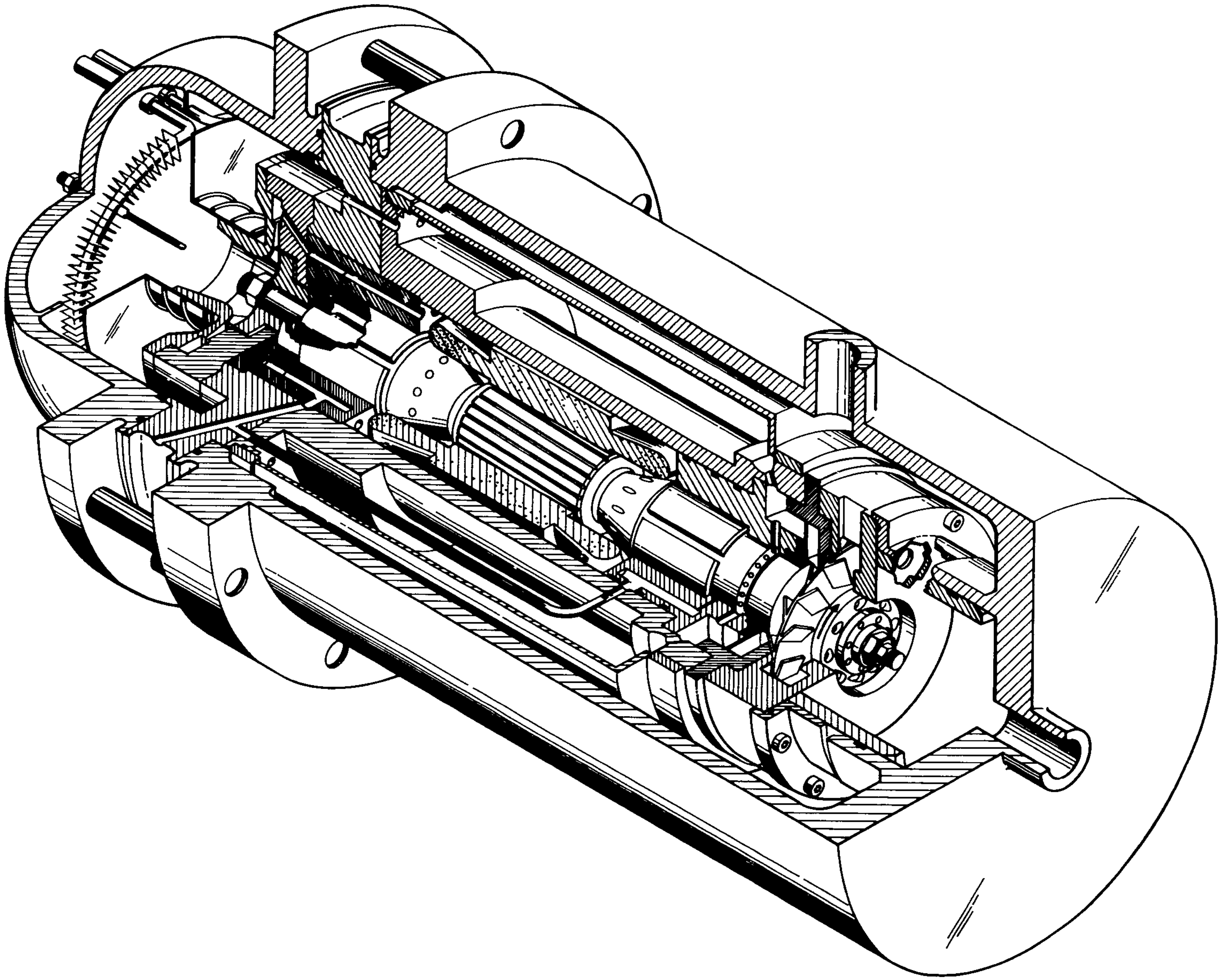

Fig. 9 Regenerative, MTI-Built Gas-Bearing Supported Compressor

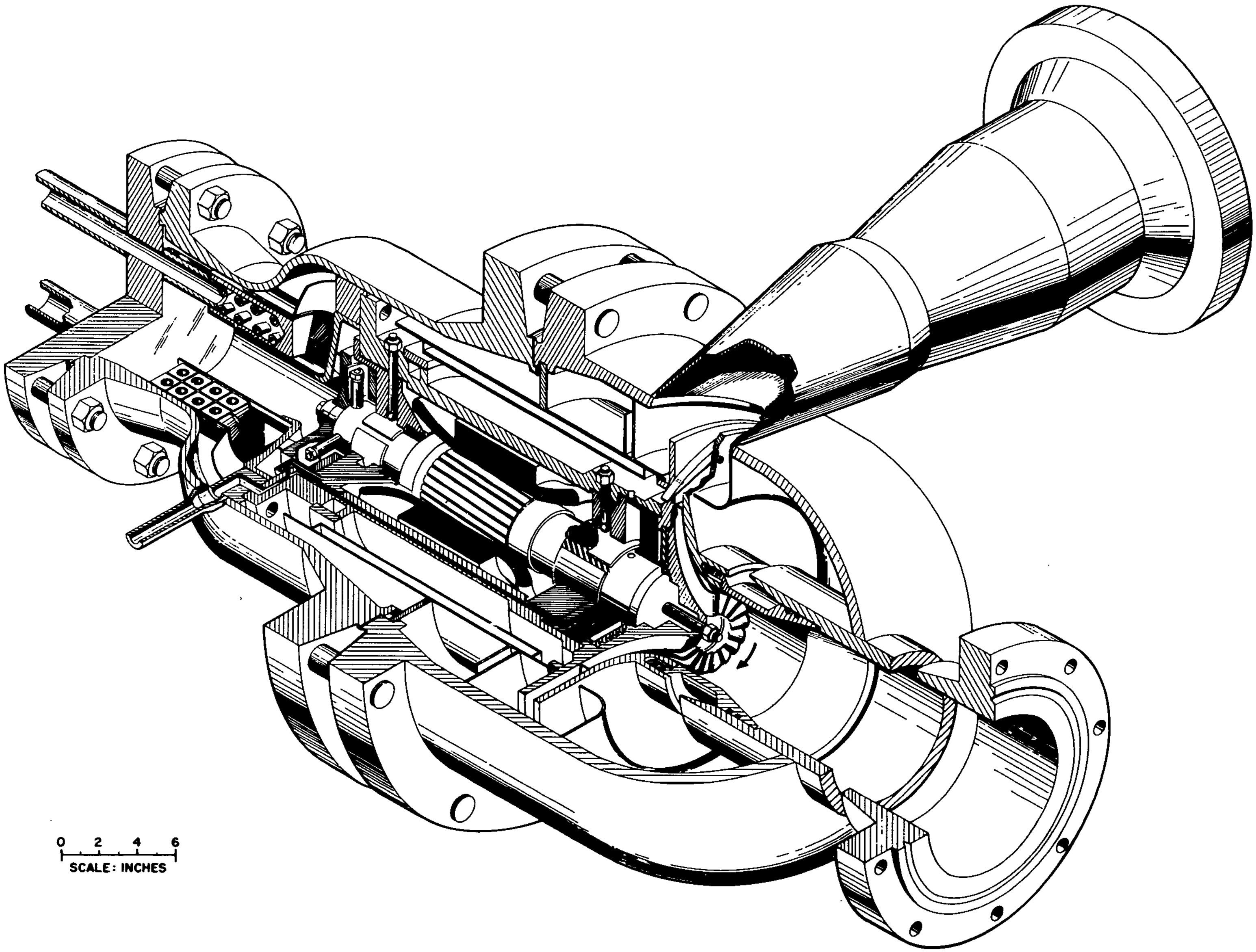

Fig. 10 Centrifugal, MTI-Built Gas-Bearing Supported Compressor

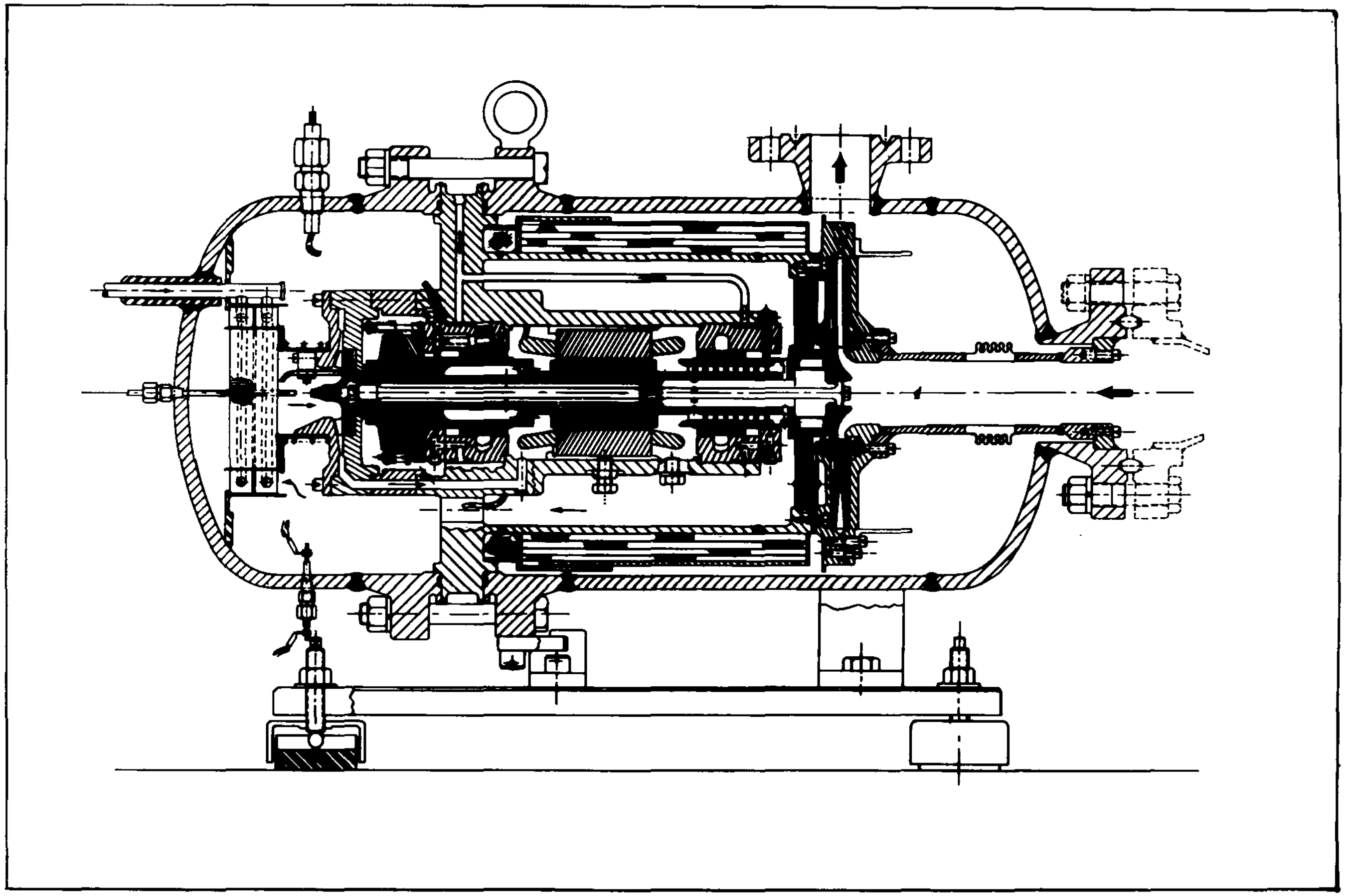

Fig. 11   1000°F, Regenerative, MTI-Built Gas-Bearing Supported Compressor

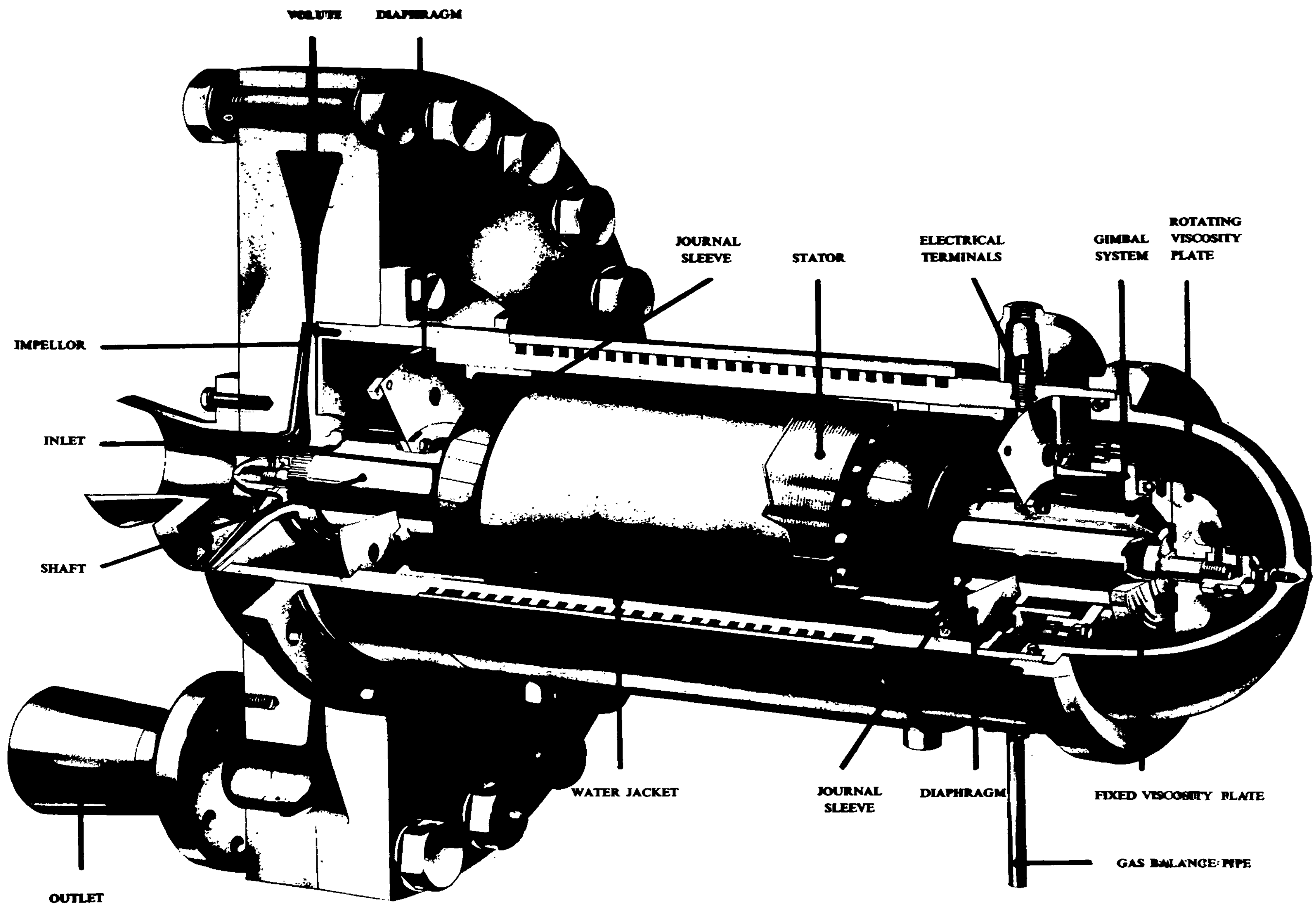

Fig. 12 Centrifugal, Bristol-Siddeley Built Gas-Bearing Supported Compressor

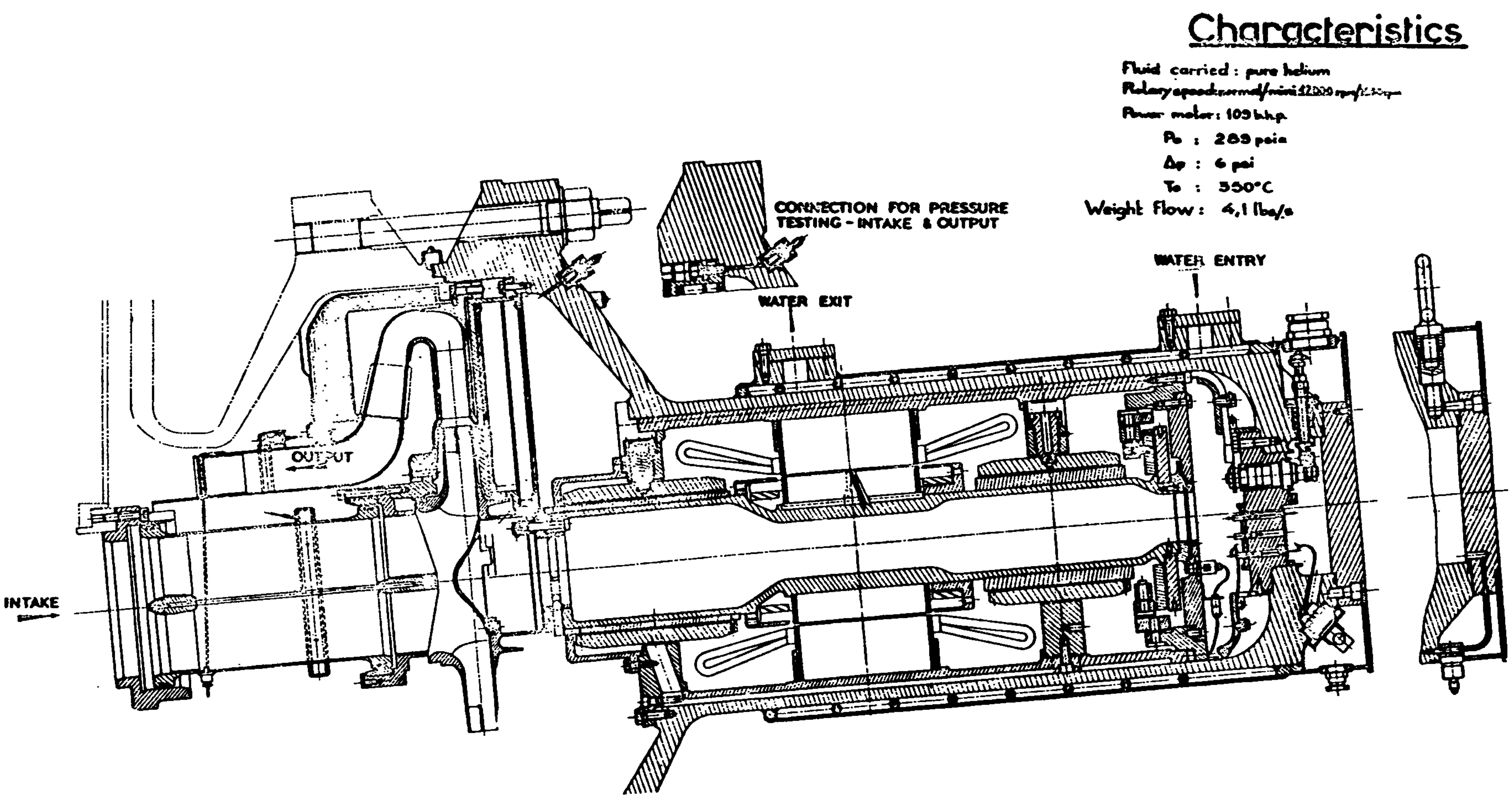

Fig. 13 Centrifugal, Société Rateau-Built Gas-Bearing Supported Compressor

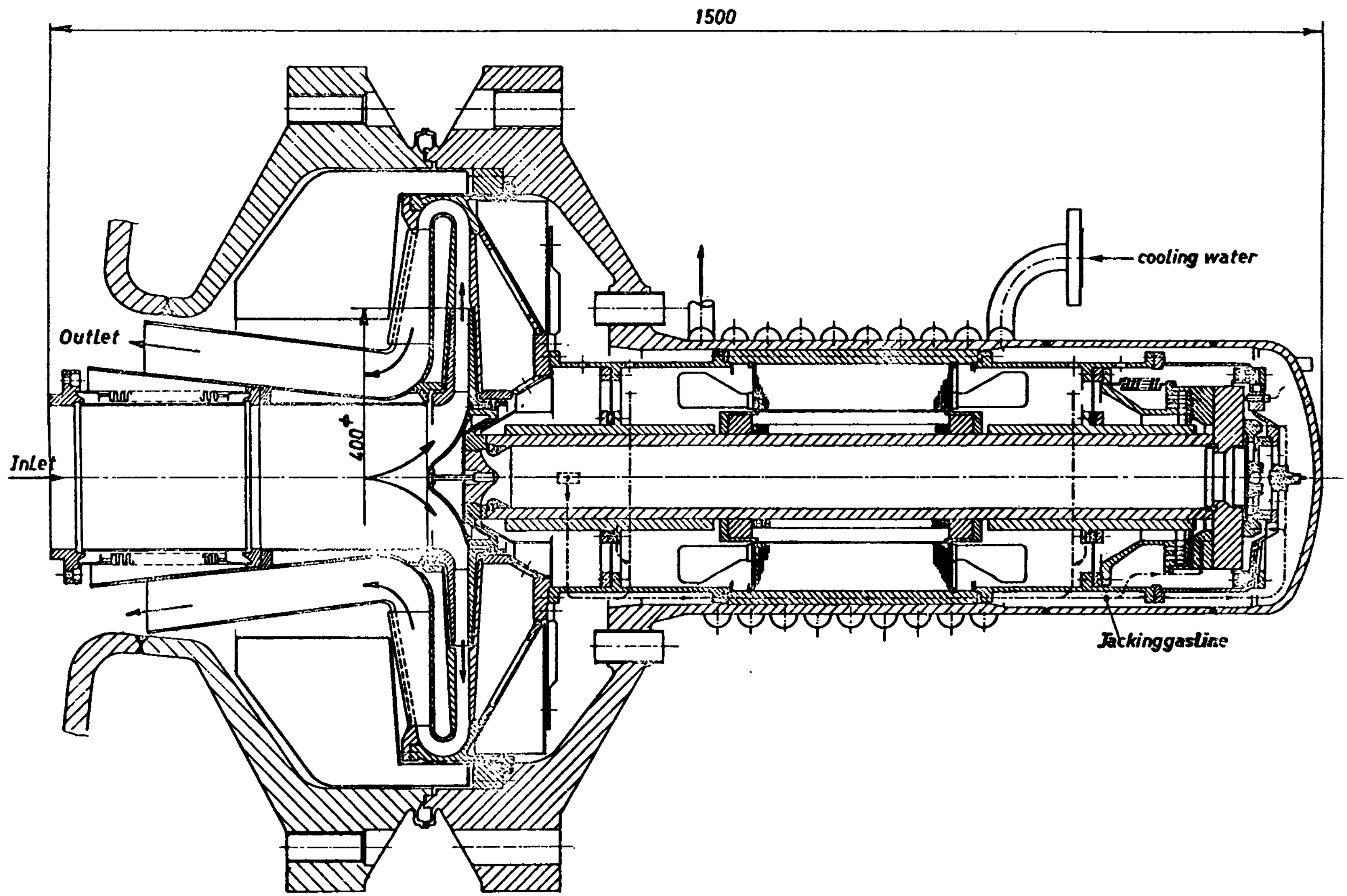

Fig. 14 Centrifugal, Brown Boveri-Built Gas-Bearing Supported Compressor

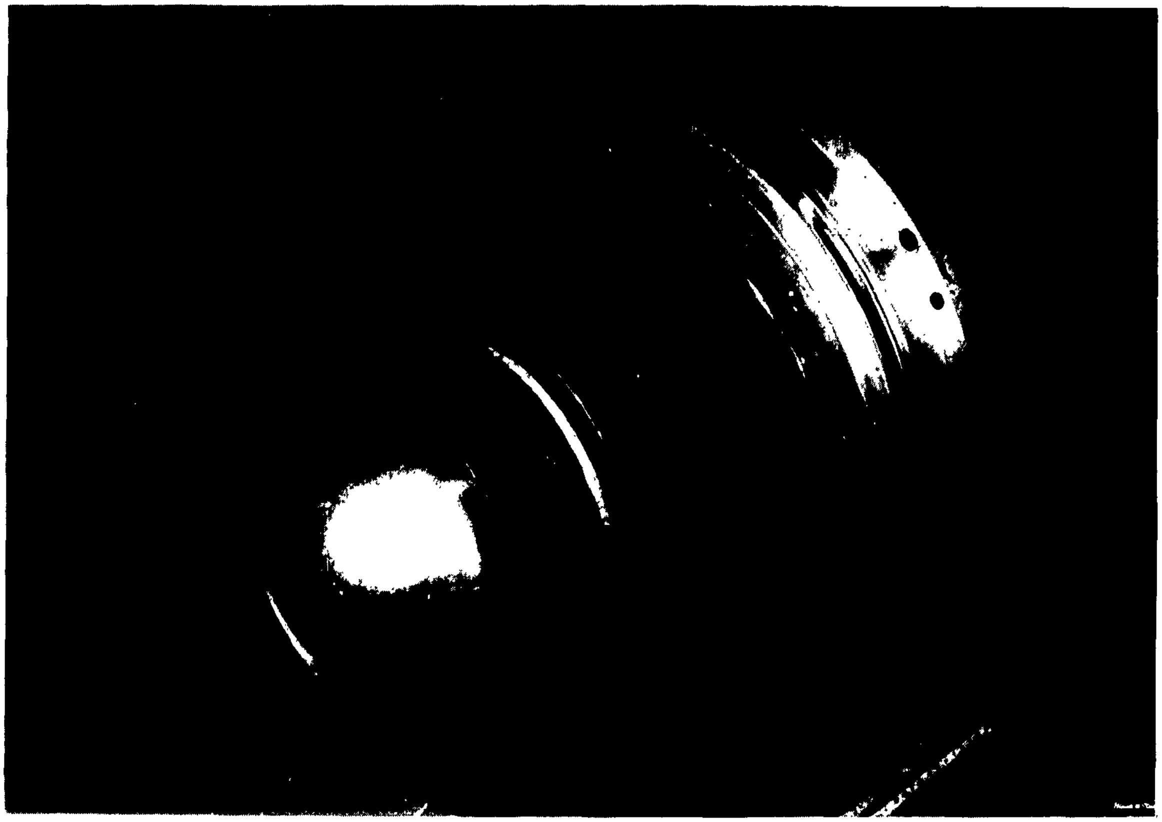

Fig. 15 First Gas Bearing-Supported Gas Turbine — Developed and Manufactured. by MTI

Fig. 16 Rotor of Gas Bearing-Supported Gas Turbine

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13. ABSTRACT

The State-of-the-Art of Gas Bearing Turbomachinery is reviewed, noting that it reflects a transition from research to applications. The application of gas-lubrication to turbomachinery is linked to the advantages inherent in process fluid lubrication and to the characteristics of gases as lubricants. The design data necessary in specific applications of gas bearings is listed and reference is made to the sources where such data is now available. The principal considerations in gas-bearing materials selections as well as the classes of materials now used in different operating temperature ranges are tabulated. The research work currently in progress is noted and the gas bearing turbomachinery that has been produced to date in this country and in Western Europe are listed. Further research in three important areas necessary to further expand the applicability of gas bearings to turbomachinery is recommended. With this as background, the anticipated developments of gas bearing turbomachinery are forecast for the year 1970. Also included in this report are the results of a survey that was made of the gas bearing work currently in progress in various organizations in this country.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Gas Bearings Gas Lubrication Process Fluid Lubrication Turbomachinery Rotating Machinery						

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