

Interim Report

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A BIBLIOGRAPHY (WITH ABSTRACTS)
ON GAS-LUBRICATED BEARINGS

by

Alec Peters
Patricia Devlin

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D. D. Fuller

November 1965

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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THE FRANKLIN INSTITUTE RESEARCH LABORATORIES

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PREFACE

The compilation presented in this bibliography has resulted from the combined effort of the Science Information Service of The Franklin Institute and the personnel of the Friction and Lubrication Laboratory. It has been prepared as a literature survey in support of an experimental and development program of research on gas lubricated bearings. This effort has been jointly supported by agencies of the Department of Defense, Atomic Energy Commission and National Aeronautics and Space Administration, under the administration of the Office of Naval Research.

The bibliography is a continuation of a similar work issued in October 1961. It contains 493 abstracts. It covers the magazine, book, periodical technical report and patent literature, both domestic and foreign. Most of the abstracts are either author's or author modified type. It is arranged in chronological order from January 1961 through December 31, 1964, according to the date of publication. The first two digits of the five digit number of each reference indicate the year. Some 55 sources, which were not recorded in the previous bibliography, are also abstracted (using the prefix 00-). The bibliography is provided with an author index (corporate and individual), subject index and patent index.

While every effort has been made to make this bibliography a comprehensive list of all references for the period covered, the compilers will be grateful to those who would call their attention to any possible omissions in this compilation.

Dudley D. Fuller

00-001

Adams, C.R.

NOW... OIL-MIST LUBRICATION FOR AIR BEARINGS. Prod. Engng.,
vol. 31, no. 35, pp. 54-55. (August 29, 1960).

The article describes ways to prevent galling or seizure in an externally pressurized air bearing. It is done by blowing oil into the air supply and depending on the resulting mist to leave a thin film on the shaft and journal. This film of oil acts as a boundary lubricant and prevents complete metal-to-metal contact during operation or shutdown. The oil-to-air ratio is not critical, and the oil can be recirculated. Best results so far are with the step-type bearing, three versions of which are illustrated.

00-002

Anderson, Norman

SHAFT OR LIKE BEARINGS. U. S. Patent 2,864,552. (to Sir George Godfrey & Partners Limited). Applied August 18, 1954. Issued December 16, 1958.

It is claimed that cylindrical and annular end "gas bearing films or cushions" are formed, so that the use of liquid lubricant may be entirely dispensed with.

00-003

Anonymous.

PIEZO-ELECTRIC PICK-UP PROVIDES ACCURATE VIBRATION MEASUREMENT.
Design News, vol. 12, no. 19, pp. 52-3. (October 1, 1957).

In a machine designed for measuring the high-frequency vibrations of precision ball bearings, low frictional loss and freedom from vibration are obtained by mounting the main spindle in air bearings. Air is supplied to smaller bearing by one row of three equally-spaced inlet holes of 0.025 inch dia. Larger bearing has two rows of holes 0.5 inch from each end. Each row contains three equally-spaced holes 0.025 inch dia. with an additional fourth hole of 0.010 inch dia. at the bottom. Bearing is made in this way because the machine is always loaded in a downward direction. With this arrangement of air inlet holes together with a radial clearance of the order of 0.001 inch, a load up to 25 lb. can be applied to bearing under test. Reaction to axial load is provided by a conical type thrust bearing supplied by air through a central orifice 0.030 inch dia. When load is applied at right-hand end of spindle, the spindle moves left and reduces the gap at conical surface. Increase in escapement resistance at cone produces an increase in pressure at end of spindle which automatically balances axial load.

00-004

Anonymous.

BEARINGS FOR GYROSCOPE ROTORS. Engineer, vol. 194, p. 651.
(November 14, 1952).

Compressed air bearings, distributed by Miniature Bearings Ltd., suitable for different kinds of gyroscopes are described. Diagrams are given and the operation is detailed.

00-005

Archibald, F.R.

A LOOK AT HYDROSTATIC THRUST BEARINGS. Mach. Design, vol. 25, no. 9, p. 170. (September 1953).

Analysis of a bearing having a conical seat is discussed. This type of bearing offers the possibilities of lateral constraint as well as thrust capacity. The load capacity of a bearing employing a spherical seat is also discussed. Equations are presented.

00-006

Bamber, M.J.

BEARINGS WITH FORCE INDICATING MEANS. U. S. Patent 2,908,164.
(to United States of America as represented by the Secretary of the Navy). Applied January 31, 1957. Issued October 13, 1959.

The present invention relates to the testing of aircraft models, and particularly to a system for supporting an aircraft model in a wind tunnel and measuring the magnitude of forces on such a model. More specifically, this invention relates to the utilization of the principal of air-lubricated bearings in a sting-type model-support and force-indicating system. What is claimed is an apparatus for measuring component forces and moments developed by relative motion of a hollow test model in a fluid medium, the apparatus comprising a sting-type tubular support, means for supplying air under relatively high pressure to the interior of the support, bearing means for supporting the test model on the support for limited movement of the model relative to the support, the support and the bearing means fitting within and being enclosed by the hollow test model, the bearing means including an air-lubricated bearing mounted on the exterior of the support in spaced relation thereto to form a clearance space between, the support having a plurality of air-supply ports leading from the interior thereof to diametrically opposite areas of the clearance space, a plurality of pressure tap-off tubes leading from diametrically opposite sides of the clearance space through the tubular support to a point remote from the support, and pressure differential indicating means connected to the remote ends of the tap-off tubes.

00-007

Baumeister, H.K.

AXIAL AND RADIAL THRUST BEARING. U. S. Patent 2,854,298.
(to International Business Machines Corp.) Applied January
13, 1956. Issued September 30, 1958.

This invention relates to axial and radial thrust type bearings and more particularly, to bearings of this type which are lubricated by a fluid lubricant such as air or oil. What is claimed is an axial and radial thrust bearing comprising a longitudinal shaft rotating on its axis; a conically shaped journal on each extremity of the shaft, the vertex of the cone having a predetermined angle; a bearing block in juxtaposition with each journal having a conical hole to receive the journal, the vertex of the cone of each conical hole having a predetermined angle smaller in magnitude than the predetermined angle of the journal; and the bearing block including an aperture intersecting the vertex of the conically shaped hole for supplying a lubricant under constant pressure to the bearing.

00-008

Brugger, R.G.

AUXILIARY BEARINGS FOR SENSITIVE INSTRUMENTS.
U. S. Patent 2,915,902. (to Sperry Rand Corp.)
Applied May 3, 1956. Issued December 8, 1959.

This invention relates to an improved bearing assembly for sensitive position maintaining instruments such as the gyro elements of directional gyroscopes and gyroscopic compasses which maintain a fixed position in azimuth. What is claimed is a bearing assembly for a gyroscopic instrument having a gyro element and a mounting element supporting the gyro element with freedom about a vertical axis comprising a thrust type air bearing having two parts relatively movable about the axis, one of which is fixedly connected to the gyro element of the instrument and the other of which includes an axially extending post with an opening therein through which air is supplied to the air bearing, and an auxiliary bearing having two parts relatively movable about the axis, one of which is connected to the mounting element of the instrument and the other to the post part of the air bearing.

00-009

Buckley, D.H. and R.L. Johnson.

LUBRICATION OF CORROSION-RESISTANT ALLOYS BY MIXTURES OF HALOGEN-CONTAINING GASES AT TEMPERATURES UP TO 1200° F. NASA TN D-197,
November 1959. AD-228 478.

Friction and wear experiments were conducted to explore the effects of high temperature, varied bromine content, and postulated reaction mechanisms on boundary lubrication with reactive gases. Dibromodifluoromethane (CF_2Br_2), monobromotrifluoromethane (CF_3Br), monobromodifluoromethane (CHF_2Br), and sulfur hexafluoride (SF_6) gases were

used to lubricate various nickel and cobalt alloys at temperatures up to 1200°F. A 3/16-inch-radius hemispherical rider under a load of 1200 grams contacted the flat surface of a rotating disk; the usual surface speed was 120 feet per minute. In some cases the surface speed was varied. A 1:1 gas blend of CF_2Br_2 and CF_3Br was found to be an effective lubricant to 1200°F for two metal combinations, Stellite 98M2 on Hastelloy C and Inconel X on Rexalloy 33. The gases CHF_3 and CHF_2Br plus 1 percent SF_6 used to lubricate 98M2 Stellite sliding on Hastelloy C were not as effective (as lubricants) as the gas blend (1:1) CF_2Br_2 - CF_3Br . Postulated reaction mechanisms can be used to select metal-gas combinations suitable for high-temperature lubrication systems.

GO-010 Cobb, W.G.

NEUTRONIC REACTOR FUEL PUMP. U. S. Patent 2,888,878.
(to U. S. Atomic Energy Commission). Applied June 16, 1958.
Issued June 2, 1959.

This invention relates to long-lifetime pumps and more particularly to pumps adapted to circulate radioactive neutronic reactor fuels. The pump comprises a rotatable shaft having first and second ends and is provided with an impeller and impeller housing at its first end. It has a journal rigidly attached to the second end of the shaft, the journal being a solid body of rotation symmetrical about the axis of the shaft, the dimension of the journal, which is perpendicular to the axis of the shaft being divergent in a direction opposite to the direction of the thrust load on the shaft, a hydrostatic gas lubricated bearing member, adapted to receive the journal, provided with a multiplicity of channels adapted to introduce a lubricating gas such as helium to the journal bearing interface, a liquid expansion chamber located adjacent the first end, which communicates with the shaft channel and is provided with liquid gas contacting means, an exit gas aperture, and a liquid return line to the inlet port of the impeller housing, a tubular member surrounding the shaft between the bearing and the expansion chamber and spaced therefrom to provide a continuous channel along the shaft connecting the bearing journal interface and the expansion chamber, whereby at least a portion of the gas escaping from the interface may be conducted to the expansion chamber.

00-011 Constantinescu, V.N.

ON TURBULENT LUBRICATION. Proc. Instn. Mech. Engrs., vol. 173, no. 38, pp. 881-900. (1959).

This paper discusses the hydrodynamic turbulent motion in the lubricant layer. Proceeding from the Reynolds equations and introducing the approximations currently used in lubrication problems, owing to the lubricant film thickness, the general motion equations for turbu-

lent lubrication are written. Using the Prandtl mixing length hypothesis, exact and approximate solutions are obtained for the velocity distribution into the lubricant layer. The results are discussed by pointing out the pressure gradient and the Reynolds number influence on the velocity distributions, as well as the differences with respect to laminar flow. In order to obtain simple formulae, the exact dependence of the rate of flow on the pressure gradient in a dimensionless form is replaced by a linear relation, the slope of which depends on the Reynolds number. This approximation permits obtaining the pressure differential equation in a simple form. The pressure equation is integrated in case of journal bearings, by assuming a constant or a variable viscosity of the lubricant. The results are compared to the experimental data obtained by M. I. Smith and D. D. Fuller and good quantitative agreement is pointed out.

00-012 Cronquist, D.H.

AIR HEAD. U. S. Patent 2,905,768. (to International Business Machines Corp.). Applied September 24, 1954. Issued September 22, 1959.

This patent describes the details of an externally pressurized air bearing for magnetic recording heads.

00-013 Crooks, W.R. and John Fulleman.

TURBOCOMPRESSOR. U. S. Patent 2,929,548. (to The Cooper-Bessemer Corp.). Applied June 29, 1956. Issued March 22, 1960.

This invention relates to small, high speed turbocompressors and to the combination of such compressors in fluid circuits in which the volume of flow is relatively small. The primary object of the invention is to provide a small, high-speed, turbine driven compressor in which the gases being pumped serve to lubricate and suspend the rotor so that the viscous shear forces associated with lubricating liquids which tend to limit rotational speeds are replaced in this invention by the much lower viscous forces of a gas. Another object of the invention is to provide a turbine compressor in which a small rotor is provided which operates suspended by a gas stream. What is claimed is a turbocompressor, in which there is a stator having a compressor end and a turbine end, and a rotor in the stator which has a central shaft and a pressure chamber formed in the stator around the shaft; a compressor wheel at one end of the shaft; a turbine wheel at the opposite end of the shaft; a source of gas under pressure higher than atmospheric; means to connect the source by passage-ways in the stator to the inlet of the compressor and to the inlet of the turbine; and a means to connect the source to the pressure chamber. The turbine wheel and compressor wheel are normally spaced a predetermined distance from the adjacent surfaces of the stator,

whereby the gas flows from the pressure chamber outwardly adjacent to the turbine wheel and inwardly to the chamber adjacent to the compressor wheel. The relative effective areas of the compressor and turbine wheels and the pressure of the gas are such that the rotor spins in the stator without frictional engagement.

00-014

Czwerwinshi, Wacław

BALL AND SOCKET COUPLING HAVING AIR BEARING MEANS.

U. S. Patent 2,869,901. (to Avro Aircraft Limited).

Applied August 15, 1957. Issued January 20, 1959.

This invention relates to pipe couplings, particularly to pipe couplings having a degree of universal movement. What is claimed is a pipe coupling including a hollow casing, an inner member within the casing, there being freedom of relative movement between the casing and the inner member in all three degrees of angular freedom, the inner member having two convex part-spherical external surfaces of the same radius of curvature, the centers of curvature of the surfaces being coincident and the surfaces lying on opposite sides of a diametral plane of an imaginary sphere having the same center of curvature and radius as said spherical surfaces, a pipe connection on the inner member, a peripheral nozzle in the inner member intermediate of the surfaces and in communication with the pipe connection, two concave part-spherical surfaces in the casing embracing and cooperating with the convex part-spherical surfaces on the inner member, a passage in the casing intermediate the concave part-spherical surfaces and in communication with the peripheral nozzle, and a pipe connection on the casing in communication with the passage, a clearance being provided between each part-spherical surface on the inner member and the cooperating part-spherical surface on the casing, each clearance decreasing from a maximum adjacent to the peripheral nozzle to a minimum remote from the peripheral nozzle, the clearances during normal operation of the coupling permitting some of the fluid passing into the coupling to escape between the convex and concave part-spherical surfaces to maintain the inner member out of contact with the casing.

00-015

Ferrand, W.A., S.G. Johnson, L.L. Kilpatrick and J.P. Lekas.

MAGNETIC DISC RECORDER. U. S. Patent 2,899,260. (to North

American Aviation, Inc.). Applied March 1, 1954. Issued

August 11, 1957.

This invention relates to a magnetic disc recorder for recording and reproducing electrical signals. What is claimed is a magnetic recorder with a first disc having a plurality of troughs disposed in and distributed over a major portion of one face of the disc. A second disc has a magnetized medium on one face and is adapted to assume a position in close proximity to the first disc. At least

one magnetic head is disposed in the first disc. Means are provided for rotating one of the discs relative to the other at a pre-determined speed to develop a self-lubricated viscous shear gas bearing between the discs over a major portion of the one disc.

- 00-016 Fischer, G.K., J.L. Cherubim and D.D. Fuller.
SOME INSTABILITIES AND OPERATING CHARACTERISTICS OF HIGH-SPEED
GAS LUBRICATED JOURNAL BEARINGS. ASME Paper 58-A-231. 12 pages.
(Abstract in Mech. Engng. vol. 81, no. 3, pp. 94-5. (March 1959)).

A system of instrumentation for measuring the instabilities of gas lubricated bearings is described. To measure these instabilities, a system of instrumentation was needed having adequate accuracy, response, range, stability and resolution. The system used was developed for the measurement of the growth of small rotating cylinders due to centrifugal forces. It measured the dynamic position of the journal to within five per cent of the diametral clearance. The system was composed of a Fielden proximity meter which measured minute static and dynamic changes at a probe. The probe was one plate of a condenser and the journal was the other. The proximity meter had a sensitivity of 0.001 micro-micro-farads and a frequency response that was flat up to 1200 cps. Various factors influencing the stable operation of high-speed rotors on gas-lubricated journal bearings were isolated such as critical speed, unbalance, film stiffness, whirl, damping, and air hammer. Experimental data are given for a number of bearings to illustrate the effects of these factors on operation of gas-lubricated bearings and correlation to mathematical analysis. The isolation and understanding of these factors have been due primarily to the instrumentation developed. Rotor assemblies on $\frac{1}{2}$ and $\frac{3}{4}$ -in.-diam. shafts have been run successfully on hydrostatic and hydrodynamic air bearings at speeds up to 165,000 rpm.

- 00-017 Fuller, D.D., Editor.
FIRST INTERNATIONAL SYMPOSIUM ON GAS LUBRICATED BEARINGS.
Office of Naval Research, Washington, D.C. October 26-28, 1959.
624 pp.

The fluid mechanics, dynamics and instabilities, correlation between theory and experiment, philosophy, applications, and the method of treating the problems and obtaining a solution for gas lubricated bearings are presented and discussed. There are twenty papers on these subjects.

00-018 Heizer, E.J.

WINDING MACHINE. U. S. Patent 2,670,146. (to Specialties Development Corporation). Applied December 24, 1952.
Issued February 23, 1954.

This invention relates to yarn package winding machines, particularly to an improved pressure roller or roller bail for such machines. The objects and advantages of this invention are accomplished by providing a roller bail assembly for yarn package winding machines which comprises a roller bail, means for rotatably supporting the ends of the bail, and a gas bearing associated with the supporting means and the ends of the bail. This bail, in one of its forms is constructed and arranged to be rotated by jet propulsion means associated with its bearings, in addition to being in driven contact with the package. The practically frictionless bearing means enables the bail to be rotated at a surface speed identical to that of the package while in extremely light contact with the package.

00-019 Hersey, M.D.

PHYSICS OF LUBRICATION, III. NOTE ON THE THEORY OF AIR-LUBRICATED JOURNAL BEARINGS. Read before the 220th Meeting of the American Physical Society, April 28-30, 1938, Washington, D.C., as given by Phys. Rev., vol. 53, p. 926. (June 1, 1938).

The thermodynamic characteristics of air-lubricated bearings differ from those outlined for oil-film bearings in Chapter V, Theory of Lubrication (Wiley, 1936), due to the increase in viscosity of a gas with rising temperature. Both the coefficient of friction and load-capacity as usually defined increase indefinitely with speed instead of approaching a limit. For a full bearing under high speed conditions satisfying Petroff's law, the equilibrium temperature rise T in the film is given by $AT^n = BK(T+T_0)^m$. The left side represents power carried off by radiation, convection, etc., as a function of temperature elevation T ; the known factor B , depending on bearing design, is proportional to the square of the speed; $K(T+T_0)^m$ expresses film viscosity in terms of the unknown T and absolute temperature T_0 of surroundings. For moderate temperature elevations, case 1, $n = 1$, $m = 4/5$; for higher ranges, case 2, n is assumed $= 3/2$, with $m = 3/4$. Convenient approximations are discussed, and the exact solution given for case 2.

00-020 Kawazaki, Y.

INVESTIGATION OF AIR BEARINGS. Trans. of Seimitsu Kikai, vol. 13, pp. 5-7. 1947. (Order from SLA \$1.10. 61-10660. 1961).

The theories for hemispherical and circular plate bearings are discussed briefly, and fundamental properties are experimentally verified. With respect to the friction of bearing rotation, stability of bearing action, and other important operation properties this bearing is much superior to others.

- 00-021 Koenders, M.A.
HYDRODYNAMIC AND HYDROSTATIC LUBRICATED BEARINGS WITH PARTICULAR
REFERENCE TO AIR BEARINGS.-A BIBLIOGRAPHY. General Electric Co.
April 23, 1957. Contract AT(11-1)-171. 43 pp.

A search of the unclassified literature and General Electric classified reports was made with reference to the use of air as the lubricating fluid in hydrostatic and hydrodynamic bearing applications. Conclusions and recommendations are included, based on information obtained from references.

- 00-022 Laub, J.H.
ELASTIC ORIFICES FOR GAS BEARINGS. Trans. ASME (J. Basic Engng.),
vol. 82 D, no. 4, pp. 980-982. (Tech. Briefs). (December 1960).

The author claims two advantages over conventional fixed-diameter type orifices: (a) lower flow requirements and (b) improved stiffness. Test data show these gains with some sacrifice in film thickness. Orifices were made from an elastomer which deformed with supply pressure so as to reduce flow area.

- 00-023 Lehmann, R.
[EXPERIENCE WITH AIR BEARINGS]. ERFAHRUNGEN MIT LUFTLAGERN.
(in German) Feingeratetechnik, vol. 9, no. 4, pp. 156-172.
(1960).

This article gives a survey on design, properties and manifold applicability of air bearings. At the Institut fur Geratebau der Deutschen Akademie der Wissenschaften, Berlin (Institute of Instrument Construction, German Academy of Sciences, Berlin) studies on prototypes were conducted by a group and instruments were fitted with air bearings for practical use and tested.

- 00-024 Macks, E.F.
AIR SUPPORTED ROTOR. U. S. Patent 2,889,474. (to Air-Glide, Inc.).
Applied March 4, 1957. Issued June 2, 1959.

This invention pertains to dynamoelectric devices, particularly to a dynamoelectric device in which the rotor and the stator are held in spaced relationship by a load carrying gas film. What is claimed is a dynamoelectric device comprising a rotor element, a stator element, one of the elements including a core wound to provide a magnetic field, and a sleeve carried by the stator. The sleeve has a smooth cylindrical surface. The rotor includes a shaft having an end formed to transmit force to a work load and also has a smooth cylindrical surface. The cylindrical surfaces have concentrically disposed portions intermediate with the shaft work end and the magnetic field. The surface portions define a pneumodynamic load carrying film producing region. The rotor element when rotating is totally supported radially by a load

carrying film of air generated in the region by the coaction of the surfaces, the air in the film being supplied by the atmosphere ambient to the machine.

- 00-025 Macks, E.F.
DYNAMOELECTRIC DEVICE. U. S. Patent 2,928,960. (to Air-Glide, Inc.). Applied December 4, 1957. Issued March 15, 1960.

This invention relates to small electric motors supported by gas-lubricated bearings. The journal bearings are of the self-acting type. The thrust bearing is essentially a piston in a cylinder with a small radial clearance and load-carrying action is achieved by squeezing the trapped gas.

- 00-026 Macks, E.F.
DYNAMOELECTRIC DEVICE WITH FLUID SUPPORTED ROTOR.
U. S. Patent 2,937,294. (to Air-Glide, Inc.).
Applied April 12, 1956. Issued May 17, 1960.

This patent is concerned with further variations and details on gas-lubricated bearings for small electric motors, one of a series of such patents by E. F. Macks.

- 00-027 Macks, E.F.
GAS LUBRICATION OF BEARINGS AT VERY HIGH TEMPERATURE. Tribo-Netics Labs. First Summary Report for period March 15, 1959 to December 15, 1959. Report WADD-TR-59-783, January 1960. Contract AF33(616)-5982. AD-237 394.

Studies were made of very high-temperature gas lubrication of high-speed bearings. An inert-gas lubricating system, gas-bearing test rig, and gas bearings were fabricated and tested in static conditions at 80 to 1500°F. The lubricating system consists in supplying gaseous nitrogen from bottles through a stainless-steel network of valves, flow-meters, pressure regulators, filters, and heaters. The test rig consists of a gas bearing mounted in a furnace in cantilever fashion supported by two bearings outside the furnace. An evaluation of a clearance-eccentricity measurement method indicated that excessively large temperature-correction factors and erratic results occur at high temperatures. (See also Ref. 280 in previous bibliography by Peters and Sciulli. AD-264 965.)

- 00-028 National Bureau of Standards.
ON THE CRYOGENIC ASPECTS OF PROJECT SHERWOOD. Fourth Progress
Report for the period October 1, 1960 to December 31, 1960,
Nat. Bur. Stand. Rep. 6737, December 31, 1960.

A superconducting Nb solenoid was constructed with a calculated maximum magnetic field of 10.3 kilogauss at 1.1°K. The development of a 100-kilogauss laboratory magnet is described. A detailed discussion is presented on the problem of defining the efficiency of an ideal refrigerator, and a method is outlined for comparing refrigeration processes. Typical load vs plate separation curves are presented for gas-lubricated bearings tested in a flat plate apparatus.

- 00-029 National Research Development Corporation.
BEARINGS. British Patent 911,490. Applied March 18, 1958.
Issued March 16, 1959.

This invention concerns a gyroscope which includes a rotor mounted within a gimbal system providing freedom for rotation about each of two mutually perpendicular axes. The rotor comprises two concentrated masses, mounted at opposite ends of a diameter perpendicular to the axle of the rotor. The rotor axle is held in one of the gimbal rings by bearings which permit a limited amount of displacement of the axle relative to the gimbal ring in directions perpendicular to the rotor axis. Gas bearings may be used for the rotor axle. The rotor may comprise sheet metal shells defining a hollow chamber containing two diametrically opposed weights, the shells being secured to a hollow sleeve which rotates about an axle pin. Compressed air flows from the pin through ports and past flow-directing blades which cause rotation of the rotor. The air then forms the bearings at each end of the sleeve.

- 00-030 Pal, Jozsef
APPARATUS FOR MOVING PARTS OF MACHINERY ON A SUPPORT.
U. S. Patent 2,942,385. (to "Licencia" Talalmanyokat Ertekesito Vallalat, Budapest, Hungary). Applied February 16, 1956.
Issued June 28, 1960.

This invention makes it possible to construct a machine tool having a power driven tool and a plane, ground or lapped bearing surface which may be easily shifted on a support the surface of which is also plane, ground and lapped, in such a way that the bearing surface is provided with at least one groove, in which compressed air or another pressure medium is introduced, so that the major part of the weight of the machine is thus compensated and the machine does not stick or adhere to the support. In such a way the machine-tool may be moved on a working table or bench or on another support quickly and easily,

without great effort and in any direction, so that the work piece may be machined in the desired way. If no pressure medium would be used, the two ground and lapped surfaces would adhere to one another so strongly that the machine could not be moved manually and the lapped surfaces would wear very quickly.

00-031 Pears, C.D.

THE TRUE STRESS-STRAIN PROPERTIES OF BRITTLE MATERIALS TO 5000°F. Southern Research Inst. Third Monthly Report, Report ORO-381, August 12, 1960.

An investigation of gas bearings is being carried out in order to provide design information. Changes made in the design of an optical extensometer included a revision of the image analyzer which will let the servo run the light to zero instead of to a balance of half-wave pulses of light. An electromechanical drive system is being superimposed on an existing hydraulic tensile machine to provide a wide range of strain rates in the tensile facility. The machine is being modified to accept the mechanical equipment.

00-032 Pears, C.D.

THE TRUE STRESS-STRAIN PROPERTIES OF BRITTLE MATERIALS TO 5000°F. Southern Research Inst. Fifth Monthly Report, Report ORO-383, October 14, 1960.

The resistance-heated check-out furnace was operated at 5500°F and is ready for use. Preliminary designs of the induction-heated furnace resulted in satisfactory operation to 4500°F. The gas bearings were checked out under loads up to 10,000 lb and demonstrated a friction force of less than 1/2 lb. at 700 lb. load. Grips were preliminarily checked out up to 10,000 lb. load on metal specimens. Detailed designs were made of the optical strain analyzer and the components ordered. The loading system is being aligned with all components now on hand.

00-033 Pears, C.D.

THE TRUE STRESS-STRAIN PROPERTIES OF BRITTLE MATERIALS TO 5000°F. Southern Research Inst. Sixth Monthly Report, Report ORO-384, November 10, 1960.

Additional furnace work using the 25-kw induction power supply indicated reliable long-time performance at 4500°F. The detailed check out of the prototype, flat, gas bearing was completed. Bearing operation was very stable at 0.0005-in. gap. The design of the spherical bearing was begun. The grips were checked with a single

graphite specimen and indicated satisfactory performance with specimen failure at the anticipated ultimate stress. The loading system was assembled, aligned, and operational check out completed. Design study of the optical strain analyzer was continued.

00-034

Pears, C.D.

THE TRUE STRESS-STRAIN PROPERTIES OF BRITTLE MATERIALS TO 5000°F. Southern Research Inst. Seventh Monthly Report, Report ORO-385, December 15, 1960.

The tubular furnace was employed to heat a graphite specimen to 5130°F. Operation was very satisfactory. The design of the spherical gas bearing was completed and fabrication started. The need to water-cool the grips was established, since they heated to 900°F at a specimen temperature of 4000°F. The loading system was operated repeatedly and the preliminary check out of the instrument system was completed. A model of the strain analyzer is being assembled to check the mechanical and optical performance.

00-035

Ramsdale, B. and P.J. Stokes.

INTEGRATION OF THE PRESSURE DISTRIBUTION BETWEEN GAS-LUBRICATED THRUST PLATES. United Kingdom Atomic Energy Authority, Development and Engineering Group. Report DEG-212, March 18, 1960.

The pressure distribution in the thrust region between gas-lubricated thrust bearing plates is approximated.

00-036

Reynolds, Osborne

ON THE THEORY OF LUBRICATION AND ITS APPLICATION TO MR. BEAUCHAMP TOWERS' EXPERIMENTS INCLUDING AN EXPERIMENTAL DETERMINATION OF THE VISCOSITY OF OLIVE OIL. Phil. Trans. Roy. Soc. London, (A), vol. 177, pp. 157-234. (1886).

This paper is of historical importance in the field of lubrication because it represents the first rigorous mathematical formulation of the theory of lubrication. Professor Reynolds may be deemed the father of modern lubrication theory because his mathematical treatment elevated lubrication practice from the empirical to a firm mathematical foundation. The governing equation representing thin film lubrication is called the Reynolds equation in honor of his early work. Prior to 1880 no mathematical foundation of the theory of lubrication existed. In 1885 Mr. Beauchamp Towers performed elaborate experiments on the pressure distribution and flow in railroad partial journal bearings. Measurements of the pressure distribution in the journal showed that the peak pressure was considerably higher than the projected bearing pressure. Reynolds, in his paper,

develops the complete theory of lubrication for an incompressible fluid. He states the assumptions of the boundary conditions of the lubricant and develops the Reynolds equation from the governing Navier-Stokes equations stating the necessary assumptions of thin film lubrication. In the derivation of lubrication equations, he introduced the concept of the now famous Reynolds number to explain why the inertia terms of the Navier-Stokes equations may be eliminated. A considerable section of the paper is devoted to the application of the Reynolds equation for a number of bearing configurations, namely, the flat inclined slider, and the partial, and full journal bearing. Reynolds also derived the journal bearing film thickness equation and integrated this approximately for the partial and full journal bearing. The approximate solution developed by Reynolds is then shown to agree closely with the experimental test data of Towers. Reynolds also devotes a section of this paper to the discussion of the viscosity of various lubricants. He compares the viscosity of water, olive oil, and air, and presents analytical expressions to predict the viscosity of these three lubricants over a range of temperatures. Although Reynolds original derivation covers only an incompressible fluid, the general equation for a compressible fluid may be easily obtained by including the gas equation of state in the continuity equation.

00-037

Richards, S.I.

RECORDING MEMBER ASSEMBLY FOR COMPUTER OR THE LIKE.

U. S. Patent 2,915,358. (to Ferranti Limited).

Applied February 24, 1958. Issued December 1, 1959.

This invention describes an information storage assembly for a computing machine of the type having a body, a head on the body, a storage member and a means for rotating the storage member with respect to the body. The storage member overlies the body and in use defines, together with the body, a space that functions as a fluid bearing as the storage member rotates with respect to the body. The body is formed with passage means whereby the fluid space is connectible to an operating fluid supply. There is an improvement of safety release means for moving the storage member with respect to the head on the body between an inoperative and operative position, the safety release means includes a pressure receiving vessel connectible with the pressurized fluid supply for operating the fluid bearing, the movable member being responsive to the pressure in the pressure receiving vessel to move the storage member to an inoperative position with respect to the head when the pressure in the pressure receiving vessel is below operating pressure. The movable member is responsive to the pressure in the pressure receiving vessel to maintain the storage member in an operative position with respect to the head when the pressure in the pressure receiving vessel is at normal operating pressure. The

storage member has a cut-away recording surface whereby the space between the surface and the head increases as the movable member moves the storage member from an operative position to an inoperative position with respect to the head. The space between the storage member and the head is greater than the space between the storage member and the body for all positions of rest of the storage member when the storage member is in an inoperative position with respect to the head.

00-038 Kippel, H.C.

BEARINGS AND BEARING LUBRICATION FOR HIGH-PERFORMANCE AIRBORNE AIR-CYCLE REFRIGERATION TURBINES. Franklin Institute Research Laboratories. Final Technical Report F-A1994, for the period October 16, 1956, March 31, 1958. Contract NOa(s) 56-1108-d.

This report deals with a study of bearings and bearing lubrication for contemplated airborne air-cycle refrigeration turbines to be used for in-flight cooling in Navy turbojet engine aircraft. Three types of bearings to support the high speed rotor of the unit in question were investigated, analyzed, and compared in order to determine the best, or optimum, bearing and lubrication system. The types of bearings considered were rolling-element with oil lubrication and fluid-film bearings, both hydrostatic and hydrodynamic. Both incompressible and compressible fluids were considered in the hydrostatic and hydrodynamic types. The result of this work was the selection of hydrodynamic thrust and journal bearings of special configuration, which use the ambient air (bleed or coolant) as the lubricant. It is believed that this design is optimum, from the standpoint of simplicity, suitability, stability and maintenance.

00-039 Sheinberg, S.A.

[GAS LUBRICATION OF SLIDING BEARINGS (THEORY AND CALCULATIONS)].
GAZOVAYA SMAZKA PODSHIPNIKOV SKOL'ZHENIYA (TEORIYA I RASCHET).
(in Russian). Trenie Iznos Mash., vol. 8, pp. 107-204. (1953).

The equation of spatial flow of a gas lubricant is derived, on the basis of the study of the lubricating characteristics of gases. The problem of the lubrication of bearings of infinite length (that is, the plane problem) is solved. The obtained solutions are extended with the help of certain assumptions to real bearings of finite length. The method of calculation of gas lubrication of bearings is described and its results are verified experimentally.

00-040

Sixsmith, Herbert

BEARINGS FOR ROTATING SHAFTS WHICH ARE LUBRICATED BY GAS.
U. S. Patent 2,884,282. (to National Research Development Corp.). Applied March 13, 1956. Issued April 28, 1959.

This patent deals with high speed, externally-pressurized journal bearings having a series of damping chambers located around the circumference. The entrance to each chamber is through a restrictive orifice. The overall effect of this design is to achieve a fairly high degree of stability and resistance to self-induced whirl at elevated speeds.

00-041

Skarstrom, C.W.

GAS BEARING. U. S. Patent 2,951,729. (to U.S. Atomic Energy Commission). Issued September 6, 1960.

A gas lubricated bearing for a rotating shaft is described. The assembly comprises a stationary collar having an annular member resiliently supported thereon. The collar and annular member are provided with cooperating gas passages arranged for admission of pressurized gas which supports and lubricates a bearing block fixed to the rotatable shaft. The resilient means for the annular member support the latter against movement away from the bearing block when the assembly is in operation.

00-042

Sliney, H.E.

LUBRICATING PROPERTIES OF SOME BONDED FLUORIDE AND OXIDE COATINGS FOR TEMPERATURES TO 1500°F. NASA TN D-478, October 1960.

The lubricating properties of some experimental ceramic coatings, diffusion-bonded fluoride coatings, and ceramic-bonded fluoride coatings were determined. The experiments were conducted in an air atmosphere at a sliding velocity of 430 ft. per minute and at temperatures from 75° to 1500°F. Several ceramic coatings provided substantial reductions in friction coefficient and rider wear (compared with the unlubricated metals). For example, a cobaltous oxide (CoO) base coating gave friction coefficients of 0.24 to 0.36 within the temperature range of 75° to 1400°F: serious galling and welding of the metal surfaces were prevented. The friction coefficients were higher than the arbitrary maximum (0.2) usually considered for effective boundary lubrication. However, when a moderately high friction coefficient can be tolerated, this type of coating may be a useful antiwear composition. Diffusion-bonded calcium fluoride (CaF₂) on Haynes Stellite 21 and on Inconel X gave friction coefficients of 0.1 to 0.2 at 1500°F. Endurance life was dependent on the thermal history of the coating; life improved with increased exposure time at elevated temperatures.

prior to running. Promising results were obtained with ceramic-bonded CaF_2 on Inconel X. Effective lubrication and good adherence were obtained with a 3 to 1 ratio of CaF_2 to ceramic. A very thin sintered and burnished film of CaF_2 applied to the surface of this coating further improved lubrication, particularly above 1350°F. The friction coefficient was 0.2 at 500°F and decreased with increasing temperature to 0.06 at 1500°F. It was 0.25 at 75°F and 0.22 at 250°F. A survey of the thermochemical properties of the halides was of considerable aid in selecting metal halides that might be chemically stable in air at 1500°F. Good correlation was obtained between predictions based on thermodynamics and the results of experimental thermal stability studies.

00-043 Snopov, A.I.

[TAKING HEAT TRANSFER INTO CONSIDERATION IN THE PLANE PROBLEM OF GAS LUBRICATION]. UCHET TEPLONENEN V PLOSKOI ZADACHE O GAZOVOI SMAZKE. (in Russian). Izv. Akad. Nauk SSSR, Otd. Tekh. Nauk, Mekh. i Mashinostr., no. 4, pp. 35-40. (July - August, 1960).

The flow of viscous gas between two non-coaxial cylinders, under the assumption of a small clearance between them, is examined on the basis of Reynolds' equation. For the case under examination the bearing is stationary and non-heat conductive, while the journal rotates with angular velocity ω . An approximate solution of the plane problem for practical calculations is reached.

00-044 Snopov, A.I.

[THE PLANE PROBLEM OF HYDRODYNAMIC THEORY OF GAS LUBRICATION]. PLOSKAYA ZADACHA GIDRODINAMICHESKOI TEORII O GAZOVOI SMAZKE. (in Russian). Izv. Akad. Nauk SSSR Otd. Tekh. Nauk, Mekh. i Mashinostr., no. 6, pp. 14-20. (November - December, 1959).

A method is described whereby simple equations are shown to be practically convenient in the calculation of bearings of any eccentricity. It is concluded that (1) the load attitude angle is almost independent of gas condition; (2) the carrying capacity of the bearing can be effectively increased at the expense of increasing the bearing's (a) relative eccentricity, (b) diameter and (c) amount of lubricant; and (3) the carrying capacity of the bearing is higher in its adiabatic than in its isothermal condition.

00-045 Taylor, M.K.
COMPUTER DRUM CONSTRUCTION. U. S. Patent 2,929,671.
(to Ferranti, Ltd.). Applied January 19, 1956. Issued
March 22, 1960.

This invention relates to a drum construction for a computer machine. The storage drum is cylindrical in cross-section and has side walls that taper outwardly from the lower end. The lower end is formed with a cylindrical bore that extends longitudinally of the drum. In use, the cylindrical bore is dropped over a hollow cylinder and air under pressure is admitted to the cylinder. Passage means are provided in the cylinder walls to permit air to escape from the interior to the space between the drum and the exterior cylinder walls. Escape passage means are provided in the drum to permit the air to escape from the core at a predetermined rate so that, in effect, the air forms a bearing for the drum on the cylinder in use. The magnetic heads which engage the sides of the drum engage the tapered exterior walls so that as the drum is withdrawn from the cylinder the spacing at the top of the cylinder between the heads and the cylinder walls increases whereby there is a considerable amount of side movement permitted in the drum as it is withdrawn from the cylinder without affecting the adjustment of the magnetic computer heads and without damaging the drum surface by reason of contact with the heads.

00-046 United Kingdom Atomic Energy Authority.
GAS LUBRICATED BEARINGS. British Patent 905,647.
Applied May 22, 1959. Issued May 10, 1960.

A gas-lubricated bearing assembly comprises a rotatable shaft having a sleeve bonded thereto by a rubber-sealing band and a non-rotating bush secured and sealed to a casing by a ring. A pipe supplies gas to the bearings via pipes and jets and a pipe also supplies sealing gas to the bearing. The gas pressure in the bearing is controlled by apertures in the bush. The sleeve is assembled on the shaft prior to introducing it into the casing, and it is held by collets. Rubber is then injected into the passageway to fill the groove in the shaft, the rubber is cured, and the collets are removed. There are also a number of modifications of the above described assembly.

00-047 Vogel, N.A.
AIR HEAD. U. S. Patent 2,886,651. (to International Business Machines Corp.). Applied April 8, 1955. Issued May 12, 1959.

This invention relates to magnetic recording heads, particularly to air-stabilized magnetic recording heads, referred to as simply "air heads". It is desirable to prevent the magnetic transducer from

engaging the recording media to thereby prevent unnecessary wear and also possible damage to the recording media. Air heads have been successfully utilized for spacing transducers from the recording surface; however, it will be understood that in most prior air heads failure of the air supply results in engagement of the recording media by the head and the concomitant ill effects. It is one object of the invention to provide an improved air head having a fail-safe characteristic whereby the head is moved away from the recording surface upon the failure of the air supply. What is claimed is an air head having a first position remote from a recording surface and a second position closely adjacent to this surface including a face on the head arranged in opposition to the surface, an orifice in the face, and means for supplying air to the head for flow through the orifice. This orifice is arranged to exhaust the air therefrom at a divergent angle lying between 20° and 40° relative to the face wherein force developed due to the air flow pulls the head from the first position to the second position.

- 00-048 Weir, A., J.L. York and R.B. Morrison.
TWO- AND THREE-DIMENSIONAL FLOW OF AIR THROUGH SQUARE-EDGED SONIC ORIFICES. ASME Paper 54-A-112. 17 pages.
(Abstract in Mech. Engng., vol. 77, no. 4, p. 353. (April 1955)).

In this investigation, the two-dimensional flow of air through rectangular, and the three-dimensional axisymmetrical flow of air through circular, square-edged sonic orifices was examined under pressure ratios ranging from 1.894 to 42.0 (upstream stagnation pressure/downstream static pressure). Mass flow measurements were made using a primary metering system, rather than another orifice or nozzle, and optical techniques were used to obtain pictures of the flow upstream, within the thickness of the orifice plate, and downstream of the orifice. Evidence is presented in this paper which indicates that square-edged sonic orifices can be treated as sonic nozzles by utilizing the concept that the air "turning the corner" of the orifice plate, in effect, makes its own nozzle. It is believed that this interpretation of experimental observations is in full agreement with established principles of aero- and thermodynamics.

- 00-049 Whitley, Stanley
GAS BEARING FOR COMPRESSORS IN GAS COOLED REACTORS. Progr. in Nuclear Energy, ser. IV, vol. 3, pp. 3-28. (1960).

The design of compressors for use in gas-cooled reactors is considerably simplified if gas bearings are used. The results of the research on gas bearings by UKAEA are summarized. The load capacity and vibration characteristics of both hydrodynamic and hydrostatic bearings

were measured and, from the results, general design methods were developed. The most useful machines employ hydrodynamic bearings; hydrostatic operation is at present limited to starting and stopping periods.

- 00-050 Whitley, Stanley and L.G. Williams.
 THE GAS-LUBRICATED SPIRAL-GROOVE THRUST BEARING. United
 Kingdom Atomic Energy Authority Industrial Group.
 Report 28(RD/CA), February 18, 1959.

An existing hydrodynamic theory of load-carrying capacity is developed and the optimum values of the four important groove variables are obtained. Three thrust plates of outside diameter 5.55, 6.5 and 9.5 in. respectively, are investigated experimentally, and the results are compared with the theory. It is shown that the theory is basically sound excepting that, for any one plate, there is a constant error depending on the geometrical configuration of the plate. A theory of distortion caused by temperature gradients set up in the thrust plates is developed, and the general form of the theory is checked experimentally. The experiments also show how much of the heat developed by the frictional drag in the gas film escapes axially through the plates. The effect of imposing a swash on the rotating plate about five times bigger than the thrust plate gap is measured at 3000 rev/min. and found to be very small. A quantitative comparison is made with a theoretical value, and reasonable agreement is obtained.

- 00-051 Wilcox, R.M.
 AIR BEARING. U. S. Patent 2,683,636.
 Applied November 12, 1949. Issued July 13, 1954.

This invention relates to improvements in bearings in which the lubricating film between the bearing surfaces is a gas, usually compressed air. More particularly the invention is specifically concerned with parallel surface air bearings. What is claimed is an air bearing comprising a pair of parallel bearing surfaces separated by a continuous lubricating film of compressed gas, and means fed from a compressed gas supply distributing compressed gas free of foreign inelastic matter throughout the film to sustain the film continuous without vibration of the bearing; means comprising a gas flow passage formulation affording a restriction between the film and the supply and having a total perimeter opening into the film not greater than 1/11 of the perimeter of the film.

- 00-052 Wildmann, M.
CONSIDERATION OF STARTING OF GAS LUBRICATED BEARINGS.
ASME Paper 60-LUB-11. 5 pages. (Abstract in
Mech. Engng., vol. 82, no. 12, p. 84.
(December 1960)).

The starting and stopping of self-acting gas-lubricated bearings differs from the starting and stopping of oil-lubricated bearings in that there is usually a complete absence of a lubricant having boundary lubricating properties. The frictional energy generated by the sliding of the two bearing surfaces has therefore to be absorbed by these surfaces. This metal-to-metal contact generates wear particles and can cause bearing deformations. These effects are very undesirable, particularly if the close tolerances and small clearances usually associated with hydrodynamic gas bearings are taken into account. The forces acting on a gas-lubricated journal bearing at start are examined, and an expression for the frictional energy dissipated on the bearing surfaces is obtained. Examination of this expression indicates that for a full gas-lubricated journal bearing, this energy is always less when the outer member rotates.

- 00-053 Woodrow, J.
VISCOSITY-PLATES FLOW AND LOADING. United Kingdom Atomic
Energy Authority Research Group. Report AERE-EM-31,
December 22, 1949.

The radially inward flow between annular viscosity plates is investigated by the methods of lubrication theory. The flow rates and pressure distribution are obtained for isothermal flow of a gas and for an incompressible fluid. The resultant force on the plates due to the radial flow are worked out for the same two cases. If the entry pressure equals the pressure outside the plates, the load can be expressed in a completely non-dimensional form, involving only the shape factor q , and the pressure ratio s . For an incompressible fluid, the load factor depends only on the shape factor q .

- 00-054 Woods, L.R.
VIBRATION TABLE. U. S. Patent 2,862,385. (to International
Electronic Research Corp.). Applied August 8, 1955.
Issued December 2, 1958.

This invention relates to vibrating machines and particularly to a vibrating machine capable of testing relatively small objects for breakdown at vibrations of extremely high frequency. An object of the invention is to provide a new and improved air floated support for a table or platform to render it virtually frictionless under a great variety of load patterns. Another object is to provide a

new and improved air floated support for a table or platform to render it virtually frictionless under a great variety of patterns. What is claimed is a vibration testing machine comprising a stationary base; a table mounted on the base adapted for the reception of objects to be subjected to vibrations; the base having upstanding columns on opposite sides and the columns having parallel longitudinally extending slots depressed outwardly into respectively inwardly facing sides of the columns; the slots having a portion lying above a horizontal plane and a portion lying below a horizontal plane; the table having outwardly extending edges fitting into the slots with a clearance of substantially a few thousandths of an inch; air passages in the columns, the passages having branches opening directly into upper and lower portions of the slots; a source of high pressure air communicating with the passages to provide an air float for the table; and vibration-producing media in spaced relationship with the table adapted to vibrate the table in a horizontal plane.

00-055 Zaid, M. and I.S. Tolins.
THE MEASUREMENT OF VERY LOW FRICTIONAL TORQUES IN ROTATING
EQUIPMENT. Trans. ASME (J. Engng. Industry), vol. 82 B,
no. 4, pp. 382-386. (November 1960).

The frictional torque in such devices as air bearings is measured and resolved into coulomb and viscous friction components by analysis of the observed deceleration during free rotation. Two methods of analysis are given. Both are based on the differential equation of motion of the rotating system and give results that are in satisfactory mutual agreement. In the first method an integration is obtained from which a phase plane diagram is derived in which the friction components are read off as slopes and intercepts. To carry out the analysis measurements of angular displacement, time and velocity are required. The second method proceeds from a different integration of the equation of motion, is more complex, but requires measurements of only angular displacement and velocity. It is believed that the general applicability of these methods will make them of interest to many workers in the fields of friction and lubrication.

- 61-001 Adams, C.R., Juraj F orski and E.M. Shoemaker
EXTERNALLY PRESSURIZED STEP JOURNAL BEARINGS. Trans. ASME (J. Basic Engng.), vol. 83 D, pp. 595-602. (1961).

An externally pressurized gas bearing which achieves its load carrying capability by utilizing flow throttling dams parallel to the direction of rotation is discussed in this paper. Test procedures and equipment used to develop this bearing concept are described. A theoretical method of determining pressure distribution and load carrying capacity for the bearing is presented and correlated with experimental data for nonrotating shafts. Experiments showing the behavior of the bearing under shaft whirl conditions are described and illustrated. Suggested ranges of the design simplicity as well as the static and dynamic stability of this bearing concept are presented.

- 61-002 Adams, P.R., G.B. Speen and C.C. Miller, Jr.
GYROSCOPES, GYROSCOPE STABILISED SYSTEMS AND GAS BEARINGS FOR THE SAME. British Patent 884,061. (to Standard Telephones and Cables, Ltd.) Applied June 3, 1958. Issued December 6, 1961.

This invention relates to highly accurate, low drift gyroscopes, and in particular, to what may be called the "bootstrap" type of gyroscope, (any type whose drift decreases nearly to zero if the main frame is maintained in nearly perfect alignment with the rotor axis.) This invention also relates to a novel form of spherical gas bearing useful in such a gyroscope. What is claimed is a gyroscope including a frame, a rotor, means rotatably supporting the rotor relative to the frame, the supporting means comprising a plurality of pairs of separate gas bearing pads, the pads in each of the pairs being disposed in opposed axial relationships, the rotor having bearing means disposed in coactive association with the gas bearing pads, the axes of the pairs being disposed in coincidence with corresponding center lines of opposed forces of an imaginary regular polyhedron, and means associated with the frame and the pads to feed gas along the gas bearing pads to form gas bearings for the rotor.

- 61-003 Allen, D.S., P.J. Stokes and S. Whitley.
THE PERFORMANCE OF EXTERNALLY-PRESSURIZED BEARINGS USING SIMPLE ORIFICE RESTRICTORS. Trans. ASLE, vol. 4, no. 1, pp. 181-196. (April 1961).

The load capacity and vibration characteristics of externally pressurized thrust and journal bearings have been investigated. The bearings used orifices sufficiently recessed back from the bearing surface to ensure that the area of the orifice is the minimum presented to the gas flow. The journal bearings consist of plain cylinders with one or two rows of eight orifices, and the thrust plates of plain discs with six

orifices drilled in equispaced circumferential grooves. The load capacity of the thrust plates agrees with that calculated but the vibrations are greater than predicted. The load capacity of journal bearings is about half that calculated assuming axial flow conditions in the bearing, but circumferential flow can account for the difference. Synchronous and half-speed vibrations of a shaft rotating within these bearings have been measured and found to agree with those calculated on the assumption that the gas films behave as linear springs.

61-004 Anonymous.

GAS LUBRICATED BEARINGS. Engng. Mats. and Design, vol. 4, no. 7, p. 425. (July 1961).

The design of pumps to circulate the hot gas for a gas cooled reactor presents a problem which cannot be solved with complete satisfaction if oil lubricated bearings are to be used. There are two particular difficulties. The greater one is that there must be no risk of oil entering the gas circuit; if it were to do so, it would be irradiated, and might interfere with the operation of the reactor. Further, any rotating shaft passing through the wall of the gas circuit must be sealed very effectively against leakage of the gas. Shaft sealing is a complexity which is desirable to avoid. If gas lubricated bearings are used, instead of oil lubricated, the problem may be solved by putting the motor and the bearings within the gas system. The bearings are then lubricated by the gas, and no rotating shaft has to pass through the wall of the pressure system. The advantages which make this design attractive in nuclear engineering apply also to other gas circuits, so gas lubricated bearings should soon be making their appearance in various other types of industrial plants. The advantages are summarized. Research work is continuing on the development of bearings capable of still higher loads, and on the solution of the various problems which appear as gas bearings are applied to special industrial projects.

61-005 Ausman, J.S.

APPROXIMATE ANALYTICAL SOLUTION FOR SELF-ACTING GAS LUBRICATION OF STEPPED SECTOR THRUST BEARINGS. ASLE Trans., vol. 4, no. 2, pp. 304-13. (November 1961).

Certain approximations are made which permit linearization of the pressure (Reynolds') equation for compressible lubrication as well as separation of variables. A series solution to the resulting approximate equation is then developed to obtain estimates of the pressure and load for self-acting, stepped, sector thrust bearings. Numerical solutions are presented showing the optimum number of sectors, the optimum step location, and the optimum depth of the step to achieve maximum load carrying capacity. A design chart permits rapid estimation of the load-deflection characteristics for optimized stepped sector thrust bearings covering a wide range of nominal operating conditions.

- 61-006 Barker, Allan and John Ashton.
IMPROVEMENTS IN OR RELATING TO GAS BEARING SYSTEMS. British Patent 876,136. (to United Kingdom Atomic Energy Authority).
Issued August 30, 1961.

A hydrodynamic gas-bearing system is designed with reciprocating movement for a compressor. The system comprises two bearing members, one of which is a sleeve enclosed in a sleeve and the other is a double-ended piston reciprocated in the sleeve by pressurized gas at one end while the other end pumps a contaminated gas. The piston is also rotated by a rotating magnetic field, thereby superimposing a sustained movement on a reciprocating movement.

- 61-007 Bennett, E.C.
GAS LUBRICATED BEARINGS IN A NUCLEAR APPLICATION.
General Electric Co. Report HW-SA-2143, March 30, 1961.
Contract AT-(45-1)-1350.

The development and operational history of gas circulators for in-reactor gas-cooled loops which use the loop gas as the lubricant are described. Circulators incorporating hydrostatic journal-and-thrust bearings were run in the DR-1 loop with He or N₂ for a total of 9533 hr. Only minor difficulties were encountered, and bearing wear was negligible.

- 61-008 Bosco, A., E.S. Cain and G.L. Green.
EXPLORATION OF BEARING LUBRICATION USING WORKING FLUID VAPORS.
The Garrett Corp. Report for the period July 15 to December 1, 1961, Report BR-5239-R, December 1961. AF contract AF33(616)-8082.

The principal objective of this program is to investigate the lubricating characteristics of potassium and rubidium vapors in self-pressurized and externally pressurized thrust bearings at conditions representative of advanced system requirements. Thrust bearing analyses were made to determine test rig requirements of flow, pressure, and general test bearing requirements. The test rig and loop layout and detail drawings have been completed, and the fabrication is approximately 50% completed. The thrust bearing analysis and design for the test bearings are complete, and the first test bearing parts have been fabricated for both types of bearings. Special test instrumentation designs have been made and feasibility checks conducted.

- 61-009 California Institute of Technology.
RESEARCH SUMMARY NO. 36-10, VOLUME I FOR THE PERIOD JUNE 1, 1961
TO AUGUST 1, 1961 (ON SPACE RELATED RESEARCH). Report NP-10832,
September 1961. Contract NASw-6.

The development and testing of a capillary gas-pumping system for gas bearing instruments are discussed.

- 61-010 Carothers, P.E.
AN EXPERIMENTAL INVESTIGATION OF THE PRESSURE DISTRIBUTION OF
AIR IN RADIAL FLOW IN THIN FILMS BETWEEN PARALLEL PLATES.
U. S. Naval Postgraduate School Thesis, 1961. 69 pp.

An experimental investigation of the pressure distribution of air in radial flow between parallel plates was conducted. Data were collected on the pressure distribution, mass rate of flow of air and film thickness. Variations were made in the load applied to the upper plate, stagnation pressure at the air supply hole, and the upper plate geometry. Two upper plates having the same outside diameters but different supply hole diameters were employed. Two flow regimes were defined, that where the flow of air is dominated by the viscous forces wherein the pressure decreases steadily from the supply hole to the outer edge of the upper plate and that where the inertia forces predominate and the flow becomes supersonic near the air supply hole. In this latter regime, it was found that the mass flow can be predicted by the theoretical choked flow through the cylindrical area defined by the film thickness and the diameter of the air supply hole.

- 61-011 Coffey, T.C., C.H.T. Pan, K.W. Jenkins and Beno Sternlicht.
DIFFERENTIAL ANALYZER STUDIES OF DYNAMIC BEHAVIOR OF GAS
LUBRICATED RIGID VERTICAL ROTORS. General Electric Co.
Report N62-13188, October 1961. Contract Nonr-2844(00).

The motion of a vertical rotor with prescribed initial conditions using fluid film forces that are based on the steady whirl analysis is studied. Specific objectives are three-fold; to check the calculated motion of the rotor against experimental evidence in order to verify the validity of the hypothesis which was employed to calculate the fluid film forces; to examine the stability of the synchronous whirl motion; and to determine the effect of damping and coupling terms on the stability of synchronous whirl. The dynamical equations of the rotor are integrated on the PACE differential analyzer. The study revealed that the differential analyzer provides a useful tool for studying the dynamic response of rotors, and that it is especially useful when the governing equations are nonlinear. The principal advantage of the differential analyzer is its ability to rapidly scan a multitude of variables for regions of specific interest. The half frequency whirl motion of a balanced vertical rotor was simulated,

and it was found that the analog simulation of synchronous whirl is not stable (in conflict with experience). Either external damping and/or improvement in theoretical fluid film forces can eliminate this discrepancy.

- 61-012 Comolet, Raymond and Gerald Gobert.
[EXPERIMENTAL INVESTIGATION CONCERNING THE FLOW THEORY IN A GAS BEARING]. RECHERCHES EXPERIMENTALES POUR UNE THEORIE DE L'ECOULEMENT DANS UNE BUTEE A GAS. (in French). Compt. Rend. Acad. Sci., Paris, vol. 253, no. 22, pp. 2460-2462. (1961).

Experimental investigation of the radial pressure distribution and viscous-friction coupling in a gas bearing. The results are found to be in reasonably good agreement with those of a previous analysis of the flow in such a bearing.

- 61-013 Constantinescu, V.N.
[DYNAMICS OF AIR BEARINGS]. SUR LA DYNAMIQUE DES PALIERS A AIR. (in French). Rev. Mecan. Appl., vol. 6, no. 3, pp. 317-330. (1961).

The author examines the motion of a shaft in an air journal bearing; analysis is considerably more difficult than for a liquid bearing, as the equation is basically nonlinear. The author makes necessary approximations to obtain the stability equation, from whose roots he deduces that an undamped component of motion may exist having a frequency one half that of shaft rotation. Experimental results confirm the theory.

- 61-014 Constantinescu, V.N.
[SIMILARITY CRITERIA IN OPERATION OF BEARINGS FOR LIQUID AND GASEOUS LUBRICATION]. KRITERII PODOBIYA DLYA RABOTY PODSHIPNIKOV PRI ZHIDKOSTNOI ILI GAZOVOI SMAZKE. (in Russian). Rev. Mecan. Appl., vol. 6, no. 4, pp. 519-537. (1961).

From general equations of motion under nondimensional conditions, parameters determining behavior of bearings are deduced for models of liquid bearing laminar lubrication, and liquid bearing turbulent lubrication, as well as gaseous lubrication.

- 61-015 Cooper, Stanley
AN ASSESSMENT OF THE VALUE OF THEORY IN PREDICTING GAS-BEARING PERFORMANCE. Trans. ASME (J. Basic Engng.), vol. 83 D, no. 2, pp. 195-200. (June 1961).

Theoretical and experimental investigation of the characteristics and potentialities of hydrodynamic gas bearings, using the plain journal

bearing as a model is discussed. Methods of solving the Reynolds' equation, using both desk and digital computers, are described, as are methods of stabilizing the processes of solution. The theoretical methods used are evaluated and compared with experimental results. Some theoretical results are presented to indicate the effects of including slip velocity, stabilizing slots, and a simple case of whirl.

- 61-016 Duncombe, Edward and Harold Pugh.
IMPROVEMENTS IN OR RELATING TO CENTRIFUGAL PUMPS AND APPARATUS FOR SAMPLING RADIO-ACTIVE LIQUIDS. British Patent 870,829.
Applied February 17, 1959. Issued June 21, 1961.

This invention relates to centrifugal pumps and to apparatus using such pumps for the sampling of radio-active liquids. The apparatus comprises biological shielding having inside the shielding a pipe for radioactive liquors and outside the shielding a pipe for radioactive liquors drawn off from the pipe inside the shielding, a centrifugal pump having its inlet communicating with the pipe inside the shielding and its outlet connected with an outlet pipe coupled to the pipe outside the shielding. The pump is contained within a casing extending from outside the shielding to be integral with the pipe inside the shielding. The pump is removable from the casing through an aperture accessible from outside the shielding. The pump is provided with air lubricated bearings and is driven by an air turbine. The outlet pipe and pipes feeding the bearings and turbine are contained within the casing to pass through the shielding.

- 61-017 Elwell, Richard
ENERGY THEORY OF HALF-FREQUENCY WHIRL. Trans. ASME (J. Basic Engng.), vol. 83 D, no. 3, pp. 478-488. (September 1961).

The author postulates that half-frequency whirl occurs when the kinetic energy of the rotating film exceeds the static "strain energy" stored in the film. The strain energy is equivalent to the work done by displacing the journal in the direction of the load, against the elasticity of the film. Calculations were carried out for a series of rotor-bearing configurations for which a measured whirl speed was available.

- 61-018 Eusepi, M.W. and D.D. Fuller.
THE APPLICATION OF GAS LUBRICATED BEARINGS TO HIGH SPEED
TURBOMACHINERY. Franklin Institute Laboratories for Research
and Development. Quarterly Technical Reports for period April
1, 1961 to August 31, 1961, Reports TID-13998 and TID-13999.
Contract AT(30-1)-2512.
- 61-019 Eusepi, M.W., A. Marmorou and D.D. Fuller.
THE APPLICATION OF GAS LUBRICATED BEARINGS TO HIGH-SPEED
TURBOMACHINERY. Franklin Institute Laboratories for Research
and Development. Quarterly Report for the period September 1,
1961 to November 30, 1961. Report TID-14962. Contract AT(30-1)-2512.

Activities in a program to develop design information for gas lubricated bearings are reported. Redesign of the tilting-pad journal bearings for an existing gas bearing rotor brought to light various limitations. The decision was made to build new simplified gas bearing rotors which should be more amenable to laboratory instrumentation and examination. Design and fabrication work on such bearings are described.

During the last quarter the component parts of the new self-acting bearing test rig (SA-2) and the modified parts of the externally pressurized test rig, with only a few minor exceptions, were completely fabricated and inspected. Assembly has begun. The instrumentation for the tests was developed around a number of commercial instruments. The range of these instruments was extended and their sensitivity increased by modification of the electrical circuits. A complete description of the modification is included along with an analysis of the improved circuitry and the expected range of measurement and accuracy. A design theory was partially completed which will permit the analysis of the tilting-pad type of journal bearing including the effect of the compressibility of the gas that is serving as the lubricant. Prior to this, such analyses as were available were based on the hydrodynamics of incompressible flow.

- 61-020 Gedeon, R.R.
DEVELOPMENT OF A ROTOR-WHEEL CONFIGURATION ORIENTED-WEDGE AIR
LUBRICATED BEARING. Chrysler Corporation Missile Division.
Interim Technical Documentary Report RL-R2, May 1961.
Contract AF 33(616)-6614.

Three types of bearing configurations were investigated (double-phase 2-wedge bearing with 2-wedge 60° end covers; double-phase 3-wedge bearing with 3-wedge flat end covers, and single phase inverted 60° bearing) to develop a combination rotor-wheel, oriented-wedge air-lubricated bearing requiring no preload and capable of almost unlimited operation at speeds in excess of 20,000 rpm. Coastdown curves were obtained for the 3 prototype bearings while operating in the radial

position under about 1g. load. From these curves, horsepower required was obtained as a measure of frictional resistance offered by the revolving rotors. Internal pressure distributions, load capacities, rotor displacements, bearing spring constant, inversion point, internal temperature, rotor vibrations, and internal air flow were investigated for three configurations studied. A brief theoretical analysis of the 2-wedge air bearing is given. It is thought that when the 2-wedge air bearing theory has been refined and verified, only minor modifications will be needed to apply this analysis to the 3-wedge bearing. Analytical study of air thrust bearings and the influence of an electromagnetic field on the performance of air bearings are areas suggested for future investigation.

- 61-021 Gobert, Gerald
[BEARINGS FOR HIGH SPEED ROTORS]. PALIERS POUR ROTORS TOURNANT A GRANDE VITESSE. (in French). J. Phys. Rad., Phys. Appl., vol. 22, no. 2, pp. 39A-42A. (February 1961).

The results are given of various experiments which have made possible the design of bearings such that the relative tangential velocity between static and dynamic parts is greater than 30 m/s for angular speeds greater than 3,000 r.p.s.

- 61-022 Goetz, Alexander
GAS SUPPORTED BEARING. U. S. Patent 3,012,827. (to California Institute Research Foundation). Applied January 6, 1959. Issued December 12, 1961.

This invention describes a gas bearing comprising a shaft, a rolling element bearing having inner and outer races with rotating elements between, a journal portion carried by the outer race of the bearing and a bearing element surrounding the journal portion. The journal portion and bearing element define confronting but spaced cylindrical surfaces. There is a means for mounting the bearing element for limited radial displacement to facilitate positioning of the bearing element in concentric relation with journal portion. It also provides for a viscous dampening medium for the bearing element.

- 61-023 Green, G.L., A. Bosco, E.S. Cain and E.L. Kumm.
MINIATURE AIR-BEARING SUPPORTED, AIR-TURBINE-DRIVEN DENTAL HANDPIECE. USAF Aerospace Medical Center, School of Aerospace Medicine. Report 61-90. December 1961.

The design, fabrication, and operation of a dental handpiece employing air-bearings and having a cutting capacity and speed range compatible with commercial handpieces are discussed. A design was first conceived, test parts constructed, and tests run to determine the operating characteristics of the test parts. The principal source of

trouble in the tests parts was the flaking off of the tungsten carbide from the high-speed rotor. In later tests solid tungsten carbide was incorporated into the instrument instead of the plating previously used. Results of these tests led to the design and fabrication of a prototype handpiece that was operated successfully. Need for improvement was noted in some areas and remedies suggested.

- 61-024 Laub, J.H. and H.D. McGinness.
RECIRCULATION OF A TWO-PHASE FLUID BY THERMAL AND CAPILLARY PUMPING. Jet Propulsion Laboratory. Report TR 32-196, December 8, 1961. Contract NASW-6. AD-268 692.

A closed-cycle gas-supply system for gas bearings and gas-floated devices is described which eliminate mechanical pumps or compressors and uses instead thermal and capillary pumping action. A small quantity of a two-phase fluid of suitable thermodynamic characteristics, such as Freon, is recirculated in a closed system. The fluid is thermally vaporized in an evaporator, and the superheated vapor, after passing through the gas bearing, is condensed and returned to the evaporator by capillary action. The system is of special interest to space applications because it can operate in a zero-g environment from solar or nuclear power sources without conversion to electrical energy.

- 61-025 Levene, M.L.
AIR LUBRICATION, A DEVELOPMENT TOOL. Mech. Engng., vol. 83, no. 12, pp. 53-55. (December 1961). (Condensed from Paper 61-Lubs-12 presented at the ASME Lubrication Symposium, Miami, Fla., May 8-9, 1961).

Gas bearings, with their great convenience and accuracy, can make possible the economical tryout of a new device, leading to an informed decision on further development. The self-centering properties of the externally pressurized bearing have proved very valuable as has the uniformity of the rotating friction torque. Devices which make use of air as a lubricant profit from its relatively low viscosity which varies little with temperature. The resulting constant friction torque is sought in many forms of tape-drive mechanisms as well as in gyros and in memory drums.

- 61-026 Litton Systems, Inc.
PRODUCT IMPROVEMENT PROGRAM FOR THE DEVELOPMENT AND FABRICATION OF A GAS LUBRICATED SPIN BEARING GYRO. Quarterly Engineering Report 3, for the period June 15 - September 15, 1961. September 15, 1961. Contract NOW 61-0280-c. AD-269-243L.

The gas lubricated spin bearing gyro, designated as the G-200G, is a modification of the existing gyro G-200, currently in production and

being delivered to Naval programs as a part of the P200 Inertial Platform. Progress is described in a product improvement program to increase the performance capabilities and operating parameters of the existing gyro.

- 61-027 Loch, Erwin
 SUPPLYING SUPPORTING GAS TO A GAS PRESSURE BEARING. U. S.
 Patent 3,013,845. (to Escher Wyss Aktiengesellschaft).
 Applied June 8, 1960. Issued December 19, 1961. Applied
 Switzerland June 26, 1959.

This invention describes a gas pressure bearing surface having a bearing member and a supported member movable in relation to the bearing member along adjacent surfaces leaving a gap between one another, and at least one restricted passage for the supply of the pressure gas to the gap. This restricted passage is formed as a Laval nozzle. The Laval nozzle eliminates certain disadvantages. With supply nozzles heretofore, it was a disadvantage that for a given inlet pressure, the flow quantitatively fell off comparatively rapidly when the back pressure rose above the critical pressure, at which the velocity in the nozzle is that of sound.

- 61-028 McGinness, H.D.
 CHARACTERISTICS OF A GAS-SUPPORTED SPINNING SPHERE. Jet
 Propulsion Laboratory. Section Report 345-1, May 17, 1961.

A sphere which is supported by a finite number of small gas bearing pads may serve as a reaction sphere for attitude control, a spherical gyro, or a near-frictionless pivot. Among the important characteristics of such a device are the following: (1) Bearing stiffness as a function of displacement from the concentric position; (2) Gas-flow rates; (3) Power required to maintain a given angular velocity; and (4) Radial dilation of sphere due to angular velocity. This analysis is based on the following assumptions: (1) The plenum pressures for all pads are identical; (2) All control orifices are identical; (3) The orifice coefficient is 0.900 for all conditions; (4) The gap at any one pad is constant over its surfaces; (5) Inertia effects are neglected; and (6) There are pads equally spaced on a north parallel and 1/2 pads equally spaced on a south parallel, and displacement is normal to these parallels.

- 61-029 McKenna, R.D.
 GAS LUBRICATED BEARINGS FOR ADVANCED SYSTEMS ELECTRICAL ACCESSORY
 EQUIPMENT. Chrysler Corporation, Missile Division. Design Manual
 RL-DM 1. Interim Technical Documentary Report, October 31, 1961.
 AF contract AF 33(616)-7919.

Design criteria are given for porous-metal bearings capable of operating

under the following conditions: temperature range of -65°F to 1000°F, nuclear radiation, and 25-lb. thrust load. The geometry of a bearing that would meet the high temperature requirements is given. Fabrication techniques, materials, processes, test conditions and procedures, results, and design procedures are discussed. A reliable electrolytic erosion method that overcomes previous machining problems was developed. This method worked on both porous bronze and stainless steel. To eliminate the seal problem in the temperature range a new micro brazing method was used to join the porous inserts to the bearing housing. All bearings were made from stainless steel. Ambient-load tests, high temperature tests, and ambient-pressure flow tests were carried out. Radial bearing parameter effects, porous thrust bearing parameter effects, and solid thrust bearing parameter effects are analyzed and these results form the basis for the design of radial bearings, thrust bearing - porous face, and thrust bearings - solid face. Tables are included to show that for a given constant load condition of a bearing, the supporting pressure increases and mass flow decreases as bearing temperature is increased.

61-030 Marcus, R.H., J.P. Capellupo and A.W. Lindberg.
RESEARCH ON A DUAL FREE-ROTOR DIRECTION-SENSING DEVICE. The
Universal Match Corporation. Technical Report ARL 127,
December 1961. AF contract AF 33(616)-6201. AD-274 365.

A preliminary feasibility study of a two-rotor gyroscope was extended to the analysis and design of a dual free-rotor gas supported gyro model. The analysis consisted primarily of determining static pressure and flow and dynamic stability characteristics for both of the externally pressurized stepped spherical gas bearings that support the two spherical rotors. Deformation in the spinning rotors was calculated and a method was developed to compensate for the deformed shapes. A description of the complete design for a research model of the dual gas bearing configuration is presented, along with a description of its operation and instrumentation, which is capable of accurately measuring the angular drift of the inner rotor spin axis. The primary purpose of this model is to provide drift measurements that will demonstrate experimentally the theoretically established feasibility of the dual free-rotor gas bearing as a precision direction-sensing device. The feasibility of a self-pumping spherical gas bearing was investigated for the purpose of applying that principle to the outer bearing so that it could pressurize the inner bearing. The complexity of the problems involved in applying this principle to the dual rotor model made it necessary to omit this feature at this stage. The feasibility of the principle was, however, established, and the results were sufficiently encouraging to indicate the desirability of further study.

61-031 Meacher, J.S.

GAS LUBRICATION OF BEARINGS AT VERY HIGH TEMPERATURES, HIGH SPEEDS, AND LOW LUBRICANT FLOW RATES. Fairchild Stratots, Inc. Stratots Division Progress Report 2, for the period June 16, 1961 - October 15, 1961. AF contract AF 33(616)-8947. AD-274 307.

Initial installation and operational testing of an experimental pre-heating oven for five separate gas-supply circuits has been completed. Modifications to the test control and instrumentation panel required for operation with the gas preheating oven have been performed. A ceramic test shaft was operated in a ceramic bearing at speeds to 65,000 rpm and at temperatures from room temperature to 1900°F.

61-032 Megroz, R.

GAS BEARINGS AND THEIR USE IN INDUSTRY. Sulzer Tech. Rev., Research Number 1961, pp. 65-8.

Gas bearings are not intended to replace the other types of bearings, but have their own specific field of application. They may be divided generally into two classes: hydrostatic and hydrodynamic bearings. The attention of Sulzer Brothers has been concentrated on the latter type. The research work and tests carried out up to the present show that there is a place in industry for machines equipped with gas bearings, and this statement applies to their manufacture as well as their use. Such machines have a natural application, for instance, as circulators or compressors for gas coolants in nuclear power plants, while the chemical industry can also use them to replace much more complex and expensive layouts.

61-033 Nahavandi, Amir and Fletcher Osterle.

NOVEL FORM OF SELF-ACTING GAS LUBRICATED THRUST BEARINGS. ASLE Trans., vol. 4, no. 1, pp. 124-130. (April 1961).

A nonpressurized parallel-surface gas lubricated thrust bearing is analyzed with the slider in steady spin and precession and found to develop a load capacity. The operation of this self-acting thrust bearing over a range of operating conditions is studied and the results applied to the so-called bevel bearing. The load capacity is obtained numerically by solving the Reynolds' equation for compressible lubricant in finite difference form on a high speed digital computer. It is found that this load capacity can be significant.

61-034 Parsons, G.C., J.A. O'Shea and F.H. McGeough.

AIR BEARING RATE TABLE. Military Sys. Design, vol. 5, no. 6. (November-December 1961).

Turntables used for testing inertial gyros have been improved by the use of air bearings which eliminate the problems encountered when

ball, roller, or oil bearings were used. The gas bearing used resembles a conventional sleeve-type journal bearing with a thin film of air or dry nitrogen separating the fixed and rotating parts. Fluid volume is maintained by supplying air through upstream restrictors or orifices spaced and sized to provide controlled flow to the bearing gap. It was found that by using air "stick-slip" is avoided, viscous drag is negligible, and the bearing surfaces kept clean. Turntables used for testing having gas bearings give about 25% more accuracy than conventional test tables.

- 61-035 Parsons, G.C. and J.A. O'Shea.
AIR BEARINGS ENHANCE GYRO TESTING. Missiles and Rockets,
vol. 9, no. 16, pp. 26-7. (October 16, 1961).

Air film bearings are being used in servo test turntables which test gyro drift rates. Air bearing suspension techniques make it possible to extend test table range capability. The air bearing as designed by Dunn Engineering Corp. is similar to a conventional journal bearing. The gas is supplied through upstream restriction or orifices. The gas may be either air or dry nitrogen.

- 61-036 Pears, C.D.
THE TRUE STRESS-STRAIN PROPERTIES OF BRITTLE MATERIALS TO
5000°F. Southern Research Inst. Eighth Monthly Report,
Report ORO-386, January 13, 1961.

The equipment for the evaluation of the stress-strain properties of brittle materials is ready for the initial tensile tests at up to 5000°F. The tubular furnace was modified slightly to permit the grips to pass through the heater and thus provide a simpler procedure for installing specimens prior to a pull. Fabrication of the spherical gas bearings was completed. Attachments are being designed to mount both gas bearings in the loading linkage. Room temperature runs were made to establish the linearity of the mechanical loading system and to develop operating techniques. Both steel and graphite specimens were run. The non-uniaxial load when not using gas bearings was established as about 20% even after very careful prealignment. The grips were redesigned slightly to provide more gripping area on the specimen. A preliminary model of the strain analyzer was assembled and initial evaluations made to establish the optical performance of the proposed system.

- 61-037 Pears, C.D.
THE TRUE STRESS-STRAIN PROPERTIES OF BRITTLE MATERIALS TO
5000°F. Southern Research Inst. Ninth Monthly Report,
Report ORO-387, February 17, 1961.

The first runs with the gas bearings operable were made on the equipment at up to 4500°F. The data indicated that the gas bearings have

a significant influence in reducing any bending of the specimen. Graphite appeared to be significantly stronger and more ductile than previously reported. Even strain cracks were observed in some specimens. The tubular furnace was enlarged slightly and performance proved up to 4500°F. No difficulty was anticipated to 5200°F since the previous design was satisfactory to this temperature. The gas bearings were mounted in the load frame. The coefficient of friction acting through the bearings on the specimens was less than 5×10^{-7} . The resulting bending stress distortion in the specimen was less than 0.2 psi. Some small modifications were made in the precision grips. Almost all major work on the load frame was completed.

61-038 Pears, C.D.

THE TRUE STRESS-STRAIN PROPERTIES OF BRITTLE MATERIALS TO 5000°F. Southern Research Inst. Eleventh Monthly Report, Report ORO-389, April 10, 1961.

The preliminary design of the induction heated furnace was operated to 5000°F. Performance was satisfactory. The gas bearings were re-installed and preliminary runs made on a dummy and one graphite specimen. Another variation in grip design was developed to permit the evaluation of the dumb-bell type specimen using conical grips. Preliminary check out of the strain analyzer indicated that focus will be no problem over an interval of at least 1/8 in. The sensitivity of the analyzer appeared to be adequate using a hot filament to simulate the flag signal.

61-039 Peters, Alec and E.B. Sciulli.

A BIBLIOGRAPHY (WITH ABSTRACTS) ON GAS-LUBRICATED BEARINGS - REVISED. Franklin Institute Laboratories for Research and Development. Interim Report I-A2049-16, October 15, 1961. AD 264,965.

Navy-DOD-AEC-NASA-MaritAdmin-supported compilation of 464 references on air-lubricated bearings. Included are a subject index, yearly index, corporate name index, and a patents list.

61-040 Pinkus, Oscar and Beno Sternlicht.

THEORY OF HYDRODYNAMIC LUBRICATION. McGraw Hill Book Co., New York. 1961.

This book is a synthesis of the principles and results obtained so far in the field of the theory of hydrodynamic lubrication. The authors' care to cover as completely as possible all aspects of the problem is to be noticed from the beginning. Thus, following some general considerations (lubrication equations, some elementary problems such as the flow between two plates, cylinders or through

holes), an examination is presented of the thrust and journal bearings of infinite and finite width, air bearings, hydrostatic bearings, bearings under variable forces and velocities, hydrodynamic instability, and thermal effects on lubrication. Further, some problems are presented which represent modern extensions of the lubrication theory, such as: lubrication of elastic bearings, hydrodynamic theory of rolling surfaces, effect of inertia forces and turbulent motions, rheology of lubrication, extension of classical theory to the case of thick layer lubrication. The book closes with a chapter containing a selection of experimental results which point out various particularities of the lubrication phenomenon and the agreement existing between theory and experiment. The authors have succeeded in including in such a concise volume most of the numerous aspects of the modern theory of lubrication. Of course, the concise synthesis has been made at the expense of certain problems (e.g., in the chapters concerning hydrostatic bearings, turbulence, etc.); however, the treatment is complex and carried out to final results. Of particular value are the chapters pertaining to bearings under dynamic loads and hydrodynamic instability. The presentation of numerous tables and diagrams obtained through numerical calculations, of which a good deal are the authors' original contribution, augment the interest and the usefulness of this book. At the end of each chapter a selected list of sources, most of them recent, is presented.

- 61-041 Powell, J.W.
 PROPELLER METER WITH A GAS BEARING. Engineering, vol. 192,
 no. 4985, pp. 566-567. (November 3, 1961).

A propeller meter with low bearing friction and a means of preventing the solid particles from entering between bearing surfaces was obtained by mounting the propeller on a pressure fed gas journal bearing and gas thrust bearings. A small journal bearing was used with sufficient strength to withstand the dynamic loads imposed by the propeller and magnet rotating at speeds of up to 20,000 rpm. The thrust bearings operated well on the exhaust air from the journal bearing.

- 61-042 Quick, D.E. and J.G. Weir.
 A COMPREHENSIVE STATUS REPORT AND DISCUSSION OF BEARING PROGRAM.
 Naval Avionics Facility. Report TR-10, January 30, 1961. AD-254 974.

Air supported lubrication test spindles and research spindles are discussed along with many other topics.

- 61-043 Rawlins, J.A.
 GAS LUBRICATED BEARING. U. S. Patent 3,006,697. (to Sperry Rand Corp.) Applied December 19, 1960. Issued October 31, 1961.

This invention describes a bearing for an ultra high-speed spindle

in which friction is reduced to a minimum. It permits spindle speeds in excess of 500,000 rpm for extended periods of time. In this air bearing shafts may be rotated at ultra high-speed without binding or seizing. The bearing is efficient in operation, of simple construction, is long-lived, and is inexpensive to manufacture and maintain. The bearing housing comprises a base section which is mounted in fixed position, and a complementary cap section which is mounted on the base section for vertical and transverse floating movement, but not longitudinal movement, with respect thereto. The two sections are provided with opposed similar semicircular bearing surfaces in which the cylindrical bearing surface of the spindle is held.

- 61-044 Sipenkov, I.E.
[ON THE AUTO-ROTATION OF AIR BEARINGS]. OB AVTOROTATSII
VOZDUSHNYKH PODVESOV. (in Russian). Trudy Leningr. Politekh.
In-ta., no. 217, pp. 140-155. (1961).

As is shown in the practical use of air bearings, there is observed the self-arbitrary rotation of the journal of the floating element of the bearing about its axis. In the article it is supposed that the reason that this phenomenon (called auto-rotation) arises is the displacement of the journal with respect to the bearing under the action of the loads applied to it. Author introduces the concept of auto-rotation as the total moment of the frictional forces with respect to the axis of rotation of the journal, due to air lubrication. Differential equations are set up for the motion of a journal in a spherical bearing, with angle of opening 90° , and the cases of compressible and incompressible gas lubrication are investigated. From the formulas obtained it is possible to conclude that the effect of the compressibility of the gas on the value of the coefficient of auto-rotation of a sphere for small angles of opening of the housing of the capsule is negligible, which considerably simplifies the calculation.

- 61-045 Sixsmith, Herbert, W.A. Wilson and B.W. Birmingham.
LOAD CARRYING CAPACITY OF GAS-LUBRICATED BEARINGS WITH INHERENT
ORIFICE COMPENSATION USING NITROGEN AND HELIUM GAS. Nat. Bur.
Stand. Tech. Note 115, August 1961.

An experimental investigation was made of the static load bearing characteristic of circular pressurized thrust bearings for bearing diameters between 0.375 and 3.375 inches and recess diameters between 25 and 250 lb/sq. in. were used with film thickness from zero to 0.006 inches. The results are presented in the form of load-vs-film thickness curves and no theoretical results are discussed.

- 61-046 Sternlicht, Beno
GAS OR LIQUID-LUBRICATED BEARINGS? NEW DESIGN CHARTS GIVE
QUICK COMPARISONS. Prod. Engng., vol. 32, no. 34, pp. 49-52.
(August 21, 1961).

These charts, based on recent analytical solutions confirmed by tests, are applicable to any type of fluid and can give quick comparisons between air and oil bearings.

- 61-047 Timms, Cecil, Maurice Graneek and C.A. Scoles.
IMPROVEMENTS IN AND RELATING TO BEARINGS. British Patent
877,555. Applied September 25, 1956. Issued September
13, 1961.

This invention relates to a precision fluid bearing to support a vertical spindle for low speed rotation in measuring instruments, precision machine tools or the like provided at least two axially spaced locations with at least three circumferentially spaced gaseous fluid supply jets and with means for accurately independently varying the fluid supply pressure to some of the jets to enable the axis of rotation of the spindle to be maintained constant or the location of the axis to be positively adjusted within a small compass, the distribution of the jets and pressures of the fluid supplied being arranged to avoid tilting of the axis of the spindle in relation to the axis of the bearing when the supply pressure to the jets is varied, longitudinal location of the spindle being provided for by the aid of a further fluid bearing.

- 61-048 Toba, Kaoru
FINITE SECTOR THRUST GAS LUBRICATED STEP BEARING. ASLE
Trans., vol. 4, no. 2, pp. 293-303. (November 1961).

The principal object of this paper is to demonstrate the effect of compressibility of lubricant gas on the performance of a particular type of sector step bearing when the lubricant undergoes an isothermal process. It is noticed that for small film thickness, deviation from the continuous medium such as the slip flow phenomenon may take irrespective of the absolute magnitude of the flow density. When the Knudsen number, which is a measure of this phenomenon, is small the flow may still be treated macroscopically. By assuming a liquid having the same viscosity coefficient, the performance of the bearing for an incompressible lubricant is also evaluated and compared with that for a compressible lubricant over a range of the important physical parameters.

- 61-049 Unterberger, R.
[THE RIGIDITY OF AIR BEARINGS]. DIE STEIFIGKEIT DER LUFTLAGER.
(in German). Feinwerk Tech., vol. 65, no. 1, pp. 17-24.
(January 1961).

In precision bearings, a change of load should not cause a substantial change of the bearing clearance and thus displacement of the axis. The bearings must have a certain rigidity. A study was made to determine how the rigidity of air bearings is created. This has shown that a pilot jet is the best measure for increasing the rigidity. A rough calculation is given which allows the advance determination of the rigidity and is in satisfactory agreement with the results, ties in the construction of machines. Thus, some data on the basic design, the calculation and application of air bearings are given. It is, however, by no means suggested that all roller and journal bearings should be replaced by air bearings, but only in those cases where existing difficulties can be eliminated by the use of air bearings.

- 61-050 Walker, Lucius and Fletcher Osterle.
A CENTRIFUGAL EFFECT SELF-ACTING THRUST BEARING. ASLE TRANS.,
vol. 4, no. 2, pp. 287-292. (November 1961).

The authors suggest using the centrifugal forces developed in the lubricant film between the runner (journal) and the bearing due to the journal rotation in a thrust bearing for developing the load-carrying capacity of the bearing. They present an analysis of this problem considering both incompressible and compressible lubricants. The profile of the runner required for optimum film thickness variation was determined. The expressions for load-carrying capacities for bearings utilizing compressible or incompressible lubricants were derived. The results are also presented in graphic form using dimensionless parameters. Investigations show that, by using this principle, a considerable capacity of a thrust bearing may be achieved in cases when the rotational speed of the shaft is high. However, when high thrust is required for given dimensions this type of bearing is not competitive with conventional self-acting thrust bearings, or with hydrostatic bearings.

- 61-051 Wunsch, H.L.
LUBRICATION WITH AIR. New Scientist, vol. 12, no. 267,
pp. 792-794. (December 28, 1961).

The principles of air lubrication including the advantages and disadvantages in their use are briefly discussed. Two types of air bearings are described. The operation of a self-acting bearing depends on pressure generated by relative motion of considerable magnitude between the two surfaces forming the bearing, whether it

be the shaft and journal of a journal bearing or the two parts of a thrust bearing. The second type of air bearing is usually known as the externally-pressurized bearing. An explanation of this bearing is accompanied by a diagram. The reasons for using an air bearing in any particular design are given. A list of these uses of pressurized air bearings and the future of air lubrication in engineering practice are discussed.

61-052 Wunsch, H.L.

DESIGN OF AIR BEARINGS AND THEIR APPLICATION TO MEASURING INSTRUMENTS AND MACHINE TOOLS. Internat. J. Mach. Tool Design Res., vol. 1, no. 3, pp. 198-212. (November 1961).

This paper describes work which has been carried out in the Mechanisms and Metrology Division of the National Engineering Laboratory, to determine the relationships between the various design factors in a flat air bearing and its performance under both steady and dynamic load conditions. The results obtained from the work on steady loading are discussed qualitatively and in addition, empirical formulae are developed to relate the design factors of the bearing. The investigation of dynamic loading, which has particular reference to the use of air bearings in machine tool slideways, is still in progress, but a description of the test rig is given and some preliminary results are discussed. The final section of the paper deals with the various ways in which air bearings have been applied to measuring instruments and machine tools. The bearings described include journal and thrust bearings as well as slider bearings and though most of the applications mentioned are of slow moving or pivot bearings, a high-speed air bearing is also included. A practical example is given to indicate the method by which the results obtained from the practical investigation have been applied to the design of a machine tool slideway. Mention is made of intended future work which will provide further basic design data for use in various applications of both flat and journal type air lubricated bearings.

61-053 Zablotskii, N.D.

[LINEARIZATION OF THE BOUNDARY CONDITIONS IN THE THEORY OF AIR BEARINGS]. LINEARIZATSIYA GRANICHNYKH USLOVII V TEORII VOZDUSHNYKH PODVESOV. (in Russian). Trudy Leningr. Politekh. In-ta., no. 217, pp. 127-132. (1961).

A method is proposed for the linearization of nonlinear boundary conditions on circular pressure-feed lines in cylindrical air bearings with an isothermal regime of flow. For simplicity, the case is considered of a single pressure-feed line situated in the central section of the bearing. When the inner and outer cylinders are placed coaxially the boundary condition on a pressure-

feed line is reduced to the fact that the derivative of the square of the dimensionless pressure with respect to the axial coordinate of the bearing is given by a function of a dimensionless quantity proportional to the dimensionless thickness of the air layer. The graph of this function is given. By this relationship the author proposes to replace the nonlinear boundary condition along the pressure-feed line in the case when the cylinders are placed eccentrically, while the values of the function of the thickness of the layer (variable in this case) must be taken from the graph, or this graph must be approximated by a polynomial. In order to check the method the problem of the distribution of pressure in an air-bearing with maximum eccentricity is considered, i.e. when the cylinders are in contact. Moreover, it is assumed that the thickness of the lubricant layer is proportional to the distance along the circumference to the line of contact raised to the power of $1/3$, which permits the problem to be reduced by Fourier's method to the solution of a Bessel equation. The coefficients of the infinite series which represents the square of the dimensionless pressure are found when the exact boundary condition on the pressure-feed line and the approximate one described above are satisfied. The agreement of the results is completely satisfactory. There are some misprints.

62-001

Adams, C.R.

NEW CONCEPTS IN DESIGN OF HIGH CAPACITY GAS STEP BEARINGS.
Mach. Design, vol. 34, no. 1, pp. 118-21. (March 1, 1962).

Hydrostatic gas bearings depend on gas pumped in under pressure to form a film lubricant that supports the shaft. Conventionally, the gas is supplied through fixed multiple orifices and allowed to escape through the clearance between the bearing and shaft. However, multiple-orifice bearings have certain disadvantages which include clogging, rubbing, difficult production, and problems in "floating" the journal when stationary. To overcome these disadvantages, the step bearing was developed. In this type of bearing, steps or dams are machined at both ends of the journal or housing. Also, an annular groove in the housing acts as a manifold to supply gas completely around the clearance between the housing and journal. The steps have a twofold purpose; they allow space for air below the shaft when it is stationary or about to start up, and they restrict air flow through the bearing to produce a pressure buildup. Now, a modified step bearing--the center step bearing--has been developed. It offers improved radial load capacity and bearing stability. This article discusses the design parameters of this type of bearing as compared with other step bearings.

62-002

Alishaev, M.G.

[CONSIDERING THE EFFECT OF HEAT EXCHANGE IN THE THEORY OF GAS LUBRICATION]. OB UCHETE VLIYANIYA TEPILOOBMENA V TEORII GAZOVOI SMAZKI. (in Russian). Izv. Akad. Nauk SSSR, Otd. Tekh. Nauk, Mekh. I Mashinostr., no. 4, pp. 27-31. (July/August, 1962).

A mathematical analysis is made of the heat balance effects for infinitely long cylindrical bearings. Low magnitudes of approximate eccentricity are considered.

62-003

Allais, D.C.

THE DESIGN OF EXTERNALLY PRESSURIZED GAS THRUST BEARINGS FOR MAXIMUM STIFFNESS AND STABILITY. ASLE Trans., vol. 5, no. 1, pp. 254-260. (April 1962).

In the first part of the paper the author reviews some of the most common forms of externally-pressurized, gas thrust bearings, namely the inherently compensated, circular recess, and slot recess bearings. He also presents and discusses mathematical expressions for determining the rate of flow, pressure ratio, pressure drop from inlet to ambient outlet, load capacity, and mean effective pressure applicable for these bearings. The author then develops expressions for "specific stiffness", which is a ratio between the bearing stiffness and the bearing load. Considering the phenomenon of pneumatic instability, the author interprets the analysis of this problem made

by Licht and Elrod and concludes that a stable bearing can be designed if sufficient land area is provided. The stiffness equations derived by the author were confirmed experimentally by use of a specially arranged test stand. Under conditions of the author's experiments, the inherently compensated bearings are the most stable, rarely exhibiting self-excited oscillations.

62-004 Anonymous.

MISSILE TESTED ON AIR BEARING. Control Engng., vol. 9, no. 5, p. 26. (May 1962).

An Aerojet General Corp. attitude control system for the Aerobee sounding rocket is tested by supporting the entire missile on an air bearing which rests on a large tripod. Moving air provides frictionless support of the missile at its center of gravity, with 360 degrees of freedom in roll and yaw, 30 degrees in pitch. The front and rear halves of the missile are joined by a 4-in. diameter, 16-in. long metal tube which diametrically penetrates an 8-in. sphere, supported by moving air. The air-bearing test stand, which permits tests of the missile's flight stability and damping characteristics without friction disturbances, costs one-tenth to one-fifth the price of a three-axis gyro system.

62-005 Anonymous.

GAS LUBRICATED BEARINGS FOR HELIUM TURBINE. J. Refrig., vol. 5, no. 3, p. 57. (May/June 1962).

Cryogenic Engineering Laboratory has developed a miniature helium expansion turbine for operation in a helium liquefier or refrigerator. Externally pressurized gas lubricated journal and thrust bearings are used. The bearings are provided with pneumatic phase-shift networks to ensure stability at extreme rotational speeds according to a design by Sixsmith, Wilson, and Birmingham.

62-006 Anonymous.

THE BARDEN BEARING THAT RUNS ON GAS. Groove, vol. 12, no. 5, pp. 1,4-5. (May 1962).

The manufacture of air bearings at Barden is briefly described. The Research Precision Mechanisms Division has built air-bearing-supported gyro wheels which maintain position within fractions of a millionth of an inch. Advantages and disadvantages of air bearings compared to conventional bearings are outlined and future channels of development are noted.

62-007 Anonymous.

SIMPLE AIR BEARINGS ELIMINATE WEAR PROBLEMS. Mill and Factory, vol. 71, no. 1, pp. 58-60. (July 1962).

The patented, precision, friction-free air bearing is so designed that a thin cushion of air supports the upper portion of the bearing. The pattern of necessary and equal support is controlled by the placement of tributary channels, which are imbedded in the interior surface of the bearing, and which permit precise control over air distribution. The bearings are designed as follows: In the flat bearings used for the first model, the working area is 64 sq. in. by 4 in. thick. Aluminum was the metal used. Seven slots, or air ducts, run lengthwise, and three crosswise, grooved to a depth of 0.005" to 0.008", by 0.125" wide. These tributaries are fed air through intake channels to which air regulators are attached. The regulators are controlled by pressure gages, which monitor the flow of inducted air from the manifold. Inert gas may also be used. Because they never wear, complete accuracy of the smallest tolerances may be maintained constantly. In ten thousand parts run on a machine so equipped, there would not be a variation of a thousandth of an inch from first to last part.

62-008 Anonymous.

MINIATURE HELIUM EXPANSION TURBINE. Nat. Bur. Stand. Tech. News Bull., vol. 46, no. 1, pp. 2-3. (January 1962).

The Cryogenic Engineering Laboratory of the Bureau's Boulder Laboratories has developed a miniature helium expansion turbine for operation in a helium liquefier or refrigerator. Rubbing friction and bearing wear have been eliminated in this device by replacing conventional rolling-element bearings with gas-lubricated journal and thrust bearings of the externally pressurized type. The life of these bearings should be indefinite, and the speed of the shaft supported by the bearings is limited only by the strength of the material. The bearings are provided with pneumatic phase-shift networks designed to ensure stability at extreme rotational speeds. During actual tests the shaft has been observed to be in a position of stable equilibrium at an operating speed of 3000 rps. The inlet pressure is 15 atm. and the outlet pressure is 1 atm. The turbine is of the mixed flow type-radial inlet and axial outlet. The rotor passages are of the impulse type, having a very small amount of reaction. The expansion ratio in the nozzle ring is about 10 and in the rotor about 1.6. A recompression ratio of about 1.07 is achieved by the diffuser, thus accounting for an over-all expansion ratio of 15. The power generated by the turbine is absorbed by means of a centrifugal blower which acts as a brake. The blower operates in a closed circuit in series with a cooler and a throttle valve. A diagram shows the main components of the turbine expander. Experimental tests showed that the gas-lubricated bearings are stable with

the turbine operating at room temperature when producing up to 7 kw of refrigeration. As the design load is approximately 3 kw, the bearings should possess more than adequate stability under normal operating conditions.

- 62-009 Arwas, E.B. and S.B. Malanoski.
FINAL REPORT - APPLICATION OF GAS BEARINGS TO TURBINE-COMPRESSOR ROTOR. Mechanical Technology, Inc. Report MTI-62TR17, August 10, 1962. Army contract DA-44-009-ENG-5023.

This investigation established that gas bearing support of a turbine-compressor rotor is feasible. Vibration analysis of a turbine-compressor rotor showed that the journal bearings should have a stiffness of about 500,000 lbs./in. Hydrostatic mode of operation was selected to achieve this stiffness, still maintaining relatively large film thickness. Journal bearings were designed and optimized for maximum stiffness with low gas flow. Performance charts for $3\frac{1}{2}$ " x $3\frac{1}{2}$ " and 4" x 4" hydrostatic bearings are included. Performance charts are also given for a hydrostatic thrust bearing with a 10" O.D. x 4" I.D. thrust plate. This has adequate capacity for a 2000 lb. load. Bearing performance curves are given for the following two conditions: bearing supply pressure equal to compressor discharge pressure; and bearing supply pressure regulated to $p_s = p_a + 79.5$ psia. The ultimate load capacity of the journal bearings computed from "lockup" consideration is, under the worst supply and ambient pressure operating conditions: 465 lbs. for the $3\frac{1}{2}$ " x $3\frac{1}{2}$ " bearing and 610 lbs. for the 4" x 4" bearing. Ultimate load capacity for the 10" x 4" thrust plates is 2800 lbs. It was found that rotation will increase the load capacity of the journal bearings by about 10% and that the threshold speed of Fractional Frequency Whirl should be well above the running speed of 20,000 rpm, at the supply pressure levels of this application (122 psia minimum).

- 62-010 Arwas, E.B. and Beno Sternlicht.
VISCOUS SHEAR COMPRESSOR. Mechanical Technology, Inc. Report MTI-62TR21, September 1962. Navy contract Nonr-3730(00).

Since externally pressurized gas bearings generally require low flow and high pressure, a viscous compressor is well suited for such an application. The analysis presented in this report considers a grooved plate viscous shear compressor under polytropic flow conditions. Several special cases are treated, e.g., incompressible flow and compressible flow with adiabatic and isothermal compression. Dimensionless curves for the calculation of pressure rise as a function of flow are given for: isothermal compression; adiabatic compression, monatomic gas; and adiabatic compression, diatomic gas. Sample results are given in graphical form for a specific size compressor operating at 24,000 RPM with four different film thicknesses, ambient pressure and temperature under isothermal and adiabatic conditions with air and helium gases.

62-011

Bard, D.O.

AIR BEARINGS. U. S. Patent 3,034,635. (to Chrysler Corp.).
Applied February 1, 1960. Issued July 10, 1962.

The air bearing of this invention is of a type which does not use any source of compressed air or any compressed gas other than that air which is naturally in the space between the rotor and housing. Either of the relatively movable members, that is, the rotor or the housing, may be provided with offset peripheral portions to provide wedge-shaped, air compression spaces between the members. These spaces cause the rotor to be suspended on an air cushion within its housing when a certain speed of rotation of the rotor is attained. It also includes the feature of offset peripheral portions on either the end of the rotor or the inner ends of the housing bore to form the necessary wedge-shaped compression spaces to provide thrust air bearings for preventing engagement of the end portions of the rotor with the housing when predetermined speeds of rotation of the rotor or housing are attained. The compression pockets will become filled with whatever fluid surrounds the system utilizing these bearings, (for example water or oil,) and the rotor will be supported on a cushion of that particular fluid in the same manner as though the fluid were a gas. A significant advantage over the prior art types of air bearings is that the present bearing requires no outside source of compressed air, but, instead compresses its own air for floating the rotor within the housing. Since the rotor actually does float within the housing there is no frictional engagement of the rotor therewith and the heat developed by the bearing is practically non-existent.

62-012

Barker, Allan

GAS LUBRICATED JOURNAL BEARING ASSEMBLIES. U. S. Patent 3,034,837. (to United Kingdom Atomic Energy Authority, London).
Applied May 17, 1960. Issued May 15, 1962.

The use of journal and bearing assemblies in which gas lubrication is employed involves maintaining very small clearances and it is the practice to support the bearing in bellows or flexible diaphragms so that the bearing can follow slight deflections of the journal without rubbing. Bellows are used where the bearing carries no substantial weight, and diaphragms when there is substantial weight. However, problems can arise, e.g., seizure of a bearing supported by bellows, or diaphragm acting as a seal can create a dangerous breach in the sealing arrangements. Further, diaphragms are not suitable for supporting a line of more than two conventional gas lubricated bearings carrying a single shaft as their transverse stiffness demands that a very high degree of accuracy exist in alignment. This invention is for a journal and bearing assembly comprising a rotatable shaft, inner and outer bearing sleeves with gas lubrication maintained between them, and an annular resilient sealing member engaged between the inner sleeve and either the shaft or the outer sleeve, so that slippage can take place on the resilient sealing member in the event of failure of the gas lubrication.

62-013

Barker, Allen.

IMPROVEMENTS IN OR RELATING TO JOURNAL AND BEARING ASSEMBLIES.
British Patent 905,647. (to United Kingdom Atomic Energy
Authority). Applied May 22, 1959. Issued September 12, 1962.

A gas-lubricated bearing assembly comprises a rotatable shaft having a sleeve bonded thereto by a rubber-sealing band and a non-rotating bush secured and sealed to a casing by a ring. A pipe supplies gas to the bearings via pipes and jets and a pipe also supplies sealing gas to the bearing. The gas pressure in the bearing is controlled by apertures in the bush. The sleeve is assembled on the shaft prior to introducing it into the casing, and it is held by collets. Rubber is then injected into the passageway to fill the groove in the shaft, the rubber is cured, and the collets are removed. There are also a number of modifications of the above described assembly.

62-014

Beane, G.A. and K.L. Berkey.

THE AIR FORCE-NAVY-INDUSTRY PROPULSION SYSTEMS LUBRICANTS CONFERENCE, Proceedings, San Antonio, Texas, November 15-17, 1960.
Technical documentary report ASD-TDR-62-465, May 1962.
AF contract AF 33(616)-7223. AD-278 843.

This report is a compilation of papers presented at the Air Force-Navy-Industry Propulsion Systems Lubricants Conference held in San Antonio, Texas on 15, 16, and 17 November 1960. The conference was attended by approximately 300 representatives of Industry, the Department of Defense, and other Government Agencies. Twenty-two papers were presented providing a review of lubrication requirements for future propulsion missions and of current research programs pertinent to gas turbine engines, rocket engines, and flight vehicle power. One paper is pertinent to gas-lubricated bearings and gas lubrication at very high temperatures. (See 62-076, E.F. Macks).

62-015

Bennett, E.C.

OPERATING EXPERIENCE WITH GAS BEARING CIRCULATORS IN AN INREACTOR TEST LOOP. Rotating Machinery for Gas-Cooled Reactor Application, Proceedings, Oak Ridge National Laboratory, Tennessee, April 2-4, 1962. Report TID-7631. June 1962. pp. 256-69.

Operating experience in the DR-1 gas loop used for testing gas-cooled reactor fuel elements is described. A review of the main loop components and the operating characteristics that are pertinent to gas seal problems is presented. It is noted that the facility presents three major gas seal problems including loop coolant losses, radioactive materials containment, and contamination of the coolant from sources external to the loop. These problems are associated with auxiliary equipment for the circulators. The circulators are dependable and the gas-lubricated bearings are considered a practical solution for shaft seal problems in gas loops. Development of self-acting bearings is recommended.

62-016

Bereitsky, I.

TWO PHASE FLOW IN THRUST BEARINGS. PART 1 - DERIVATION OF EQUATIONS. Mechanical Technology, Inc. Report MTI-62TR9, June 11, 1962. Navy contract Nonr-3731(GO) (F&M).

The governing equations are derived for an externally pressurized vapor thrust bearing in which condensation of the lubricant occurs on one of the surfaces due to an imposed temperature difference. The analysis involves two different problems, depending on whether the cooled surface is either the bearing or the runner. For the case of the cooled runner, the problem involves consideration on the rotating surface; the vapor entering through the nozzle begins condensing on the rotating surface; subsequently, the condensate is continuously pumped out radially due to the shear stress of the vapor resulting from the radial pressure gradient and the centrifugal force. The second problem is the case in which the bearing is cooled. Here the gas phase is adjacent to the rotating surface. The substantial difference between this case and the cooled runner case is that the inertial terms of the liquid phase are significantly smaller since the liquid film is not condensing on the rotating surface. The equations of motion for the liquid phase in the case of condensation on the rotating surface cannot exclude the effect of the inertial terms. For the liquid phase equations, it is shown that for a thrust bearing the force due to the radial pressure gradient must be considered and not neglected compared to the centrifugal force. The analysis presented in this report reduces the governing equations to a set of four simultaneous first order nonlinear differential equations which can be solved by numerical integration. The analysis has definite applications in heat transfer, e.g., space condensers. Also, the analysis includes simultaneous effects of mass, energy, and momentum coupling for a two phase fluid in a thrust bearing.

62-017

Block, J.R.W. and J.D. Braithwaite.

HYDRODYNAMIC GAS LUBRICATED BEARINGS. Paper presented at the Symposium on Non-conventional Lubricants and Bearing Materials Such as Used in Nuclear Engineering, of The Institution of Mechanical Engineers, Manchester, April 12, 1962. (Summarized in Sci. Lub., vol. 14, no. 6, p. 27. (June 1962).)

The performance of hydrodynamic journal bearings as affected by variations in operating conditions and design factors is discussed. The resistance to wear of various materials as journals and bushes is also discussed. A thrust bearing test machine for testing these bearings under conditions of elevated ambient pressures is described.

62-018

Bourquard, Fernand

IMPROVEMENTS IN FLUID FILM DYNAMIC BEARING-SYSTEMS. British Patent 903,055. (to Commissariat a l'Energie Atomique). Issued August 9, 1962.

A gaseous film dynamic bearing system is designed with means for reducing the leaks at the end portions. The means comprise annular recesses on the inner wall of the bearing element within the leak sector, the

recesses forming two or more partitioned grooves at each end. The pressure in the region of these grooves is higher than that for uninterrupted circular grooves of the conventional type, making it unnecessary to increase the length of the bearing element for a given load of the rotating shaft.

62-019

Bowden, B.V.

IMPROVEMENTS IN OR RELATING TO GYROSCOPES. British Patent 911,490. Applied March 18, 1958. Issued November 28, 1962.

In a gyroscope which includes a rotor mounted within a gimbal system providing freedom for rotation about each of two mutually perpendicular axes, the rotor comprises two concentrated masses, mounted at opposite ends of a diameter perpendicular to the axle of the rotor and the rotor axle is journalled in one of the gimbal rings by bearings which permit a limited amount of displacement of the axle relative to the gimbal ring in directions perpendicular to the rotor axis. The bearings for the rotor axle may comprise a ball-race supported within a housing by springs. These springs may be tuned to provide resonance at frequency 2Ω , where Ω is the angular velocity of the rotor axle. Alternatively, gas bearings may be used. The rotor may comprise sheet-metal shells defining a hollow chamber containing two diametrically-opposed weights, the shells being secured to a hollow sleeve which rotates about an axle pin. Compressed air flows from the pin through ports and past flow-directing blades on to blades which cause rotation of the rotor. The air then forms the bearings at each end of the sleeve.

62-020

Brehm, P.D.

MPB AIR BEARINGS USED FOR SATELLITE TEST PROGRAM. MPB Engng. News, vol. 8, no. 3, pp. 1-2. (June 1962).

The hydrostatic bearing designed as the support for a test simulator of the Bell System Telstar is composed of a $2\frac{1}{2}$ inch diameter partial spherical, or ball and socket configuration. The design allows 360° of rotation combined with tilting up to 40° from the vertical in any direction. Because both a downward gravity load and a radial dynamic driving load had to be carried a full 180° , socket design was used with both thrust and radial air pads. Dry filtered air at approximately 90 psig is supplied to the bearing clearance spaces through controlled orifices and pressure pads.

62-021

Buckley, G.W. and Sigmund Rappaport.

AIR BEARINGS. U. S. Patent 3,026,150. (to Sperry Rand Corp.) Applied August 15, 1960. Issued March 20, 1962.

This invention describes the use of a standard air bearing sleeve having end plates. In the sleeve and end plates holes are drilled within which removable plugs are placed. The plugs have a main vertical air passage which ends in crossed air passages which are at right angles to each other and perpendicular to the main air passage. The end of the plug which contains the crossed air passages is slightly smaller than the rest of the plug thereby allowing the air coming out of the crossed passages to pass around

the plug and find its way to the chamber within which the rotative member is supported, thereby eliminating the directional property of the air and also decreasing the air velocity and thus minimizing the turbine effect. The main air passage of the removable plug is covered with an individual piece of aluminum foil. A hole is pierced in the aluminum foil substantially concentric with the main air passage of the plug.

- 62-022 Cameron, A. and W.G. Robertson.
ON THE DERIVATION OF REYNOLDS EQUATION. Sci. Lub., vol. 14,
no. 6, pp. 14-19, 42. (June 1962).

The complete Reynolds equation in three dimensions is derived by three methods which differ basically in the way in which the continuity condition is applied. The apparent divisions of the mechanisms of hydrodynamic lubrication which are suggested by these derivations, such as "wedge", "squeeze" terms etc. are compared and it is shown that such a division is in every case somewhat arbitrary, since it merely depends on the volume to which the continuity condition is applied. A form of the Reynolds equation is given for the case where both surfaces are curved (as in gears, for example), the x-axis being taken along the common tangent at the contact zone. The reason for the differences in the forms of the equation derived in this paper and that given by Reynolds in his original paper, is pointed out to avoid possible confusion. The error involved in neglecting the variation in the horizontal surface velocity component of a journal bearing is considered. This is shown to be negligible under typical operating conditions.

- 62-023 Chaboseau, J.S.
PROCEEDING DEVELOPMENTS ON GAS-BEARING AT SOCIETE RATEAU (FRANCE).
Rotating Machinery for Gas-Cooled Reactor Application, Proceedings, Oak Ridge National Laboratory, Tennessee, April 2-4, 1962.
Report TID-7631. June 1962. pp. 397-402.

Activities in a basic research program to determine working principles of tilting pad gas-bearings are described. Included is a review of geometrical pad-parameters, physical parameters, and mechanical parameters which affect hydrodynamic operation. It is believed that gas bearings present the possibility of building very reliable machines which are easily operated and maintained.

- 62-024 Chaboseau, J.S. and C. Mech.
GAS-BEARING DEVELOPMENT AT THE SOCIETE RATEAU (FRANCE).
Rotating Machinery for Gas-Cooled Reactor Application,
Proceedings, Oak Ridge National Laboratory, Tennessee,
April 2-4, 1962. Report TID-7631. June 1962. pp. 292-306.

Development of the gas-bearing technique used in the Marcoule reactors is described. Included are discussions of cylindrical bearings and multi-pad bearings. Experience with existing bearings operating with gases such as UF_6 , CO_2 , and He is also reported.

- 62-025 Cherubim, J.L. and Stanley Abramovitz.
A HIGH-TEMPERATURE MOTOR TEST UNIT UTILIZING GAS BEARINGS.
Rotating Machinery for Gas-Cooled Reactor Application,
Proceedings, Oak Ridge National Laboratory, Tennessee,
April 2-4, 1962. Report TID-7631. June 1962. pp. 335-343.

Activities in a program to develop circulators with gas-lubricated bearings for use in gas-cooled reactors are described. The objective is to achieve continuous operation in He at 400 psia and 800 to 1000°F. A circulator was designed and tested at 12,000 to 18,000 rpm at gas pressures of 60 to 200 psi and 150°F using tilting pad bearings with a vertically mounted circulator.

- 62-026 Christian, E.L.
AIR BEARINGS CARRY HEAVY LOADS. Iron Age, vol. 189, no. 11,
pp. 135-7. (March 15, 1962).

Some examples of the commercial application of air bearings are given. One 20 sq. in. x 3 in. thick air bearing, made of aluminum, required an air pressure of only 86 psi to lift a 15,000 lb. load. The production welding of extremely thin materials was made possible by the use of four friction-free air bearings installed on a straight-line welder's carriage. The smooth-riding airborne carriage permitted welding that was only 0.0003 in. thick. The air bearings decreased vibration action 400 times for horizontal deflections. They also curbed vertical deflections by a factor of 23:1 over the roller bearings, gear drives, and wheel racks formerly used.

- 62-027 Comolet, Raymond
[FLOWING OF A GAS BETWEEN A PLANE AND A ROTATING DISK. A STUDY
ON THE FRICTION TORQUE EXERTED ON THE DISK]. ECOULEMENT FORCE
D'UN GAZ ENTRE UN PLAN ET UN DISQUE EN ROTATION. ETUDE DU COUPLE
DE FROTTEMENT EXERCE SUR LE DISQUE. (In French). J. Mecan.,
vol. 1, no. 3, pp. 233-253. (September 1962).

An attempt is made to analyze the forced laminary flow of a viscous

gas (similar to that in a gas thrust bearing) between a fixed plane and a rotating disk. Specifically the author analyzes the viscous torque exerted on a disk. The law of friction derived from experiments is compared with theoretical results.

62-028 Constantinescu, V.N.

[VISCOUS FLOW OF A GAS BETWEEN TWO PARALLEL PLATES]. SUR L'ÉCOULEMENT À FROTTEMENT D'UN GAZ, ENTRE DEUX PLAQUES PARALLÈLES. (in French). Rev. Mecan. Appl., vol. 7, no. 1, pp. 23-40. (1962).

Author considers viscous flow of a gas injected between two parallel planes in both the two-dimensional and the axially-symmetric cases. An externally-pressurized gas bearing is the intended application. The inertial terms of the equation of motion are taken into account approximately by a perturbation procedure for small ratios of inertial to viscous forces. Agreement of isothermal theory with experimental data from the literature for the two-dimensional case is excellent. Reviewer feels that this agreement is made less significant by the smallness of the effect being considered. One result of practical significance is that the inertial terms effect an increase in the static pressures between the surfaces. Therefore the load-bearing capacity of the gas should be increased.

62-029 Constantinescu, V.N.

[HIGH SPEED GAS FLOW IN THIN LAYERS]. О ТЕЧЕНИИ ГАЗОВ С БОЛЬШОЙ СКОРОСТЬЮ В ТОНКИХ СЛОЯХ. (in Russian). Rev. Mecan. Appl., vol. 7, no. 6, pp. 1081-1097. (1962).

The paper discusses gas lubrication taking account of the inertia forces. Differential equations of pressure and the pressure distribution for flat-surface bearings are analyzed. The author observes that due to the velocity reached in the present technology the effect of inertia forces is extremely low.

62-030 Constantinescu, V.N.

[CONSIDERATIONS OF THE PRESSURE DISTRIBUTION IN HYDROSTATIC BEARINGS]. CONSIDERATIONS SUR LA DÉTERMINATION DE LA DISTRIBUTION DES PRESSIONS DANS LES PALIERS ALIMENTÉS SOUS PRESSION. (in French). Rev. Mecan. Appl., vol. 7, no. 2, pp. 363-379. (1962).

Description of a method for the determination of pressure distribution in bearings lubricated with liquid or gases under pressure. The method is based on the development of the solution in series form. The results are applied to the case of rectangular surfaces and circular segments pressure-fed through a central slot and used in the construction of certain axial bearings. In addition, the results are applied to the calculation of circular bearings.

62-031

Constantinescu, V.N.

[SOME CONSIDERATIONS ON THE CALCULATION OF HYDROSTATIC GAS BEARINGS SUPPLIED THROUGH A LARGE NUMBER OF HOLES OR THROUGH POROUS SURFACES]. UNELE CONSIDERATII ASUPRA CALCULULUI LAGARELOR CU AER ALIMENTATE SUB PRESIUNE PRINTR-UN-NUMAR MARE DE ORIFICII SAU PRIN SUPRAFETE POROASE. (in Romanian). Studii si Cercetari Mecan. Apl., Inst. Mecan. Apl., Acad. Repub. Pop. Romine, vol. 13, no. 1, pp. 173-191. (1962).

The equations of gas lubrication in the presence of a porous surface are written and the case of the surfaces with a large number of supply holes is simulated with the permeable surfaces having an equivalent porosity coefficient. Further, the pressure differential equation is integrated and the operating characteristics of journal bearings supplied under pressure through a porous surface are determined.

62-032

Constantinescu, V.N.

[ON SOME APPROXIMATE METHODS FOR THE ANALYSIS OF GAS LUBRICATED JOURNAL BEARINGS]. ASUPRA UNOR METODE APROXIMATIVE DE CALCUL ALE LAGARELOR CIRCULARE LUBRIFICATE CU GAZE. (in Romanian). Studii si Cercetaria Mecan. Apl., Inst. Mecan. Apl., Acad. Repub. Pop. Romine, vol. 13, no. 4, pp. 935-955. (1962).

This paper analyzes the sense and the magnitude of approximations introduced by various existing methods of analysis for gas lubricated journal bearings. On the basis of these considerations, corrected analytical expressions are deduced whose calculation accuracy is emphasized by comparisons with numerical data.

62-033

Constantinescu, V.N.

[ON GAS LUBRICATION IN TURBULENT REGIME]. ASUPRA LUBRIFICATIEI CU GAZE IN REGIM TURBULENT. (in Romanian). Studii si Ceretari Mecan. Apl., Inst. Mecan. Apl., Acad. Repub. Pop. Romine, vol. 13, no. 5, pp. 1157-1175. (1962).

This paper analyzes the conditions of transition from the laminar flow to the turbulent one in the gas lubricant layer, as well as the possibilities of the occurrence of turbulence in actual gas bearings. Further, by employing the Prandtl's mixing length theory, previously used by the author for liquid film bearings, an analysis is made of the pressure distribution in both externally pressurized and self acting gas bearings. For self acting bearings it is found that the turbulence has usually a negligible influence on the load carrying capacity. Its effect on friction forces is of course significant.

- 62-034 Constantinescu, V.N.
[DETERMINING THE PRESSURE DISTRIBUTION IN HYDROSTATICALLY LUBRICATED BEARINGS BY USING A HYDRODYNAMIC ANALOGY]. SUR LE CALCUL DE LA DISTRIBUTION DES PRESSIONS DANS LES PALIERS ALIMENTES SOUS PRESSIONS EN UTILISANT UNE ANALOGIE HYDRODYNAMIQUE. (in French). Rev. Mecan. Appl., vol. 7, no. 3, pp. 503-521. (1962).

It has been shown that the usual methods for solving the lubrication problem can be applied only to certain cases of hydrostatically lubricated bearings. In other cases the calculations become laborious. However, if one starts in these latter cases from the observation that the pressure equation is homogeneous and that the thickness of the lubricant layer is constant, and the pressure is a harmonic function of the film thickness one can arrive at a reasonable solution.

- 62-035 Cooper, Stanley
IMPROVEMENTS TO FLUID BEARINGS. British Patent 893,045. (to Rolls-Royce Ltd.). Applied November 10, 1960. Issued April 4, 1962.

This invention relates to journal bearings of the kind employing hydrodynamic fluid lubrication. In particular the invention relates to the type of bearing arrangement in which a shaft or journal is supported on pivoted pads so that during rotation of the shaft a fluid film is set up between the pad and the shaft bearing surface. The shaft is rotated and the rotation results in a film of air being set up between the pads and bearing surface which causes the rotor to stabilize between the pads, so that there is a film of air between each pad and the adjacent part of the shaft surface. The radius of curvature of the pad exceeds the shaft bearing radius by at least twice the value of the minimum film thickness along a radial line joining the pivot of the pad and the center of the journal bearing.

- 62-036 DiPrima, R.C.
A NOTE ON THE STABILITY OF FLOW IN NON-CONCENTRIC ANNULI. Mechanical Technology, Inc. Report MTI-62TR15, August 14, 1962. Navy contract Nonr-3731(00)(FBM).

If two non-concentric cylinders are rotating, a circumferential pressure gradient is created. The effect of this pressure gradient flow on the stability of the local velocity profiles is discussed. It is concluded that, in the most critical regions, the flow due to the pressure gradient has a stabilizing effect.

- 62-037 Escher Wyss S.A.
OPERATING PROCESS FOR A MOTIVE POWER INSTALLATION COMPRISING
A NUCLEAR REACTOR, AND DEVICE FOR PERFORMING THIS PROCESS.
French Patent 1,307,545. Issued September 17, 1962.

Nuclear power installations, with a gaseous working medium flowing in a closed circuit consisting of a compressor, a nuclear reactor for heating the medium, and a turbine, in which the medium is expanded while a small amount of the gas is continuously bled off to a cleaning circuit, are considered. A method was developed by which at least a part of the cleaned gas is injected into at least one of the bearings of the turbo-machine to form a gas layer lubricating and supporting the turbo-machine axle, before it is reintroduced into the main circuit. The cleaning circuit also contains an auxiliary compressor for increasing the pressure of the gas injected into the bearings.

- 62-038 Eusepi, M.W. and D.D. Fuller.
PROGRESS REPORT ON THE DEVELOPMENT OF GAS-LUBRICATED BEARINGS
FOR HIGH-SPEED ROTATING MACHINERY. Rotating Machinery for Gas-
Cooled Reactor Application, Proceedings, Oak Ridge National
Laboratory, Tennessee, April 2-4, 1962. Report TID-7631.
June 1962. pp. 307-34.

Activities and results associated with the first year's program at the Franklin Institute Laboratories on gas-lubricated bearings are summarized. The program was directed along two parallel avenues. One investigation was concerned with the characteristics of a 3-in. dia. rotor weighing 100 lb. used to simulate the shaft of a turbine-compressor unit. The other effort was concerned with a rotor shaft that is to be supported on bearings which are completely self acting, rather than externally pressurized.

- 62-039 Eusepi, M.W., A. Marmarou and D.D. Fuller.
THE APPLICATION OF GAS LUBRICATED BEARINGS TO HIGH-SPEED TURBO-
MACHINERY. Franklin Institute Laboratories for Research and
Development. Quarterly Technical Report, Report TID-16105,
December 1, 1961 to February 28, 1962. Contract AR(30-1)-2512.

Several advances were made in both the instrumentation and experimental testing required on the program. The final results are presented of instrumentation work, calibration, the modified instrument circuits, and a noise level evaluation. Also reported are results of experiments performed on the EP-2 rig (externally-pressurized bearings) including rotational testing up to a speed of 9000 rpm. Significant results were also obtained on the operational testing of the SA-2 rig (self-acting bearings, 4" d. shaft). The rig was completely de-bugged and the first rotational tests made. At the close of the report period a speed of 20,180 rpm. was reached.

- 62-040 Frost, Alan
IMPROVEMENTS IN AND RELATING TO GAS BEARINGS. British Patent
901,004. (to Bristol Siddeley Engines Ltd.). Applied April
4, 1961. Issued July 11, 1962.

This invention relates to a gas bearing which is of cheaper construction than the prior art from porosity than previously available and whose surfaces are of compatible materials and can be repaired. The gas bearing has both the elements formed from mild steel, one being chromium plated on its bearing surface, and the other having its bearing surface provided by a thin layer of an alloy having the approximate composition 66% cobalt, 26% chromium, 5% tungsten, 1% carbon and 2% impurities which has been flame sprayed on to it and fused.

- 62-041 Garrett Corp., AiResearch Mfg. Div. of Arizona
TECHNICAL PROPOSAL- ADVANCED CLOSED BRAYTON-CYCLE SPACE POWER
SYSTEM. Report SY-5394-R, vol. 1, August 24, 1962.

The results of an extensive study of a Brayton cycle space power system using the SNAP-8 reactor as a heat source are reported. The system presented is a closed, recuperated, inert gas cycle, comprising a combined rotating power unit supported on gas bearings, a primary heat exchanger, a recuperator, a radiator, and a start and control system.

- 62-042 Geary, P.J.
FLUID FILM BEARINGS - A SURVEY OF THEIR DESIGN, CONSTRUCTION,
AND USE. British Scientific Instrument Research Association,
Chislehurst, Kent. 1962.

A concise recital of principles of liquid- and gas-lubricated bearings with external pressure generation and gas-lubricated bearings with internal pressure generation, but excluding hydrodynamic lubrication using liquid lubricants is given. Chiefly useful as a guide to the literature, 50 pages of text and diagrams explain the principles and refer the reader to relevant books and papers. Those parts of text and the 53-page bibliography of 306 references dealing with gas bearings are meant to complement, not duplicate, other surveys. Discussion is mainly "practical" but includes basic expressions for film thickness and lubricant flow. There are brief notes on squeeze film.

- 62-043 Getler, Michael
NEW GYRO AIMED AT TACTICAL MISSILES. Missiles and Rockets,
vol. 11, no. 10, pp. 34-35. (September 3, 1962).

A description of the "Hydrogyro" a new "gimbal-less" gas-bearings

gyro, with low drift rate and high-g capability, to be used in short-range tactical missiles is given. The proposed instrument uses hydrostatic pressure to run up and support the only moving part - a brass or aluminum rotor. Photos of the instrument and a test diagram are included.

- 62-044 Gilbert, Sr., C.E., and Donald Winget, Jr.
SLIDE BEARING CONSTRUCTION. U. S. Patent 3,042,460. (to Cincinnati Gilbert Machine Tool Co.). Applied July 15, 1960. Issued July 3, 1962.

This invention relates to an improved precision slide bearing construction wherein a layer of air is maintained between two relatively moving members which constitute the bearing so as to minimize the friction otherwise restraining movement of the one bearing member relative to the other. The principal objective of this invention has been to provide a bearing construction where air under pressure is employed to maintain a virtually frictionless layer or film of air between relatively movable members constituting the bearing, and where oil or other liquid is introduced into the air interface of the bearing to act as a seal preventing excessive escape of air from the bearing margins and to damp or suppress fluctuations in the thickness of the air interface which might otherwise occur under varying load conditions. The supply of air to the bearing interface area is automatically controlled or regulated to maintain an air film of substantially uniform thickness, regardless of fluctuations in the loading of the bearing or of fluctuations in the unit bearing pressure. A liquid seal is effective to minimize air escape and thereby minimize the consumption of compressed air required to serve or maintain the bearing under severe variations in the load conditions to which the bearing is subjected.

- 62-045 Gobert, Gerald
[APPLICATION OF GAS LUBRICATED BEARINGS TO GYROSCOPES]. APPLICATION DES PALIERS A GAZ AUX GYROSCOPES. (in French). J. Phys. Rad., Phys. Appl., vol. 23, no. 3, pp. 43A-46A. (March 1962).

A study of the friction in gas lubricated bearings has led to the construction of a gyroscope. The rotor is 4 cm. in diameter and runs at 180,000 r.p.m. Its weight is 500 g.

- 62-046 Gobert, Gerald
[EXPERIMENTAL CONTRIBUTION TO THE STUDY OF GAS BEARINGS]. CONTRIBUTION EXPERIMENTALE A L'ETUDE DES PALIERS A GAS. (in French). Commissariat a l'Energie Atomique. Centre d'Etudes Nucleaires, Saclay. 1962.

Developments for gas-lubricated bearings are discussed. The study of how the fluid film behaves compared to what one can expect is discussed. Various devices are described which have allowed us to go up

to peripheral velocity greater than 400 m/s, leading to rotational speed of several thousand revolutions per second. This is obtained by using an automatic setting for the distance between fused and rotating walls.

62-047 Gray, D.L.

OPERATING CHARACTERISTICS OF GAS-BEARING COMPRESSORS BUILT BY BRISTOL SIDDELEY ENGINES, LTD. Rotating Machinery for Gas-Cooled Reactor Application, Proceedings, Oak Ridge National Laboratory, Tennessee, April 2-4, 1962. Report TID-7631. June 1962. pp. 280-91.

Tests of two similar but slightly different gas-bearing compressors are described. The single model of one type compressor was operated under a variety of conditions for about 760 hr. since it was installed in the ORNL test loop. The test equipment and test results associated with this compressor are described. Two models of the other type compressor were tested at the manufacturer's plant. Over 100 hr. of satisfactory service was accumulated with these compressors. Equipment and results associated with these tests are also presented.

62-048 Gross, W.A.

GAS FILM LUBRICATION. John Wiley & Sons, Inc., New York. 1962. 424 pp.

This is an excellent academic book on gas bearings. The author presents the theory of the problem rather than writing a handbook of do-it-yourself rules for getting a bearing under way. The chapter headings indicate the scope of the book. "Hydrodynamic equations" gives the basic equations more fully than has appeared almost anywhere else. Chapter 3 on the steady-state hydrodynamic solutions for long bearings gives virtually all the known theory. Chapter 4 lists similar calculations for finite length bearings. The next chapter deals with externally-pressurized bearings. Finally, bearings subject to instability are studied. Mathematical proofs are presented. All the foundations on which industrial "know how" can be built are given.

62-049 Gross, W.A.

GAS LUBRICATED BEARINGS. Appl. Mech. Rev., vol. 15, no. 10, pp. 765-769. (October 1962).

A Navy-supported investigation of gas-lubricated bearings, covering (1) the status of knowledge of properties of steady-gas-lubricating films, and (2) the dynamics of gas-bearing systems is discussed. Types of films, bearings, configurations, and shapes are treated, and attention is given to the operating conditions and environmental and material problems involved in the area in which the properties of gas-lubricating films need to be understood. Available solutions are then described, and their use with bearing systems discussed.

62-050

Gross, W.A.

INVESTIGATION OF WHIRL IN EXTERNALLY PRESSURIZED AIR-LUBRICATED JOURNAL BEARINGS. Trans. ASME (J. Basic Engng.), vol. 84 D, no. 1, pp. 132-138. (March 1962).

The effects of several parameters upon the whirl properties of air-lubricated journal bearings were experimentally investigated. The whirl was composed of two components, one at the frequency of rotation, and the other at about half the rotational frequency. The behavior of the synchronous whirl component was like the response of a passive system to the excitation due to rotor unbalance, and the half-frequency whirl was a self-excited oscillation. Both components were in the predominantly cylindrical or translatory mode because this corresponded to the lowest critical frequency. These characteristics were predicted using a lumped parameter, quasi-static analysis. The threshold of self-excited whirl was important because, although the whirl path was stable, the amplitude increased rapidly with speed. The threshold for any journal supply pressure occurred at about twice the lowest critical frequency of the non-rotating system using the film stiffness at $\xi = 0$. Because of the small clearance ratio, the effective damping was more than critical. At moderate speeds, four sources per journal bearing were sufficient; more were necessary at higher speeds. Factors which raised the threshold speed were increased pressurization, reduced rotor mass, and, in limited cases, unbalance. Additional work is in progress to examine the effect of clearance ratio, slenderness, and roundness of rotor and shaft.

62-051

Gunter, Jr., E.J., J.G. Hinkle and D.D. Fuller.

THE APPLICATION OF GAS LUBRICATED BEARINGS TO HIGH SPEED TURBOMACHINERY. Franklin Institute Laboratories for Research and Development. Quarterly Technical Report, June 1 - August 31, 1962. Report TID-17311. Contract AT(30-1)-2512.

Procedures are being developed for designing practical gas lubricated bearings for use in high-speed turbomachinery. Effort was applied to the design and analysis of two separate bearing systems; one system requiring external pressurization, and the other of a self-acting nature. Because of stability problems frequently encountered in 360° journal bearings, particularly if gas lubricated, attention was directed toward the development of pivoted-pad, self-acting bearings. This bearing arrangement is inherently more stable than the conventional full journal bearing; and in addition has the capacity to be self aligning. A review of the theoretical and experimental work that was performed on both the self-acting (SA-2) and the externally pressurized (EP-2) rotors is presented. The EP-2 rotor was dynamically balanced and run. Failure was encountered at 15,000 rpm. The rotor was studied in an effort to determine possible reasons for failure. The SA-2 rotor was tested at speeds up to 18,000 rpm. The load-deflection characteristics of the hydrostatic lifters were

determined. Film thickness measurements of the self-acting pivoted shoes were taken. A preliminary design of a self-acting thrust bearing was tested up to speeds of 5,000 rpm. Correlation of film thickness measurements and theory is presented.

- 62-052 Gunter, Jr., E.J., J.G. Hinkle and D.D. Fuller.
THE APPLICATION OF GAS LUBRICATED BEARINGS TO HIGH-SPEED TURBO-MACHINERY. Franklin Institute Laboratories for Research and Development. Quarterly Technical Report, September 1, 1962 - November 30, 1962. Report TID-18292. Contract AT(30-1)-2512.

A program directed towards developing procedures for designing practical gas lubricated bearings for use in high-speed turbo-machinery is discussed. Effort has been applied to the design and analysis of two separate bearing systems; one system requiring external pressurization, and the other of a self-acting nature. A review of the theoretical and experimental work that has been performed on the self-acting, gas bearing rotor is presented. This rotor was tested at speeds up to 20,200 rpm. Film thickness measurements of the self-acting pivoted shoes were obtained for various pivot positions to ascertain the optimum pivot location. A secondary technique to measure film thickness indirectly was developed to permit the monitoring of two shoes simultaneously. In addition, a shaft attitude-eccentricity locus was obtained. Theoretical performance of pivoted-pad, partial journal bearings is presented in the form of computer field maps for values of $\Lambda = 1.5, 2.5, 3.0, 3.5, \text{ and } 4.0$. Extended theoretical load deflection curves for a shoe pivoted at $\phi\alpha = 2/3$, are presented. An analytical equation, which was derived from the computer data, is given to predict the load-carrying capacity of a pivoted-pad bearing. Performance characteristics of the pivoted-pad gas bearing are compared to the characteristics of a flat slider bearing using an incompressible lubricant.

- 62-053 Halliday, R.F.
AN IMPROVED AIR LUBRICATED SWIVELLING PIPE COUPLING OR JOURNAL BEARING. J. Sci. Instrum., vol. 39, no. 11. pp. 572-3. (1962)

In order to conduct compressed air to a small model of a ground effect machine which was undergoing dynamic tests, a frictionless swivelling pipe coupling was required. Externally pressurized air bearings were the choice for lateral restraint of the moving part of the coupling, and since continuous rotation was not required fine strained wires acting along the axis provided the longitudinal restraint. Longitudinal grooves in the journal control pressure distribution and a continuous, though very thin, circumferential slot replaces the individual throttling orifices.

- 62-054 Herbert, Jr., T.A., and E.L. Christian.
AIR BEARINGS FOR MACHINE TOOLS? Prod. Engng., vol. 33,
no. 10, p. 177. (May 14, 1962).

The authors claim that up to now, none of the many air bearings developed in recent years has been practical for use in machine tools. But now, a new method of distributing air pressure over the face of the bearing has greatly increased the potential uses of air bearings. In fact, four air bearings are already doing the work of ten roller bearings on a straight-line welder at General Dynamics/Astronautics. They are doing the job so well that carriage travel is accurate enough to permit welding of foil-thickness metals. Vibration is virtually non-existent.

- 62-055 Hodapp, Jr., A.E.
EVALUATION OF A GAS BEARING PIVOT FOR A HIGH AMPLITUDE DYNAMIC STABILITY BALANCE. Arnold Engineering Development Center.
Report AEDC-TDR-62-221, December 1962. Contract AF 40(600)-1000.
AD-290 948(K).

The results of a study of the load capacity and damping level of a gas journal bearing are presented. Experimental data indicate that the bearing is capable of supporting radial loads in excess of 300 pounds, and that the damping parameter has some inverse relationship to frequency which is determined by the radial load. It is shown that the damped motion of the gas bearing can be approximated adequately with the viscous-damping equation.

- 62-056 Hopkins, W.G.
LOW PRESSURE AIR BEARING SLIDER. IBM, Tech. Disc. Bull.,
vol. 5, no. 5, p. 16. (August 1962).

This device torsionally loads an air-lubricated slider towards a moving surface. The slider is pivotally mounted in f-shaped arm by pins received in openings in the extremities of an arm. The slider is initially loaded towards the moving surface by a small force. A torsion force is then applied to the arm in the direction of reducing the angle of attack of the slider. As the angle of attack is reduced, a partial vacuum is created under the trailing edge of the slider. An equilibrium condition develops between the torsional force and the vacuum, which maintains nearly constant air film thickness for both positive and negative normal loads.

- 62-057 Hopkins, W.G. and D.H. McClung.
AIR BEARING. IBM, Tech. Disc. Bull., vol. 5, no. 2, p. 12
(July 1962).

An air lubricated slider bearing supports a magnetic transducer in proximity to a recording disk. A transducer-supporting slider is provided with one or more vents located symmetrically about the roll axis and forward of the pitch axis. The vents bleed off a portion of the lubricating film carried by the rotating disk. This reduces the film thickness and, consequently, the slider-to-disk spacing, while increasing the stiffness of the bearing. The angle of attack of the slider is controlled by the positioning of the vents ahead of the pitch axis. This reduces the sensitivity of the slider to changes in surface velocity. The rates of change of film thickness and angle of attack with variations in surface velocity decrease as the angle of attack is reduced. Thus, the vents permit nearly uniform slider-to-disk spacing over the effective radius of the disk.

- 62-058 Hughes, B.G.
AIR BEARING. U. S. Patent 3,070,407. (to U.S.A. as represented by the National Aeronautics and Space Administration).
Applied May 16, 1961. Issued December 25, 1962.

This patent deals with an air bearing, with external-pressurization, having special design provisions to eliminate "turbine torque".

- 62-059 Katto, Y. and N. Soda.
THEORETICAL CONTRIBUTIONS TO THE STUDY OF GAS-LUBRICATED JOURNAL BEARINGS. Trans. ASME (J. Basic Engng.), vol. 84 D, pp. 123-131. (March 1962).

A transformation previously used to obtain an approximate solution to Harrison's isothermal equation for infinite-width bearings is applied to the study of finite-width bearings, under a general pressure-density relationship. Approximate solutions for high values of eccentricity ratio are obtained, as is a solution which permits insight into the characteristics of journal bearings operating at low rotating speeds. Comparison with experimental data indicates that actual bearings operate under a condition which is intermediate between isothermal and adiabatic at high speeds, and under the isothermal conditions at low speeds.

62-060

Kerr, J.

AIR-LUBRICATED JOURNAL BEARINGS AT HIGH COMPRESSIBILITY NUMBERS. Paper presented at the Symposium on Non-conventional Lubricants and Bearing Materials Such as Used in Nuclear Engineering, of The Institution of Mechanical Engineers, Manchester, April 12, 1962. (Summarized in Sci. Lub., vol. 14, no. 6, p. 26. (June 1962)).

An experimental investigation of induced pressure (hydrodynamic type) air lubricated plain journal bearings operating at high speeds and sustaining steady loads is described. Air-film thickness measurements are reported and the experimental results compared with available theoretical predictions. Results are given for bearings with breadth/diameter ratio of unity and a journal diameter of 1 in.

62-061

Larson, R.H. and A.G. Piken.

BEARING AND LUBRICANT REQUIREMENTS FOR SOME AEROSPACE PROJECTS: DISCUSSION AND PRELIMINARY INVESTIGATION. ASLE Trans., vol. 5, no. 1, pp. 1-7. (April 1962).

Some of the pressing bearing and lubrication problems which confront the aero-space industry today are illustrated. Specific requirements of bearings and lubricants for nuclear engine controls and a hot gas flight stabilization system are given. The results of a lubricant survey are discussed, and the preliminary test results obtained in a 600°F lubricant evaluation program are presented. A brief discussion of the merits and limitations of gas-lubricated bearings in extreme environments is included. The concluding remarks emphasize the need for increased bearing and lubricant research.

62-062

Larson, R.H. and H.H. Richardson.

A PRELIMINARY STUDY OF WHIRL INSTABILITY FOR PRESSURIZED GAS BEARINGS. ASME Trans. (J. Basic Engng.), vol. 84 D, no. 4, pp. 511-520. (December 1962).

Experimental data are presented for the threshold of whirl instability for a short, rigid rotor supported in externally-pressurized, compensated gas journal bearings. The effects of supply pressures from zero to 200 psig and of radial clearances from 0.0006 to 0.0032 in. are discussed for one type of bearing configuration. A simple stability criterion is presented which explains qualitatively the observed trends. Whirl instability was observed when the frequency of rotation of the shaft exceeded from two to six times the lowest natural frequency of the shaft-bearing system.

62-063

Laub, J.H.

GAS LUBRICATION IN INSTRUMENTS AND CONTROL DEVICES. ISA Trans.,
vol. 1, no. 4, pp. 305-14. (October 1962).

The use of compressed gases or vapors for lubrication and flotation of rotating, pivoting, or sliding elements of instruments offers significant advantages. The viscosity of gaseous lubricants is several orders of magnitude lower than that of incompressible lubricants, resulting in reduced friction torques, smaller losses, and lower operating temperatures and in virtually vanishing starting torques for hydrostatic bearings. Gases are suitable for lubrication at extreme temperatures, both high and low, and in other environments where conventional lubricants may become unstable, for instance, under exposure to nuclear radiation. A number of examples of applications in instruments and control devices are cited, e.g., the support of the gimbal and spin axes of gyros, pivot bearings for wind-tunnel balances and attitude-control simulators, metrological instruments, and readout devices in random-access computers. Recent progress in the analysis of thin-film gas lubrication at the Jet Propulsion Laboratory of the California Institute of Technology in Pasadena is briefly reviewed. Prediction of the performance characteristics and the accuracy of design data for gas bearings has been greatly improved. This is exemplified by the development of a viscous-flow theory for externally pressurized instrument bearings of various configurations, which yields very satisfactory correlation with experimental data.

62-064

Lee, R.E.

BEARING MATERIALS AND LUBRICANTS FOR HIGH TEMPERATURES. Matsl.
in Design Engng., vol. 55, no. 3, pp. 109-14. (March 1962).

Gas bearings are not a cure-all for high temperatures, and several materials problems are being encountered. Engineers would like to have materials with comparable coefficients of expansion and materials that resist galling and do not wear excessively during momentary contact. They would also like to have bearing materials that will not oxidize and that will remain dimensionally stable at high temperatures. Some of the bearing materials that look promising for high temperature gas bearings are: carbon-graphite, copper or silver-impregnated graphite, nickel austenitic iron, sintered metals, such as nickel impregnated with a solid lubricant, beryllium alloys, and hard coatings, such as aluminum oxide. Some of the shaft materials that look promising are: oxidation resistant alloys that can be hardened by heat treatment, nitriding or hard chromium plating, flame or plasma arc sprayed steels, and cermets and ceramics.

62-065

Lehmann, R.; A. Wiemer and R. Rogal.

[AIR BEARINGS]. LUFTLAGER. (in German). Feingeratetechnik, vol. 7, no. 4, pp. 151-160. (1962).

Air bearings can be equipped - depending on their use - with plane, cylindrical, or spherical surfaces. They have a number of openings for admission of air under pressure, with constrictions which operate as air nozzles. Between the constrictions are chambers for damping the air velocity; their shape and size influence the capacity of the bearing. Depending on the distance of the nozzles from each other, a certain pressure develops, which is, however, lower than the pressure in the chamber. If the chambers are oblong and arranged parallel to the border, there will be a linear air flow, and the capacity of the bearing will reach a maximum. In order to equalize the pressure, the air nozzles at the corner should have a somewhat larger diameter than the others. Parameters on which the capacity of the air bearing depend include: the size of the bearing surface, the pressure of the air in front of the bearing, the size and arrangement of the air nozzles, the shape of the chamber and the height of the aperture. A number of applications for air bearings are given, e.g. in single shaft- and multiple shaft-boring machines, in headstocks of lathes, in stereotype printing plates, in paper cutting machines, etc. A new application, recently installed in the Berlin Office of Weights and Measures, is the mirror of the Michelson Interferometer, which is mounted on a sliding carriage, equipped with air bearings.

62-066

Lemon, J.R.

ANALYTICAL AND EXPERIMENTAL STUDY OF EXTERNALLY PRESSURIZED AIR LUBRICATED JOURNAL BEARINGS. Trans. ASME, (J. Basic Engng.), vol. 84 D, pp. 159-165. (March 1962).

A simplified analytical method for the calculation of the characteristics - such as, stiffness, flow, and load - of an externally pressurized gas journal bearing, on the basis of a one-dimensional flow approach, with allowance for the effect of circumferential pressure variations is presented. The analysis shows that bearing stiffness has an optimum which can be chosen through a proper selection of bearing design parameters, such as radial clearance, upstream resistor, and supply pressure. Experimental data are found to verify the assumptions and predictions of the analysis. Recessed and non-recessed bearings are compared.

62-067

Lewis, P., S.F. Murray and M.B. Peterson.

INVESTIGATION OF COMPLEX BEARING AND/OR LUBRICATION SYSTEMS. Mechanical Technology, Inc. First Quarterly Progress Report for the period May 1962 - August 1962. Report MTL-62TR14, August 5, 1962. AF contract AF33(657)-8666.

Progress is reported in evaluating complex bearing and/or lubrication systems for flight accessory equipment that operates at temperatures from -60°F to 1500°F , in high vacuum or normal atmosphere, and during exposure to nuclear radiation. Two systems have been selected for further study on the basis of materials availability and adaptability to the combined-system concept: (1) the solid-lubricated rolling element bearing and (2) the externally pressurized gas bearing.

62-068

Ling, M.T.S.

ON THE OPTIMIZATION OF THE STIFFNESS OF EXTERNALLY PRESSURIZED BEARINGS. Trans. ASME (J. Basic Engng.), vol. 84 D, no. 1, pp. 119-122. (March 1962).

This paper presents theoretical studies of the method of optimization of the stiffness of externally pressurized bearings. When an externally pressurized bearing is designed to operate at any given film thickness, it is found that the maximum bearing stiffness can be obtained by proper selection of the value of the ratio of recess to supply pressure, P_v/P_s . While various values of P_v/P_s can be attained by either varying the restrictor constant for a given film thickness or varying the film thickness for a given restrictor constant, the important quantity to vary in determining the optimum condition is the restrictor constant rather than the film thickness. For an incompressible fluid, the P_v/P_s value for which the bearing stiffness is optimized depends only on the type of compensation used, while for a compressible fluid it is slightly affected by exhaust pressure.

62-069

Loch, Erwin

[AEROSTATIC THRUST BEARINGS]. AEROSTATISCHE AXIALLAGER. (in German). Doctoral Dissertation, Technical University of Graz, Austria. (1962).

A generally applicable equation for small disc dimensions was derived for the radial equilibrium of the compressible clearance flow, including consideration of rotation. It was found that heat transfer of a flowing gas between two adjacent discs is very high and that the clearance flow undergoes, under certain conditions, an isothermal change of state. The calculations were extended to include bearings in which the flow occurs in two directions, outwards and inwards. For the laminar, isothermal radial flow the pressure distribution in the clearance and the amount of flow were derived by means of a

simple and an extended approximation. An analysis of the flow equations obtained showed the influence of kinetic energy, of rotation of a disc, of gas-dynamic effects and of labyrinths. The conditions at the transition from laminar to turbulent flow were analyzed, including the observations reported by previous authors. Based on the literature data on friction values for the turbulent clearance flow, the course of pressure and the amounts of flow were calculated for a simple case of turbulent, isothermal radial flow. The load-carrying capacity of any bearing whatsoever could be determined by introducing into equations, known previously, a non-dimensional factor which depends only on the radii and pressures. Solutions of the load capacity integral of laminar flow in the negative r-direction and of the integral for the turbulent, isothermal radial flow were found. Optimization and economy of the bearings were also discussed, including criteria which lead to the optimum bearing geometry relative to the location of gas inlet. The power losses found when different gases were used, were compared. An optimum nozzle pressure ratio was defined and calculated for bilateral and symmetrical thrust bearings. The individual throttle elements were described. The advantage of Venturi nozzles over cylindrical nozzles was shown. In another chapter, the non-radial isothermal clearance flow was investigated. Disregarding the influence of inertia, and the rotation of the discs, the flow distribution was represented as a potential function. General relations between the course of pressure, the load capacity and the amount of flow were studied. Non-dimensional bearing characteristics were derived and represented as functions of gas and pressure parameters for the laminar and turbulent clearance flow in the form of curves. Experiments on heating of bearings, bearing characteristics, change of pressure in the clearance, amount of flow and load capacity confirmed the data derived theoretically. The influence of the inlet nozzles and of other parameters on the stability of the bearings was studied. Methods for damping the oscillations were described. Finally, axial oscillations of bilateral bearings were investigated.

62-070

Loch, Erwin

DAMPING VIBRATIONS IN A GAS BEARING. U. S. Patent 3,049,383.
(to Escher Wyss Aktiengesellschaft). Applied June 8, 1960.
Issued August 14, 1962. Applied Switzerland June 26, 1959.

This invention concerns a device for damping vibrations in a gas bearing. For this purpose, at least one resonator consisting of a chamber closed toward the outside and a channel connecting the chamber to the gap between the parts moving relatively to each other is provided in the bearing member. The resonator channel contains a gas column capable of oscillating in the longitudinal direction of the channel.

62-071

Loch, Erwin

[GAS FEED ACROSS SURFACES OF POROUS MATERIAL IN EXTERNALLY-PRESSURIZED THRUST BEARINGS]. GASZUFUHR UBER FLACHEN AUS POROSEN MATERIAL IN AEROSTATISCHEN AXIALLAGERN. (in German). Schmieretechnik, vol. 9, no. 6, pp. 307-313. (1962).

Externally-pressurized thrust bearings of high load capacity and stability can be designed with throttling members of porous raw materials. Starting from the flow equation for porous materials and the basic equations of laminar, isothermal flow through narrow radial clearances, relations are derived by means of which the course of pressure, the load capacity and the amount of gas can be calculated in externally-pressurized thrust bearings in which the gas is fed through a ring of porous material. In the limit for zero permeability of the porous material, the relations thus established furnish the equations which describe the compressible flow through a clearance with solid walls. An example is given for the calculation of a bearing with a load capacity of 1430 kp which explains specifically the application of the boundary conditions.

62-072

Loch, Erwin

[INVESTIGATION OF AEROSTATIC AXIAL BEARINGS FOR TURBO-MACHINERY]. UNTERSUCHUNGEN UEBER AEROSTATISCHE AXIALLAGER FUER TURBOMASCHINEN. (in German). Atomkernenergie, vol. 7, no. 12, pp. 489-95. (December 1962).

The purpose, properties, and industrial application of gas lubricated bearings are discussed. For a pressurized thrust bearing with separate supply-nozzles leading directly into the bearing clearance, the character of the compressible flow was investigated. It is shown, that the laminar flow of gases in narrow slots can be described by potential theory. The pressure distribution, load capacity, and flow rate for a slot with parallel walls formed as a sector of an annulus having one source (supply nozzle) were calculated for different sector-angles and compared with test results.

62-073

Lund, J.W.

HYBRID GAS LUBRICATED JOURNAL BEARING. Mechanical Technology Inc. Report MTI-62TR2, March 15, 1962. Contract Nonr-3730(00).

The purpose of this report is to analyze the load carrying capacity of an external pressurized gas journal bearing including the hydrodynamic effect caused by the rotational speed of the journal. The analysis is an approximate first order perturbation solution, i.e., it assumes that the gas feeding takes place through orifices in the center-plane of the bearing and that the number of feeding holes is sufficiently large to be considered a line source.

62-074

McKenna, R.D., D.O. Bard and J.G. Gievers.

GAS LUBRICATED BEARINGS FOR ADVANCED SYSTEMS. ELECTRICAL
ACCESSORY EQUIPMENT. Technical Documentary Report ASD-TRE-62-170,
September 1962. AF contract AF 33(616)-7919. AD-295 481.

Design criteria, fabrication techniques and an analysis of experimental test data for 1-inch bore externally-pressurized gas-lubricated journal bearings are discussed. Bearings were investigated to satisfy the following conditions: speed range, 0 to 24,000 RPM; temperature range, -65° to 1500°F; and starting, bringing up to maximum speed, and the coasting or braking to a stop under concurrent radial and axial loads of 50 pounds and 25 pounds respectively. A reliable electrolytic erosion method was developed which eliminates previous machining problems. To eliminate the seal problem caused by the temperature range required, micro brazing was used to join the porous inserts to the bearing housing. All bearings were fabricated from stainless steel. Procedures for ambient load tests, high temperature tests, and ambient-pressure flow tests are outlined. Many tables and graphs are included.

62-075

McKenney, H.F.

AIR BEARINGS. U. S. Patent 3,070,406. (to Chrysler Corp.).
Applied February 11, 1960. Issued December 25, 1962.

This invention relates to air bearings which may be used in apparatus such as gyroscopes where a minimum of frictional bearing resistance is required and also where a substantially complete absence of frictional heat is required. The bearing is a type which does not use any source of compressed air or any compressed gas other than that air which is naturally in the space between the rotor or the housing, and may be provided with offset peripheral portions to provide wedge-shaped, air compression spaces between the members. These spaces cause the rotor to be suspended on an air cushion within its housing when a certain speed of rotation of the rotor is attained. The same result is attained when the housing is made the rotatable member. The compression pockets will become filled with whatever fluid surrounds the system utilizing these bearings, for example, water or oil, and the rotor will be supported on a cushion of that particular fluid in the same manner as though the fluid were a gas. A significant advantage over the prior art types of air bearings is that the present bearing requires no outside source of compressed air, but, instead compresses its own air for floating the rotor within the housing. Since the rotor actually does float within the housing there is no frictional engagement of the rotor therewith and the heat developed by the bearing is practically non-existent.

62-076

Macks, E.F.

GAS LUBRICATION OF BEARINGS AT VERY HIGH TEMPERATURES. The Air Force-Navy-Industry Propulsion Systems Lubricants Conference, Proceedings, San Antonio, Texas, November 15-17, 1960. Technical Documentary Report ASD-TDR-62-465, May 1962. AF contract AF 33(616)-7223. AD-278 843. pp. 211-225.

The prime objectives of this program include thrust as well as journal self-acting and externally pressurized bearings and means of evaluating the lubricant-bearing systems at temperatures from 80 to 1500°F or higher at low lubricant flow rates. Specific equipment details and program requirements are given in the paper. Flow orientation studies have been conducted at room temperature to speeds of 64,000 rpm (DN equivalent value 2.44 million). Gas bearings have been operated over the temperature range 80 to 1500°F with flow rates from 1.3 to 30 lb/hr over a range of speeds and loads. Theoretical analyses result in generalized flow data for Type I (orifice compensated) and Type II (modified step) bearings which serve as a guide for experimental studies. Analyses of experimental data lead to an explanation of lubricant flow deviations between theoretical and experimental results at room and high temperatures. Generalized curves compare flow and load capabilities of many gases and saturated vapors from 0 to 2400°F with nitrogen as a reference lubricant.

62-077

Meacher, J.S.

GAS LUBRICATION OF BEARINGS AT HIGH TEMPERATURES. Fairchild Stratos, Inc., Stratos Division Progress Report 1, for the period February 15 - May 15, 1962. AF contract AF 33(657)-8216.

The performance of gas-lubricated bearings at high temperatures was experimentally determined. Measurement of bearing operating clearances and eccentricity was attempted. A variable inductance device for measuring bearing clearances is described. Methods of calibration and application are defined. Modifications to the bearing test rigs and test facility to improve test conditions and facilitate clearance measurements have been made. Analysis of the effects of temperature and viscosity changes on the load capacity of gas lubricated bearings was performed.

62-078

Meacher, J.S.

GAS LUBRICATION OF BEARINGS AT HIGH TEMPERATURES. Fairchild Stratos, Inc., Stratos Division Progress Report 2, for the period May 16 - August 15, 1962. AF contract AF 33(657)-8216.

A preliminary test of a step journal bearing was performed using variable inductance clearance probes. Grit contaminants in the bearing and temperature variations at the measurement station required further development and modification of the test facility

and techniques. An externally pressurized orifice-type journal test bearing and three test shafts were fabricated. A test rig incorporating this bearing was assembled and installed in the test facility. Testing of this bearing rig was begun.

- 62-079 Modrey, Joseph
 THE PROBABILITY OF INTERMITTENT CONTACT OF EXTERNALLY PRESSURIZED
 GAS BEARINGS EXCITED BY STOCHASTICALLY DEFINED FORCING OF THE
 BEARING SUPPORTS. Union College, Mechanical Engineering Department,
 Research Report, August 1962. Navy contract Nonr(G)-
 00028-62. AD-282 809.

This report describes the analytics necessary to express the reliability of gas bearings in terms of the probability of damage due to the random vibration of bearing supports encountered in a service environment. The case of a flexible rotor supported on externally pressurized gas bearings is specifically referred to. Both the linear and nonlinear bearing stiffness examples are investigated.

- 62-080 Mori, Haruo, I. Shizuma, Toshiyuki Shibayama and T. Yamamoto.
 [RESEARCH ON EXTERNALLY PRESSURIZED JOURNAL GAS BEARING].
 (in Japanese). Trans. Japan Soc. Mech. Engrs., vol. 28,
 no. 196, pp. 1713-1719. (December 1962).

The theoretical research on externally pressurized journal gas-bearings has been reported by T. Sasaki and H. Mori. In their paper, the experimental data employed in comparison with the theoretical results were for the bearing with single gas supply hole without restriction. It is general to use externally pressurized gas-bearing with multiple gas supply holes arranged circumferentially and axially. In this paper, gas-bearing with multiple gas supply holes is designed theoretically and the pressure distribution, flow rate, and optimum restriction were examined and compared with the complex potential theory. The experimental results show good agreement with the theoretical results.

- 62-081 Neher, H.V.
 AIR-BEARING MAXWELL TOP. Amer. J. Phys., vol. 30, no. 7,
 pp. 503-506. (July 1962).

The Maxwell top described here is suitable for use in a student laboratory. With it, measurements may be made on angular acceleration and precessional motion. Over a wide range of angular speeds, friction is too small to affect the measurements. The precision attainable is limited primarily by the patience and skill of the experimenter.

- 62-082 North American Aviation.
LUBRICANTS AND BEARINGS AT ULTRA-HIGH TEMPERATURES. A PARTIALLY
ANNOTATED BIBLIOGRAPHY. January 17, 1962. AD-282 462.

A survey of the unclassified literature from 1959 through 1961 on friction, lubrication, and bearings at temperatures above 1200°F. is presented.

- 62-093 Oak Ridge National Laboratory.
ROTATING MACHINERY FOR GAS-COOLED REACTOR APPLICATION, PROCEED-
INGS, Oak Ridge National Laboratory, Tennessee, April 2-4, 1962.
Report TID-7631. June 1962. 409 pp.

A total of 30 papers are included in this cumulation. Separate ab-
stracts were prepared for 29 papers. No abstract was prepared for
a single presentation concerned with the performance characteristics
of a centrifugal compressor for He at 1000°F and 250 psig. Only
nine papers are concerned with gas-lubricated bearings.

- 62 084 Pan, C.H.T.
ON TIME DEPENDENT EFFECTS OF SELF-ACTING GAS DYNAMIC JOURNAL
BEARINGS. ASME Paper 62-LUB-10. 12 papers. (Abstract
in Mech. Engng., vol. 84, no. 11, p. 95.
(November 1962)).

A mathematical procedure is given for uncoupling the time-dependent isothermal Reynolds equation, related to the motion of the journal, from the dynamical equation, which depends on the initial condition of the fluid film. Two basic assumptions are employed: time-dependent effects are small and consequently the equation is linearized; and time dependence is recognized to include a true transient and implicit time dependence. The true transient is neglected. This assumption is referred to as the implicit hypothesis. Beginning with the steady-state solution, the governing equations for various time-dependent orders are developed in succession. The recurrence relation for these equations is established. For the case of a nearly concentric journal undergoing a small translational motion, closed-form solutions are obtained for "implicit" time-dependent effects up to the second order. This analysis permits the computation of "implicit" time-dependent fluid-film forces, which can be used for the stability analysis of all steady-state rotor motions, without solving for rotor dynamics at the same time.

- 62-085 Pan, C.H.T. and Beno Sternlicht.
COMPARISON BETWEEN THEORIES AND EXPERIMENTS FOR THE THRESHOLD
OF INSTABILITY OF RIGID JOURNAL BEARINGS. Mechanical Technology
Inc. Report MTI-62IR13, August 3, 1962. Navy contract Nonr-
3730(00).

The threshold of half frequency whirl for a rigid rotor in self-acting, plain cylindrical journal bearings is analyzed by several methods and the results are compared. The correlation between the various approaches appears to be good. The simplest method of analysis is therefore used for comparison with experimental data. Experimental results showing the effect of bearing length and bearing load are compared with theory. The influence of bearing length on the threshold speed agrees with the trend of the calculated results. However, the experimental threshold speeds are always a little higher. In comparing the effect of bearing load it is seen that the calculated threshold speed is consistently somewhat over-pessimistic but the influence of rotor inclination is in very good agreement with experiment. The methods presented in this paper can be readily used in design to insure stable operation with plain cylindrical journal bearings.

- 62-086 Pan, C.H.T. and Beno Sternlicht.
ON THE TRANSLATORY WHIRL MOTION OF A VERTICAL ROTOR IN PLAIN
CYLINDRICAL GAS-DYNAMIC JOURNAL BEARINGS. Trans. ASME (J. Basic Engng.), vol. 84 D, no. 1, pp. 152-158. (1962).

For the theoretical prediction of the dynamical characteristics of a rotor system it is necessary to have an accurate knowledge of the bearing fluid film forces under dynamical conditions. With a small clearance ratio and at a moderate speed, the motion of the lubricant is governed by the generalized Reynolds equation. If the lubricant is a gaseous medium, the Reynolds equation is complicated by the compressibility effects, which include nonlinearity and time-dependence under dynamic conditions. In the case of a vertical rotor operating in plain cylindrical journal bearings, the steady whirl approximation is appropriate and time-dependence in the Reynolds equation can be removed by a co-ordinate transformation. The form of the transformed equation is identical to the static Reynolds equation except that the compressibility number is modified by a factor which depends on the angular speed of the whirl motion. The attitude angle, in the presence of the whirling motion, is quite different from the static attitude angle. On the other hand, the magnitudes of the forces are not very different. The steady whirl analysis may be used to determine the synchronous whirl motion of an unbalanced rotor. The phase angle between the fluid film force and the maximum film thickness plane is the complement of the attitude angle according to the quasi-static whirl analysis. Also, the modified compressibility number is reduced to zero at half-frequency

whirl, and the Reynolds equation, for an isothermal gaseous film with the small eccentricity ratio approximation, becomes identical to that of the liquid film. Since it has been established that the threshold of half-frequency whirl for vertical rotors operating in plain cylindrical journal bearings is at zero speed, the same conclusion applies to the corresponding gas-dynamic bearing.

62-087

Patterson, A.G.

GAS LUBRICATION APPLIED TO GYROS. Instrument Practice, vol. 15, no. 4, pp. 426-32. (April, 1962).

The basic principles of gas lubrication are given. There is a table showing the relative merits of hydrodynamic gas lubricated bearings in comparison with ball and oil lubricated types. Advantages and disadvantages are listed. It is significant that the information obtained separately about the behavior and characteristics of journal and thrust bearings does not give an accurate indication of their performance together. This is one of the difficulties encountered in predicting performance of these bearings, which requires a considerable amount of research work before it can be solved. Performance prediction is made more difficult by the probability that the net performance of a complete set of bearings is the resultant of several physical effects which may be assisting or opposing each other. It has been found that geometry is a critical factor in the operation of a gas lubricated bearing and that very small departures from tolerances, which might well pass normal inspection can make the difference between complete success and complete failure. Dynamic balance also has been found to be a critical factor, as unbalance can cause internal vibrations which can make a bearing inoperative. Balancing is carried out on a Strobodine balancer capable of detecting residual unbalance of 0.001 g/cm.

62-088

Pearson, H.

THE POLYTROPIC EXPANSION OF AIR THROUGH A CONVERGENT NOZZLE AT INFINITE PRESSURE RATIO - AN INTERESTING ANOMALY. Aeronaut. Quart., vol. 12, no. 4, pp. 301-307. (November 1962).

Previous papers have examined the implications of an assumed polytropic expansion law on the performance of nozzles. In this paper a peculiar anomaly is examined when the convergent nozzle is exhausting into a vacuum. It is shown that, on the strict assumptions of a polytropic expansion law, and the assumption that the flow will maximize for a given throat area, the thrust per pound of air increases progressively with falling polytropic efficiency, becoming infinite when the polytropic efficiency is zero. The author suggests that this anomaly is either concerned with the assumption that the flow will maximize or means that polytropic expansion efficiencies below a certain limit are theoretically impossible, but he believes that there may be some other explanation.

- 62-089 Peyton, Robert
GAS LUBRICATED SLIDER BEARINGS. Ampex Corp. Report TR-62-8;
UC-270, November 1962.

The object of this study has been to determine a method of maintaining a precise space between two surfaces. One of the most promising ways is by supporting one surface on a self-lubricating slider bearing. The report gives a qualitative description of the hydrodynamic lubrication process and quantitative information on several types of sliders. It is apparent, although not proven here, that a pivot-loaded, curved-step slider bearing is the most desirable type for this purpose. The range of available surface speeds under atmospheric conditions is from 500 to 5000 ips, or to the burst strength of the rotating material. Loads of about one atmosphere may thus be supported with a film thickness of 60 to 100 μ in. These spacings may be held easily within 1 percent. This, of course, depends on keeping the slider mass small. The lubricating film acts as a spring, with a rate on the order of 10^5 lb. per square inch of slider surface.

- 62-090 Poritsky, H.
A NOTE ON THE WORK DONE ON THE JOURNAL BY THE FORCES EXERTED BY A COMPRESSIBLE LUBRICANT IN A JOURNAL BEARING. Trans. ASME, (J. Basic Engng.), vol. 84 D, no. 4, pp. 486-90. (December 1962).

In the study of dynamical stability of a rotor supported in journal bearings with a compressible lubricant, while the complete calculation of forces on the journal is quite difficult, certain relations regarding these forces can be obtained in a relatively simple manner. In particular, an interesting relation is established connecting the rate at which the bearing reaction forces do work on the rotor, and the rate at which the lubricant is escaping from the bearing. As a special case, for "an infinitely long" bearing in which the "end effects" are neglected and the motion of the fluid is assumed normal to the axis, one proves from this relation that the work done by the lubricant forces on the journal always vanishes. Under these conditions it can be shown that the equilibrium position of the journal center, for the steady load on the journal under consideration, is always stable, no matter what is the speed of rotation. This points to the conclusion that the infinitely long bearing theory forms a poor approximation for consideration of instability of a rotor bearing system.

- 62-091 Powell, J.W.
HYDRODYNAMIC EFFECTS IN HYDROSTATIC GAS BEARINGS. Engineer, vol. 214, no. 5557, pp. 148-50. (July 27, 1962).

The author describes the results of various tests on an externally pressurized gas journal bearing having a diameter of two inches and

length of four inches. Speeds up to 7500 rpm were used and the applied load was varied between 0 and 130 lb. while the supply pressure was varied from 0 to 50 lb/sq in. Several shafts were used giving a clearance range from 0.56×10^{-3} to 1.53×10^{-3} inches. The results are expressed in terms of a load coefficient C_L and a compressibility number Λ where $C_L = \text{load}/(\text{projected bearing area} \times \text{gauge supply pressure})$ and $\Lambda = 6\mu a U / P c^2$, where μ is the viscosity, a is the bearing radius, U is the surface speed, P is the supply pressure and c is the mean radial clearance. It was found that C_L was proportioned to Λ for any given value of eccentricity and that the load carrying capacity of this type of bearing when rotating may be much as three times as large as its value when it is stationary.

- 62-092 Powell, J.W. and N. Tully.
WHIRL INSTABILITY OF EXTERNALLY PRESSURIZED GAS JOURNAL BEARINGS.
Engineer, vol. 213, no. 5553, pp. 1121-2. (June 29, 1962).

The upper limit of speed at which any shaft system may be operated in gas journal bearings is invariably set by some form of unstable whirl. In the experiments described, the whirl frequency always corresponded to the lowest natural frequency of the rotor mass and the bearing spring stiffness, and the onset of whirl occurred at shaft speeds which were integral multiples of the natural frequency. The whirl is therefore termed "fractional speed whirl" and observations were made of whirl at between one-third and one-seventh shaft speed.

- 62-093 Rentzepis, G.M. and Beno Sternlicht.
ON THE STABILITY OF ROTORS IN CYLINDRICAL JOURNAL BEARINGS.
Trans. ASME (J. Basic Engng.), vol. 84 D, pp. 521-532.
(December 1962).

The regions of stability for plain cylindrical journal bearings have been determined analytically in this paper. The linear "variational" equation of motion has been employed to obtain the stability regions bounded by families of load-carrying capacity and operating eccentricity curves. The results were applied to the "quasi-static" equilibrium case for gas lubricated cylindrical journal bearings of $L/D = 2$. They show that there exists a "minimum" in the stability curves, a prediction supported by experimental evidence. The results of this work seem to bridge together observation on stability at very small clearances and large ones.

- 62-094 Reynolds, D.B. and W.A. Gross.
EXPERIMENTAL INVESTIGATION OF WHIRL IN SELF-ACTING AIR LUBRICATED
JOURNAL BEARINGS. ASLE Trans., vol. 5, no. 2, pp. 392-403,
(November 1962).

Bearing characteristics influencing the threshold speed at which large-amplitude self-excited whirl occurs in complete, air lubricated journal bearings were experimentally investigated. Various combinations of rotors having clearance ratios, $\psi = c/r$ ranging from 0.268×10^{-3} to 2.350×10^{-3} and symmetrical bearing assemblies having slenderness ratios, $L' = L/D$, ranging from $1/4$ to 1 were tested. By varying slenderness and clearance ratios and unit load, by opening or closing supply orifices, or by adding imbalance, the whirl threshold speed could be varied between zero and the limit set by the available power. Experimental methods of identifying the cylindrical and conical modes of synchronous and self-excited whirl are described. The whirl hysteresis region and the nature of whirl at speeds above the threshold are examined. Three methods of avoiding large-amplitude self-excited whirl are discussed.

- 62-095 Rylander, H.G. and K.Y. Li.
PERFORMANCE OF SOLID-FILM LUBRICANTS RELATIVE TO GAS-SOLID AND
GAS-LIQUID LUBRICANTS. ASME Paper 62-LUBS-13. 7 pages.
(Abstract in Mech. Engng., vol. 84, no. 9, p. 83.
(September 1962).

An investigation of bearings using circulating multiphase lubricants over a range of operating conditions is reported upon, and the advantages of such a system relative to bearings using liquid or solid lubricants are set forth. The authors report that the ability to obtain good performance on gas-solid lubricants was demonstrated with coefficients of friction less than 0.05 and no measurable wear. Satisfactory operation was also obtained with gas-oil lubricants over a range of operating conditions. Lubricants tested included combinations of oil, air, nitrogen, carbon dioxide, molybdenum disulfide, graphite, and Teflon.

- 62-096 Rylander, H.G. and C.T. Mocerman.
ANALYTICAL STUDY AND NUMERICAL SOLUTIONS FOR JOURNAL-BEARING
HYDRODYNAMIC LUBRICATION USING GAS, OIL, AND MULTIPHASE LUBRI-
CANTS. ASME Paper 62-LUBS-12. 11 pages.
(Abstract in Mech. Engng., vol. 84, no. 10, p. 72.
(October 1962).

The pressure and temperature distributions using gas, oil, and multi-phase lubricants in a journal bearing and numerical computer solutions used to solve the Reynolds equation and general energy equation for pressure and temperature distributions, respectively, are described. The solutions given are said to include the effects of

temperature and pressure on viscosity and the effects of compressibility and flow work on the temperature. Relative performance of a 180° combination hydrodynamic-hydrostatic bearing is discussed by comparing the eccentricity and coefficient of friction at different Sommerfeld numbers for various lubricants.

62-097

Salbu, Erik

PRELIMINARY REPORT ON SQUEEZE BEARINGS. International Business Machines Corp. IBM Research Note, October 10, 1962. Navy contract Nonr 3448(00).

The claim is made that the validity of the isothermal assumption in gas bearings has been proven, and that the existing solutions of the "squeeze part" of the Reynolds equation have been verified. When the squeeze action is present, through relative normal motion between bearing surfaces in a gas bearing, the second order effect at high squeeze numbers will result in a net positive film force, hence, the squeeze bearing. The squeeze bearing in itself is a very efficient bearing with high load-carrying capacity at high operating clearances. This reduces machining requirements and costs measurably. Both thrust and journal squeeze bearings are possible and appear to have numerous practical applications. Piezo electric materials seem to be an efficient and inexpensive way of solving the problem of driving sources although a power supply is required to get the squeeze bearing effect. The power consumption is low, and, due to high operating clearances, the viscous friction losses will be reduced. It is, therefore, conceivable that a squeeze bearing would be even more efficient than a hydrodynamic bearing.

62-098

Scott, R.D.

ON THE HYDRODYNAMICALLY SUPPORTED MAGNETIC RECORDING HEAD.
ASME - ASLE Paper 62-LUB-11. 8 pages. (Abstract in
Mech. Engng., vol. 82, no. 10, p. 72. (October 1962).)

A particular design approach is described for a magnetic recording head which is hydrodynamically supported (air-lubricated) on a rigid recording medium, such as disk or drum. The capabilities of the head and medium together are 2-4 megacycles and an amplitude modulation of less than + 1/2 db. The low-amplitude modulation reflects the ability of the gas bearing to maintain extremely constant separation of surfaces. Certain problems of implementing gas-bearing techniques and their solutions are discussed. Relatively large angles of inclination of a plane slider bearing are used as the design foundation.

62-099

Shaw, R.L.

AIR BEARING. U. S. Patent 3,053,583. (to The Monarch Machine Tool Co.). Applied March 10, 1960. Issued September 11, 1962.

This invention describes the use of gaseous fluid bearings, preferably air bearings, for replacing the metal-to-metal bearings lubricated with a thin film of highly viscous oil. The use of a low viscosity fluid such as air substantially reduces the frictional drag yet provides equally accurate guidance. The specific air pads of this invention are designed to allow minimum air volume to eliminate the oscillations encountered due to the compressibility of air in any volume of consequence. The invention provides low volume air pads for guiding and supporting a reciprocable member to prevent oscillations thereof, and adequate guidance along linear V's and flats. It also provides adjustment means for the air pads so that they are properly spaced relative to the reciprocating member.

62-100

Shawbrook, Henry and D.G.A. Thomas.

IMPROVEMENTS IN DYNAMIC GAS BEARINGS. British Patent 895,328. (to Dowty Fuel Systems Ltd.). Applied July 17, '958. Issued May 2, 1962.

This invention relates to dynamic gas bearings of the kind in which a cylindrical shaft fits with small clearance in a cylindrical sleeve and which during rotation employs gas in the clearance to form a substantially friction-free and wear-free bearing. The object of the present invention is to provide a simple axial thrust bearing for use with a dynamic gas bearing of the kind referred to. What is claimed is a dynamic gas bearing of the kind referred to comprising an extension from one end of the sleeve enclosing either the end of the shaft or a shoulder on the shaft to form a working space, a vent in the sleeve adapted to carry gas from the working space to a low pressure zone, this vent being adapted to be partially closed by the end or the shoulder of the shaft when the shaft is in its desired axial position, a supply port entering the working space at a position not obstructed by the shaft, and a restricted supply passage adapted to supply gas under pressure to the supply port, so that in operation gas pressure is varied in the working space in dependence on the escape flow of gas permitted by the shaft through the vent to obtain automatic balance of axial thrust on the shaft by gas pressure in the working space.

62-101

Sheinberg, S.A.

A GAS LUBRICATED BEARING. Translation MCL-1227; AD-265 693. October 13, 1961. 5 pages. (Translation from Byulleten' Izobretenii (USSR), no. 16 (1960). USSR patent application announcement no. 649006/25, December 30, 1959. Abstract in Technical Translations, vol. 7, no. 11, p. 913. (June 15, 1962).)

The gas lubricated bearing, a one piece cylindrical sleeve, fitted with an aperture on one side for gas supply under pressure, is distinguished by the fact that, in order to increase the dynamic sta-

bility of the shaft in rotation and the ease of starting, a longitudinal groove is made in the sleeve, which supplies gas through the above mentioned aperture, and in the wall of the sleeve, opposite the longitudinal groove, supplementary curved grooves with capillary apertures for the gas supply are made. The finished form of the bearing is distinguished by the fact that in order to simplify manufacture of the apertures, two annular capillary borings, having an operating cross section smaller than the operating cross section of the supply apertures, are made at the ends of the bearing.

- 62-102 Slater, J.M.
EXOTIC GYROS - WHAT THEY OFFER, WHERE THEY STAND. Control Engng., vol. 9, no. 11, pp. 92-97. (November 1962).

A discussion of the status, advantages, and problems of free-rotor gyros, specifically covers the following: (1) autolubricated (self-acting) gas bearings, (2) electrostatic support with the aid of a servosystem, and (3) magnetic support of a superconductive body under cryogenic conditions.

- 62-103 Speen, G.B.
PRESSURE AND FLOW STUDIES OF AN EXPERIMENTAL EXTERNALLY PRESSURIZED GAS LUBRICATED BEARING. ASLE Trans., vol. 5, no. 1, pp. 242-53. (April 1962).

This paper describes the results of pressure distribution measurements made with the combined thrust and journal bearing. The common radius of the thrust and journal bearings was approximately 2.25 inches and a supply pressure of 130 lb/sq. in. was used for loads between 10 and 75 lbs. It was found that greater thrust stiffnesses could be obtained with the integral design which also has a wider range of stable operation.

- 62-104 Speen, G.B. and J.M. Grant.
OMNI-DIRECTIONAL SUPPORT OF SPHERES USING EXTERNALLY PRESSURIZED GAS LUBRICATED BEARING PADS. ASLE Trans., vol. 5, no. 2, pp. 375-84. (November 1962),

The advantages of using a multiplicity of externally pressurized gas lubricated thrust bearing pads to completely support a sphere are discussed. The minimum number (six) of pads that can provide all-axis, isoclastic support must be arranged in three opposed pairs to form a mutually orthogonal system. Analytical expressions for the load capacity of such a system are given. It is proven that only this type of support system (six pads or multiples thereof) can provide isoelastic support. An experimental apparatus, used to determine the operational properties of a six-pad spherical support system, is described. Experimental curves of sphere deflection vs. source pressure for various loads are given and compared with theory.

62-105 Stanley, I.W.

AERODYNAMIC FILMS BETWEEN CARBON BRUSHES AND SLIP-RINGS.

Wear, vol. 5, no. 5, pp. 363-377. (September/October 1962).

Experiments have been made to determine the conditions under which air films are formed between electrographite brushes and slip-rings. It is shown that aerodynamic pressures both above and below atmospheric can exist when the brush is inclined to the slip-ring at angles between 1×10^{-3} and 5×10^{-2} rad. The pressure has a maximum value at 7×10^{-3} rad, which remains unchanged at loads and speeds up to 1 kg and 3,000 cm.sec⁻¹ respectively. The aerodynamic pressure may become large enough to support the load completely at loads below 100 g; the brush then behaves approximately as predicted by simple hydrodynamic theory. Heavy loads are only partly supported by the air films and the pressures only agree with theory at angles larger than about 9×10^{-3} . At smaller angles the pressures are very much lower than those predicted and it is shown that the discrepancy can be qualitatively explained when the influence of compressibility of the air is taken into account. Various methods for reducing the pressure beneath brushes are described. A porous brush grade reduces the air pressure by 58%; holes and various combinations of slots in the brush result in a maximum decrease of 91%.

62-106 Stark, K.W.

THE DESIGN OF VARIOUS TYPES OF AIR BEARINGS FOR SIMULATING FRICTIONLESS ENVIRONMENTS. National Advisory Council for Aeronautics. Report T.N.D.-1100, May 1962.

Although there is some justification for quoting coefficients of friction for hydrodynamic bearings since both load and friction are functions of speed, the practice is confusing in the case of hydrostatic bearings, since the friction tends to zero as the speed decreases. An example of this is given in this report in which a coefficient of friction of 4.06×10^{-6} is quoted. After discussing and analyzing the characteristics of various types of externally pressurized gas bearings, the author describes two designs which were built and tested but unfortunately no comparison with predicted and experimental results is made. Only low supply pressures (i.e. 4 to 8 lb/sq in) were used and no attempt to allow for compressibility effects was made.

62-107 Steele, H.J.

GAS LUBRICATED BEARINGS. U. S. Patent 3,058,785. (to Joseph Lucas Industries, Ltd.). Applied September 14, 1960. Issued October 16, 1962. Applied Great Britain September 21, 1959.

This invention relates to air or other gas lubricated bearings for use with shafts which are intended to rotate at very high speeds, for example, 200,000 revolutions per minute. The bearing has a

hollow shaft with a wall thickness which is so chosen in relation to the diameter of the shaft and the material from which it is made, that when the shaft is static there is sufficient clearance to allow the shaft to start rotating freely, and the clearance is reduced with increasing angular velocity owing to the radial expansion of the shaft due to centrifugal forces so that half-speed whirl will not develop at angular velocities for which the bearing is designed.

62-108 Stella, R.

PERFORMANCE OF A GAS-BEARING COMPRESSOR IN THE GENERAL ATOMIC HTGR IN-PILE LOOP. Rotating Machinery for Gas-Cooled Reactor Application, Proceedings, Oak Ridge National Laboratory, Tennessee, April 2-4, 1962. Report TID-7631. June 1962. pp. 270-9.

Operation of parallel-connected compressors for the HTGR in-pile loop is described. During normal operation, only one compressor is running; the second is an on-line spare. The compressors operate at temperatures up to 640°F. A total of three compressors were purchased and loop tested. A gas bearing in each compressor failed. The operating history of each machine is discussed and presented tabularly.

62-109 Sternlicht, Beno

GAS BEARING STATE OF THE ART. Rotating Machinery for Gas-Cooled Reactor Application, Proceedings, Oak Ridge National Laboratory, Tennessee, April 2-4, 1962. Report TID-7631. June 1962. pp. 344-60.

The state-of-the-art appraisal includes detailed examinations of gas-lubricated bearing advantages and problem areas, terminology definitions, and bearing classification by mechanisms which generate load-carrying capacity. Also included are design information on steady state and dynamic performance, and a review of current knowledge concerning steady state operations, dynamic operations, and materials.

62-110 Sternlicht, Beno

ON STABILITY OF ROTORS SUPPORTED BY GAS BEARINGS. Rotating Machinery for Gas-Cooled Reactor Application, Proceedings, Oak Ridge National Laboratory, Tennessee, April 2-4, 1962. Report TID-7631. June 1962. pp. 361-97.

Experimental results are presented for plain cylindrical and axial groove gas journal bearings and they are compared with the available theory. These results represent several years of experimental work. The measured initial disturbance and onset of half frequency whirl (hfw) are reported for a variety of conditions. The effect of load, mass, L/D, and clearance on the threshold of instability for plain

cylindrical journal bearings are shown and compared with theory. The threshold of instability as a function of groove location, number of grooves and orifices, etc. is also discussed. It is reasonably well known that grooves reduce the hydrodynamic load-carrying capacity. Theoretical analyses are included which give load carrying capacity as a function of groove location.

- 62-111 Stevenson, C.H. and Lazar Licht.
EXPERIMENTAL DETERMINATION OF STABILITY BOUNDARIES FOR AN
EXTERNALLY-PRESSURIZED, GAS-LUBRICATED THRUST BEARING. Franklin
Institute Laboratories for Research and Development. Report
I-A2049-1; TID-15340, February 1962. Contracts Nonr-2342(00)
and AT(30-1)-25E5. AD-272 899.

Tests were made to determine the stability boundaries of a 5-inch diameter thrust bearing having a recess diameter of one inch. Loads up to 600 lbs. were applied and the maximum value of the supply pressure was 100 lb./sq. in. Various recess depths from 0.0075 inch to 0.1 inch were used and the total throat area of the nozzles supplying compressed air to the recess was varied from 0.876×10^{-3} to 0.732×10^{-2} sq. in. It was found that a small recess volume, a large throat area and a small supported load, generally tended to increase the stable region and that there was always a limiting supply pressure below which the bearing was stable for all the loads which it could support. In addition, it was found that the pressure fluctuations accompanying the instabilities were transmitted upstream beyond the nozzles supplying the recess when large throat areas were used and there were indications that inertia fluid forces became significant when the oscillations had a large amplitude.

- 62-112 Tang, I.C. and W.A. Gross.
ANALYSIS AND DESIGN OF EXTERNALLY PRESSURIZED GAS BEARINGS.
ASLE Trans., vol. 5, no. 1. pp. 261-84. (April 1962).

Equations for flow rate, pressure, load, and stiffness of externally pressurized thrust and journal bearings are given for purely viscous, isothermal gas films with longitudinal or radial flow and no relative surface motion. Charts are presented by means of which the bearing characteristics can be evaluated in terms of the bearing parameter, the bearing configuration, and the ratio of supply to ambient pressure. Sample characteristics of thrust and journal bearings are established using the curves and experimental confirmation shown. A method of treating bearing films with two inlet-restricting orifices in series is described.

- 62-113 Thomas, G.C.
NEWEST ON THE HANDLING HORIZON: UNIT LOADS THAT WALK ON AIR.
Modern Mater. Handl., vol. 17, no. 9, pp. 72-75. (September 1962).

Now in the testing phase, the air-film method of handling is proving that man can out-perform a lift truck in short-haul handling. Prototype tests indicate handsome savings in dock and carrier operations.

- 62-114 Thomason, H.E.
SERVO LOOP DESIGN FOR AIR BEARING INERTIAL COMPONENTS.
NASA TN D-1120, May 1962.

This report is a comprehensive discussion of the problems, both analytical and practical, encountered in designing the electronics for air bearing inertial components. The analytical problems are treated both by classical and transform methods. Extensive use is made of Laplace transformations, Nyquist and Bode analysis. Results from these several methods are presented in the form of graphs and plots where appropriate in the text. A functional discussion of the various electronic subassemblies points out where the major mechanization problems occur. These problems are treated in sequence as they arise in the servo loop starting at the transducers and ending at the torquers. In each instance the design considerations, including the major problem areas and their practical solutions, are presented.

- 62-115 Tipei, Nicolae
THEORY OF LUBRICATION, edited by W.A. Gross. Stanford University Press, Stanford, Calif., 1962. (Translation of 1957 Roumanian edition).

Subjects covered include full range of hydrodynamic lubrication theory - dry friction, lubricants, and sliding bearings. Rolling element bearings are not covered. Sliding bearings are covered very completely, most of the material representing original work by the author. Bearings with constant forces and velocities are treated as two-dimensional problems (infinitely long bearings) and as three-dimensional problems (finite length bearings). Solutions for variable lubricant viscosity are considered in detail. Also treated are partial fitted journal bearings, squeeze films, film stability under cyclic and centrifugal loading, gas lubrications, and turbulence. The author's approach to every topic is highly analytical, and the format of book is such as to make it difficult to select pertinent results for application. Liberal use is made of vector and tensor analysis. Many ideas and approaches should be found helpful and useful by mathematically inclined researchers. Some approximate solutions using power series may be found useful for computer solutions to bearing problems.

- 62-116 Tunstall, John
AIR BEARINGS, PRECISION MACHINING FACE BRITISH DESIGN CONFERENCE.
Prod. Engng., vol. 33, no. 2, pp. 88-90. (January 22, 1962).

Engineers at the National Engineering Lab in Scotland recently completed a prototype medium size vertical milling machine with compound slideways mounted on automatically compensating hydrostatic air bearings (pitch and azimuth). Effect of the compensation is to give the table equivalent stiffness approaching 6 million lb/in. Development of hydrodynamic gas bearings is still slowed by lack of instability data. It is said that recent tests have established the validity of theories describing steadily loaded bearings at high compressibility numbers (around 6 to 12). Unstable loading conditions can now be investigated using the new-found stability data as feedback. Several applications of the hydrodynamic bearings are under study, including a 400-spindle textile machine, gyroscopes for missiles, and gas circulators for nuclear power.

- 62-117 Turnblade, R.C.
THE DESIGN OF EXTERNALLY PRESSURIZED GAS LUBRICATED BEARINGS
BY THE METHOD OF BEARING EQUIVALENCE. ASLE Trans., vol. 5,
no. 2, pp. 385-91. (November 1962).

By considering the general form of the streamlines between the bearing surfaces of any externally pressurized bearing, it is possible to derive the geometry of a rectangular bearing which has the same load support, clearance, area, source pressure entrance losses and mass flow as the bearing under study. After deriving the necessary conditions for similarity, the author studies a combined thrust and journal bearing for a shaft. The equivalent rectangular bearing for the thrust bearing is derived and its predicted steady state characteristics are compared with measured ones obtained from the actual bearing. Good agreement was obtained and in view of the fact that the method provides approximate results for configurations for which it would normally be difficult to predict the performance, the technique should be of some value to design engineers.

- 62-118 Unterberg, W., J.S. Ausman and G.K. Fischer.
INVESTIGATION OF CONDENSING VAPOR LUBRICATED SELF-ACTING JOURNAL BEARINGS. Rocketdyne Corp. Annual report for the period October 1, 1961 - September 30, 1962, November 30, 1962. Contract Nonr-3617(00).

The operating characteristics of condensing-vapor, self-acting journal bearings were investigated analytically and a steam bearing experiment was initiated. Thermohydrodynamic considerations suggest the isothermal equilibrium behavior of the lubricant. 'Linearized ph' analyses are carried out for an infinite and a finite heat transfer model. For the infinite length, isothermal, full plain journal

bearing with constant lubricant mass, the condensing vapor operation results in a bearing pressure limit at the saturation vapor pressure value. The load capacity of the condensing vapor bearing is correspondingly reduced below that of the non-condensing bearing. The experimental steam bearing rig and steam generation system and their operation are described.

62-119

Whitley, Stanley

JOURNAL BEARINGS. U. S. Patent 3,039,830. (to United Kingdom Atomic Energy Authority). Applied October 16, 1958. Issued June 19, 1962. Applied Great Britain October 18, 1957.

This invention describes a hydrostatic gas journal bearing having a load carrying capacity in excess of that provided by an externally-pressurized orifice compensated journal bearing of equivalent size and using equivalent power in supplying gas to sustain the bearing. It is characterized in having at least three portions in sequence along the bearing from one end of the bearing, the first being an externally-pressurized orifice compensated journal bearing portion, the second being a circumferential groove with means for controlling the pressure in the groove and the third being a journal bearing portion having means for applying pressure which is circumferentially asymmetric. It may also have fourth and fifth portions added in sequence, comprising respectively another circumferential groove with means for controlling the pressure in the groove and another externally pressurized orifice compensated journal bearing portion.

62-120

Whitley, Stanley and D.S. Allen.

IMPROVEMENTS IN OR RELATING TO GAS LUBRICATED JOURNAL AND JOURNAL BEARING ASSEMBLIES IN PUMPS. British Patent 891,039. (to United Kingdom Atomic Energy Authority). Applied May 2, 1960. Issued March 7, 1962.

This invention relates to gas lubricated journal and journal bearing assemblies in pumps. A gas lubricated journal and journal bearings assembly is proposed where the journal bearings have defined between them at each end of the assembly three or more part-circumferential viscosity grooves, the grooves each having at corresponding ends a hole providing communication between the grooves and the atmosphere ambient to the assembly. What is claimed is a pump comprising a casing having an inlet and an outlet, a gas lubricated journal and journal bearing assembly housed in the casing, the journal and journal bearing having defined between them, at the central region of the assembly, rings of part-circumferential viscosity grooves, the grooves each communicating at one end with the inlet and at the other with the outlet, and means within the casing for rotating the journal.

- 62-121 Whitley, Stanley and L.G. Williams.
IMPROVEMENTS IN OR RELATING TO THRUST BEARINGS. British Patent 887,695. (to United Kingdom Atomic Energy Authority). Issued January 24, 1962.

A gas lubricated thrust bearing is designed which is of simplified construction. The bearing comprises two optically flat plates having on one plate a series of three or more radial feed grooves and a series of arc-shaped concentric viscosity grooves which terminate before the next feed groove is reached.

- 62-122 Whitley, Stanley, A.J. Bowhill and P. McEwan.
HALF-SPEED WHIRL AND LOAD CAPACITY OF HYDRODYNAMIC GAS JOURNAL BEARINGS. Proc. Instn. Mech. Engrs., vol. 176, no. 22, pp. 554-601. (1962).

A phenomenological theory of the half-speed whirl of gas bearings is developed; it predicts the existence of four modes of whirl which depend variously on the mass and transverse inertia of the bearing and on the mass and transverse inertia of the shaft. All four modes of whirl have been distinguished experimentally and related to each other theoretically. From these measurements, it is shown that the half-speed whirl properties of a plain bearing can be considerably improved by cutting an axial slot in the bearing. Further improvement, if required, can be effected by introducing an ovality into the bearing or cutting of circumferential grooves in it. The introduction of these anti-whirl devices, however, reduces the load capacity, although measurements have shown the effect is not serious except for the circumferentially grooved bearing.

- 62-123 Whitley, Stanley and L.G. Williams.
PRINCIPLES OF GAS-LUBRICATED SHAFT SEALS. J. Mech. Engng. Sci., vol. 4, no. 2, p. 177. (June 1962).

Four types of gas lubricated seals for rotating shafts are described, each based on a corresponding type of gas bearing. These seals are the hydrodynamic disc seal (based on the spiral-groove thrust plate), the hydrostatic disc seal (based on a hydrostatic full-face thrust plate), the hydrodynamic sleeve seal (based on a hydrodynamic full journal bearing), and the hydrostatic sleeve seal (based on a hydrostatic journal bearing). Each seal consists of two parts, a gas bearing region and a gland region. The gas bearing region must provide a gas film of the correct thickness between the seal surface, and this film must be sufficiently stiff to prevent excessive vibration. The gland region, which is the seal proper, must restrict the flow of gas into and out of the sealed system to a minimum acceptable standard. The theory of the gas bearing region of the seals is based on standard gas bearing principles and these have been summarized into a form suitable for seal application. The theory of the gland

region is that of gas flow between parallel surfaces and this is described only in the viscous flow regime. To clarify the principles of the seals, examples are given of the design of each type of seal for use on a 2-in. diameter shaft operating at 9000 rev/min with zero pressure in the sealed system.

- 62-124 Wiemer, A., R. Lehmann and R. Rogal.
[THEORY AND USE OF AIR BEARINGS: PARTS 1 AND 2]. EINIGES UEBER
THEORIE UND ANWENDUNG VON LUFTLAGERN. TEIL I UND TEIL II. (in
German). Maschinenbautechnik, vol. 10, no. 12, pp. 619-624.
(December 1961); vol. 11, no. 1, pp. 24-27. (January 1962).

The general principles behind air bearings are described and charts given to permit the estimation of lift and consumption of air for flat plates. This allows (as an example) friction-free movement of heavy parts. A fully self-aligning knuckle joint is shown and also the replacement of a conical pivot by an air bearing. A small turbine bearing taking radial load and thrust, 20-mm diam, 125,000 rpm is illustrated, though this vibrated in spite of every effort.

- 62-125 Wilson, D.G.
AMERICAN NEWSLETTER. Chartered Mech. Engr., vol. 9, no. 6,
pp. 336-338. (June 1962).

Fluid bearings are now being seriously considered in a variety of applications. Perhaps one of the less obvious ones makes use of the greater accuracy of alignment and the inherent vibration damping characteristics of air bearings. These, in linear form, have contributed to the success of General Dynamics electronically controlled welding machine. This is capable of joining metals down to 0.003 in. thick. The quality of the welds shows a great improvement over those obtained with the conventional roller-bearing mounted carriage, mainly because the solidifying metal is not disturbed by vibration and because of the greater accuracy of alignment of the head. The bearing gaps used are from 0.0001 in. to 0.001 in. wide with shop air supplied at 5 to 55 p.s.i.g.; the cost of air for supporting a load of 1800 lb. for an eight-hour day is reckoned to be less than a halfpenny. Other air bearing applications planned include the support of a large radio telescope.

- 62-126 Winn, L.W. and Beno Sternlicht.
THE LOAD CARRYING CAPACITY AND STABILITY OF HYBRID GAS BEAR-
INGS. General Electric Co. Engineering Report TR R62ATS,
March 11, 1962

A Navy-supported theoretical and experimental investigation of instabilities occurring in a rotor-bearing system, including critical pneumatic hammer is discussed. Results of testing performed on

externally pressurized air bearings of L/D ratios of 1 and 0.5 are described and compared with analytically calculated values of load carrying capacity and system criticals. An analytical method of determining fractional frequency whirl (destructive form of instability closely related to half-frequency whirl of self-acting bearings) is also given.

- 62-127 Wood, Nat
DRAMATIC AIR BEARING IMPROVES WELDING 50%; 'FLOATS' HEAVY MACHINERY, CUSHIONS EXPLOSIVE FORMING. Western Metalworking, vol. 20, no. 4, pp. 25-7. (April 1962).

A precision friction-free air bearing is used by General Dynamics/Astronautics engineers to move equipment to carry straight line welders to improve welding of extremely thin materials, to study weightlessness and as protective cushioning in forming operations. The bearing resembles a simple platform. High pressure air is forced into a series of channels underneath.

- 62-128 Wunsch, H.L.
LUBRICATION WITH AIR. Certif. Engr., vol. 35, no. 4, p. 146. (April 1962).

Air bearings are proving their value in a wide range of uses. Their special properties have aided, for example, the nuclear power engineer, the missile designer and the measuring instrument manufacturer, and they show much promise for machine tool applications. Their principles and prospects, advantages and disadvantages are discussed.

- 62-129 Wunsch, H.L.
DESIGN AND APPLICATIONS OF AIR BEARINGS. Engineering, vol. 194, no. 5030, pp. 345-8. (September 14, 1962).

This paper describes the basic principles of the two types of air bearings, self-acting and externally-pressurized. The advantages and disadvantages associated with the operation of self-acting bearings are also given. There is a discussion of the load capacity of these bearings and applications, such as for machine tool and instruments, are described.

62-130

Wunsch, H.L.

PROPERTIES AND APPLICATIONS OF EXTERNALLY PRESSURIZED AIR BEARINGS. Sci. Lub., vol, 14, no. 4, pp. 14-23. (April 1962).

This paper is a review of the two types of air bearings, self-acting, and externally pressurized, with particular emphasis on the latter. Advantages and disadvantages of externally pressurized air bearings are listed. There is a description of a test rig which may be used to obtain practical design data. The results of these tests are summarized in the form of design curves of bearing gap (or lift) and against bearing load. The effects of orifice pocket dimension, supply pressure, and orifice diameter are shown, and conclusions as to ultimate load bearing capacity and bearing stiffness are drawn. A modification of the test rig, by the addition of a vibration generator and a displacement pick-up, makes it possible to estimate the behavior of a bearing under dynamic loading.

62-131

Yeh, T.F.

VISCOUS TORQUE IN SPHERICAL GAS BEARINGS. J. Aerospace Sci., vol. 29, no. 2, pp. 160-1. (February 1962).

This paper shows how to calculate viscous torque in a spherical gas bearing when the bearing eccentricity, e , is taken into account. For a high value of eccentricity -- i.e., above 0.5 -- the error introduced by neglecting the eccentricity effect is large, and should not be neglected. An expression for the percentage of this error, which is introduced into the calculations by assuming that the radial clearance, h =constant, is also given. A complete expression for viscous torque in a spherical bearing when the eccentricity is taken into consideration is given.

- 63-001 Alishaev, M.G.
[COMPRESSIBILITY OF THE LUBRICATING GAS LAYER]. O SDAVLIVANII
SMAZOCHNOGO SLOYA GAZA. (in Russian). Izv. Akad. Nauk SSR,
Otd. tekhn. Nauk, Mekh. i Mashinostr., no. 2, pp. 153-154.
(March-April, 1963).

The problem of pressure distribution in a layer of lubricating gas is considered. The investigation is limited to steady-state conditions in the gas film.

- 63-002 Angell, P.T.
TRENDS IN SPACE POWER AND ANTICIPATED LUBRICATION NEEDS.
Paper presented at the USAF Aerospace Fluids and Lubricants
Conference, Session 1, San Antonio, Texas, April 16-19, 1963.

The important characteristics of representative turbopower systems being developed to meet the increased needs for propulsive and auxiliary power for future space missions are described. Problems and approaches to lubrication of these systems are discussed. The working fluids used in both closed or open cycle power systems are chosen on the basis of the power level and operating temperature sought. Alkali metals are preferable for higher temperature operation, but problems of heat transfer, corrosion, and structural design must be solved before systems using these fluids are available. Mercury is used at lower operating temperatures, and hydrogen-oxygen mixtures for shorter-time open-cycle applications. The requirements placed on the bearings and lubricants by closed-cycle systems are determined by considering the pressures and temperatures associated with the operating cycle. The Rankine operating cycle operates with a fluid in the temperature range where there is a liquid-vapor phase change, whereas the Brayton cycle operates with the fluid entirely in the vapor or gas phase. The use of the working fluid as the lubricant is desirable to eliminate seals and lubricate the bearings within the system pressure and temperature range. This concept dictates the use of fluid film bearings, and although some operating and application problems remain, the success demonstrated by the SNAP 1/SPUD 2500 hr test and repeated endurance tests of the Sunflower turbomachine shows that there are no fundamental problems that will prevent achievement of a one-year life.

- 63-003 Anonymous.
LUBRICATING WITH GAS. Chem. Week, vol. 92, no. 17, pp. 64-66.
(April 27, 1963).

Clark Bros. Co. (Olean, N.Y.), division of Dresser Industries, Inc., is designing what it says is the first prime mover to use gas-lubricated bearings. The unit, part of a project to develop compact power conversion equipment for mobile U.S. Army nuclear power plants,

includes a gas turbine and centrifugal compressor-equipment operating in many CPI plants. The unit, like the water-lubricated compressors for oxygen service developed by Elliott Co., division of Carrier Corp., is aimed at preventing oil leakage into the process stream. In the mobile nuclear power plant, hot nitrogen is used as the working fluid that expands in the turbine and provides energy to drive compressor and load. However, in an emergency, Clark says, the turbine-compressor set could operate on air, rather than nitrogen. In the turbine-compressor system, nitrogen is compressed from 9 to 24 atmospheres. It then passes through a recuperator where it picks up heat from the turbine exhaust. (Final unit in the experimental system is an oil-fired heater that simulates nuclear reactor heat). The system is designed to generate more than 600 hp., yet will weigh less than 1 ton.

63-004

Anonymous.

GAS BEARING TURBINE FLOWMETER. Engineer, vol. 216, no. 5631, p. 1073. (December 27, 1963).

The turbine is supported by gas bearings and these are normally supplied with the same gas as that being metered in order to avoid contamination; the flow requirement of the bearings is less than 0.5% of the maximum metered flow. Typical operating pressures are up to 400 lb./sq. in. gauge and temperatures up to 300°C. The lower limit of operating temperature is defined by the liquefaction temperature of the fluid being metered. The flowmeter is produced in standard sizes of 1 in. and 2 in. bore dimensions, and can be supplied with turbine angles of 15°, 20°, 30°, 45°, and 60°, to match the appropriate flow rate. The turbines are interchangeable and the flowmeters can be supplied with two or more turbines. Overall accuracy of the flowmeter is claimed to be normally better than 1% of the rated maximum flow, when operated with a digital counter.

63-005

Anonymous.

LOAD 'FLOATS' INTO VAN ON LOW AIR PRESSURE. Steel, vol. 152, no. 12, p. 81. (March 25, 1963).

Nearly frictionless movement of loads into and out of a van type trailer has been demonstrated by Clark Equipment Co., Buchanan, Mich. The load floats on low pressure air. Without additional equipment, one man can unload or load the contents of a 20 ton capacity trailer. The floor of the trailer and the loading dock area are plenum chambers that carry low pressure air. Ball valves hold the air within the chamber; when they are depressed slightly by the palletized load, they allow the air to escape in a thin film, lifting the load from direct contact. While the van is moving over the road, the air is shut off, and the loads rest on the floor and show no tendency to skid. The unit, called Load Glide Air-In-Floor, is a further development of an air supported load system announced last May.

- 63-006 Anonymous.
 [AIR CUSHIONS AS CONVEYING MEANS]. LUFTKISSEN ALS FOERDERMITTEL.
 (in German). Werkstatt u Betrieb, vol. 96, no. 10, p. 778.
 (October 1963).

A pallet with stacked goods is lifted by compressed air just sufficiently to eliminate adhesive friction with the floor so that the load can be readily moved by hand into any desired direction. The compressed air flows from special valves when the pallet slides over them, exerting pressure upon them. The pressure required depends on the weight of the load and the type of floor surface and is, as a rule, between 0.28 and 2.1 kg/cm². This new device is called "Load Glide" and is available from Clark Equipment Co.

- 63-007 Anonymous.
 TABLE FLOATS ON AIR BEARINGS WHILE TESTING OAO CONTROLS.*
Mach. Design, vol. 35, no. 11, p. 10. (May 9, 1963).

Stabilization and control system for the Orbiting Astronomical Observatory has started a test program mounted on a unique air bearing table which weighs 5208 lbs. and is sensitive to 0.07 oz-in. of unbalanced torque about any axis. The table sits upon a bearing which floats in a socket through which compressed air is forced at 26 psi, providing a 0.0001-in. air film support.

* OAO stands for Orbiting Astronomical Observatory (NASA satellite) scheduled to be launched in 1965.

- 63-008 Ausman, J.S.
 LINEARIZED pH STABILITY THEORY FOR TRANSLATORY HALF-SPEED WHIRL OF LONG, SELF-ACTING GAS LUBRICATED JOURNAL BEARINGS. Trans. ASME (J. Basic Engng.), vol. 85 D, no. 4, pp. 611-19.
 (December 1963).

The linearized pH approximation to the time-dependent Reynolds equation is solved simultaneously with the equations of motion for a rotating journal shaft supported by a rigidly mounted bearing sleeve. Given the two bearing parameters

$$\lambda = \frac{6\mu\omega R^2}{p_a C^2} \quad \text{and} \quad \Omega = \frac{MC\omega^2}{\pi p_a DL}$$

a critical operating eccentricity ratio is determined below which the bearing is unstable and above which the bearing is stable. Whirl frequency of the threshold point is computed to be equal to or slightly less than one-half rotor speed.

- 63-009 Ausman, J.S.
GAS LUBRICATED BEARINGS. International Symposium on Lubrication and Wear, Proceedings, Houston, June 1963. McCutchan Publishing Corp., Berkeley, Calif., 1965. pp. 825-53.

Analysis of gas-lubricated bearings using the non-linear Reynolds equation is examined. Methods of obtaining approximate solutions are discussed. Results are presented in forms intended to illustrate the fundamental nature and behavior of gas lubrication. Typical design curves are given as guides and stability problems are discussed.

- 63-010 Barlow, Edward
EXTERNALLY PRESSURIZED, AXISYMMETRICAL FOIL BEARINGS. Ampex Corporation. Research and Engineering Publication RR 63-4. April 1963. Navy contract Nonr-3815(00).

An externally pressurized axisymmetrical foil bearing was analyzed in order to obtain the qualitative effect of side leakage in a foil bearing. One or two circumferential pressure sources, symmetrically placed, were used. In the analysis, bending stiffness of the foil was included and was found to be not negligible. Curves were obtained which show the effects of the various physical parameters on the gap profile.

- 63-011 Bennett, E.C.
FOR A NUCLEAR LOOP: GAS BEARINGS. Mech. Engng., vol. 85, pp. 26-9. (June 1963).

The development of gas-lubricated bearings for the gas circulators in the coolant system of the DR reactor at Hanford is described. The loop is designed to operate at a nominal pressure of 200 psig. Either helium or nitrogen may be used as a coolant, with flows up to 450 lb. per hour of helium or 2000 lb. per hour of nitrogen. Temperatures at different points in the loop vary widely.

- 63-012 Brown Boveri
DESIGN FEATURES AND TEST RESULTS OF THE MAIN CIRCULATORS FOR THE DRAGON REACTOR. O.E.C.D. High Temperature Reactor Project. Dragon Project Report 217. October 1963.

The main coolant air-circulators are totally enclosed blowers with self acting (hydrodynamic) gas-lubricated bearings designed to operate with very pure helium with less than 10 ppm of O_2 , H_2O , CO , and CO_2 , at pressures between 8 and 25 kg/cm^2 , and at temperatures between ambient and $420^\circ C$. The speed range is between 1,100 and 12,000 rpm, infinitely variable with the aid of frequency changers.

The bearings are made of nitrided steel. The design of the entire system is discussed, as well as experimental tests and results. During the tests, the journal bearings were run at high temperatures and under certain conditions there were temperature differences of up to 70°C between one end and the other of the impeller side bearing. Starting and stopping was carried out without any ill effects at a temperature difference of at least 40°C in the bearings. There were no noticeable effects on the bearings due to aerodynamic forces on the impeller and magnetic forces of the motor at full power. During the testing there were some bearing failures. Thrust bearing instability caused by insufficient thrust was blamed for most of these. A contactless touch-indicator was developed which shows the slightest metallic contact and can be used for occasional checking of the bearings during the life of the reactor.

(Note: With slight additions this paper is also published in: ROTATING MACHINERY FOR GAS-COOLED REACTOR APPLICATION, PROCEEDINGS OF MEETING, Gatlinburg, Tennessee, November 4-6, 1963. Sponsored by Oak Ridge National Laboratory, May 1964. TID-7690. pp. 189-206. The addition consists of a 500-word historical description of the "Development of Gas-Lubricated Bearings" during a ten-year period (1953-1963) at the UKAEE.)

- 63-013 Brown, L.T.
GAS LUBRICATED BEARING SYSTEM. U. S. Patent 3,107,129.
Applied February 13, 1962. Issued October 15, 1963.

This invention relates to a gas lubricated bearing system which has a transitional operation in both the hydrodynamic and hydrostatic modes. The invention comprises a hydrodynamic wedge-type bearing in which a bearing has formed on its internal circumference at least one internal longitudinal step portion and has a journal member mounted for rotation therein with a mechanical clearance therefrom. A source of pressurized gas is provided with a porous metal outlet for the gas, coplanar with the inner surface of the bearing, and substantially coextensive in length with the bearing. A transducing means is mounted on the bearing which monitors the displacement of the journal from its normal hydrodynamic operating position and is operable to initiate gas flow from the source of pressurized gas to the outlet whenever additional lubricating gas is required to support the journal.

- 63-014 Bulkeley, P.Z. and W.E. Langlois.
EQUATIONS OF MOTION FOR THE AIR-LUBRICATED FLEXIBLE DISC.
International Business Machines Corp., Report RJ-233,
January 7, 1963. Contract Nonr 3448(00).

Equations are formulated for the motion of a spinning elastic disc over an air bearing. Some approximation methods are indicated, but no detailed solutions are carried out.

- 63-015 Castelli, V. and H.G. Elrod, Jr.
SOLUTION OF THE STABILITY PROBLEM FOR 360° SELF-ACTING, GAS-LUBRICATED BEARINGS FOR INFINITE LENGTH. Franklin Institute Laboratories. Interim Report I-A2049-20, TID-18691, March 1963. Contract Nonr-2342(00).

An investigation was made of the stability of self-acting, gas-lubricated bearings. Two approaches to the solution are presented and their results are compared. The relation is discussed between this work and other, more simplified, methods available in the literature. The particular case of a 360° journal bearing of infinite length is treated, and the changes necessary to use the same theories with other geometries are pointed out. Available experimental results are collected and compared with theory.

- 63-016 Cheng, H.S. and P.R. Trumpler.
STABILITY OF HIGH-SPEED JOURNAL BEARING UNDER STEADY LOAD-COMPRESSIBLE FILM. Trans. ASME, (J. Engng. Industry), vol. 85 B, no. 3, pp. 274-280. (August 1963).

The governing equations for the dynamical system of a self-acting gas-lubricated journal bearing are formulated. An approximate solution for the equilibrium position of the journal center is obtained by use of Galerkin's method. The equilibrium solution shows close agreement with the exact numerical computer solution obtained by Elrod. The stability of the equilibrium solution is investigated by solving the linearized equations on an analog computer. The solution of the set of linearized equations shows that there exists a threshold speed of instability for each equilibrium position. The value of this threshold speed is presented in a stability chart. In addition, approximate particular solutions for the nonlinear dynamical equations are obtained by use of the analog computer. The results are shown as trajectories of the journal center when it is displaced arbitrarily from the equilibrium position.

- 63-017 Compagnie Parisienne d'Outillage À Air Comprimé.
IMPROVEMENTS IN AND RELATING TO AIR LUBRICATORS. British Patent 930,813. Applied April 5, 1961. Issued July 10, 1963.

This invention relates to symmetrically operating air lubricators. The various appliances operated by compressed air require, like all mechanisms, continual lubrication of the different moveable parts. The problem is generally solved through the driving fluid itself, which carries the necessary lubricant to the mechanisms. For this purpose the air is loaded with pulverized oil while passing through devices known as air lubricators, which function by utilizing the dynamic properties of the fluid flow. Such devices

generally have the feature of being able to function in only one direction of the passage of air. The present invention has as its object to remedy this disadvantage by allowing pulverization of oil in the air, whatever the direction of passage of the fluid. The invention relates to a symmetrically operating air lubricator characterized by the feature that it comprises: a main channel interposed by its ends in the piping for the air to be lubricated, a branch channel opening at its ends into two points of the main channel, a pressure chamber interposed in the branch channel and having a larger cross-section than the latter and a receptacle which contains a supply of liquid lubricant and is connected to the pressure chamber for delivering the lubricant to a distributing device, leading it to the main piping.

- 63-018 Constantinescu, V.N.
 [EFFECT OF METHOD OF VARYING LUBRICANT FILM THICKNESS ON OPERATING CHARACTERISTICS OF GAS LUBRICATED BEARING].
 VLIYANIE SPOSOBA IZMENENIYA TOLSHCHINY SMAZCHNOGO SLOYA NA KHARAKTERISTIKI RABOTY PODSHIPNIKOV S GAZOVOI SMAZKOI. (in Russian). Rev. Mecan. Appl., vol. 8, no. 1, pp. 47-57. (1963).

The author compares the operating characteristics of ten principal design types of thrust gas bearings. These are evaluated in terms of their optimum performance at various speeds.

- 63-019 Constantinescu, V.N.
 THEORY OF TURBULENT LUBRICATION. International Symposium on Lubrication and Wear, Proceedings, Houston, June 1963.
 McCutchan Publishing Corp., Berkeley, Calif. 1965. pp. 159-205.

Operating characteristics of gas-lubricated bearings in both the steady and unsteady turbulent regimes are discussed. One section of this paper, presents the basic elements of a theory of turbulent lubrication based on the concept of "mixing length".

- 63-020 Constantinescu, V.N.
 SOME APPROXIMATE METHODS FOR CALCULATING GAS LUBRICATED JOURNAL BEARINGS. (in English). Rev. Mecan. Appl., vol. 8, no. 2, pp. 325-345. (1963).

With a slightly changed title this article was also presented in Trans. ASME (J. Basic Engng.), vol. 85 D, no. 3, pp. 475-7. (September 1963). (See no. 63-021)

- 63-021 Constantinescu, V.N.
ON SOME ANALYTICAL METHODS FOR THE ANALYSIS OF GAS-LUBRICATED JOURNAL BEARINGS. Trans. ASME (J. Basic Engng.), vol. 85 D, no. 3, pp. 475-7. (September 1963).

Several analytical methods for the study of gas lubricated journal bearings exist. There are four methods cited for infinitely long bearings. However, some must be corrected. Except for the first-order perturbation theory all these methods give a load carrying-capacity greater than that obtained by means of numerical methods. One can obtain the same conclusion by analyzing the errors introduced by each method. Among the existing analytical methods, the better one is the constant pH method, if corrected by a factor. The Scheinberg method also is of some interest because of its accuracy, but its results cannot be given in analytical form.

The following erratum on the above article appeared in Trans. ASME (J. Basic Engng.), vol. 86 D, no. 2, p. 416. (June 1964).
An additional figure, the load factor $\xi = \frac{P}{2p_0 r L}$ function of the bearing number H for $\epsilon = 0, 8$, and aspect ratio $\lambda = 1$ which was omitted from the original article is now added.

- 63-022 Constantinescu, V.N.
[GAS LUBRICATION]. LUBRIFICATIA CU GAZE. (in Romanian). Academia Republicii Populare Romine. 1963. 633 pp.

Beginning with the equations of the gas lubrication problem, the first chapters in this book study the flow in the lubricant layer for externally pressurized bearings. The remaining chapters concentrate mainly on the self-acting bearings operating hydrodynamically. Chapter IV examines gas lubrication at low speeds for which the lubricant can be considered as a first approximation to be incompressible. Chapters V and VI approach the simplified (two dimensional) problem of infinitely-long bearings, while Chapter VII treats the operation of real bearings of finite dimensions. Finally, Chapter VIII deals with the dynamic regimes and with the stability of gas lubricated bearings. The influence of turbulence on motion in the lubricant film was not examined since it will constitute the subject of a separate work.

- 63-023 Cooper, Stanley
THE MANUFACTURE AND OPERATION OF SELF-ACTING GAS LUBRICATED JOURNAL AND THRUST BEARINGS. Paper presented at the ASME Spring Lubrication Symposium, Session IV, Boston, Mass. June 4, 1963.

The problems arising from the manufacture of gas lubricated bearings are discussed. These include ordinary machine tool operations, honing and lapping. Special manufacturing requirements for various

bearing types are described. The photomechanical production of thrust bearing features is outlined. The problems of thrust runners are briefly treated. Operation of pivoted pad journal bearings is examined. The pivoted pad bearing is not safe for starting under load without pressurization, as is the full journal bearing. Operation of thrust bearings is also examined. Alignment, fluid flow, and attitude angle are briefly reviewed.

63-024 Dimoff, T. and B.F. Payne.

APPLICATION OF AIR BEARINGS TO AN ELECTRODYNAMIC VIBRATION STANDARD. J. Res., Nat. Bur. Stand., (Engng. Instrum.), vol. 67 C, no. 4, pp. 327-33. (October - December 1963).

In an attempt to eliminate unwanted resonances and transverse motions in an electrodynamic exciter used as a vibration standard, the mechanical suspension-guide for the moving element was replaced with air bearings. The transverse motions of this exciter showed a distinct improvement over the transverse motions of the exciters with flexure plate and tensioned wire supports. The improved stability of the moving element of the air-bearing exciter made it possible to calibrate this exciter easily by an interferometer method. Agreement between three methods of calibration, reciprocity, interferometer, and optical target, was very good. The results of calibrations of two types of pickups on this modified standard are presented.

63-025 Dyer, R.F.

NEUTRON TIME-OF-FLIGHT SPECTROMETER DRIVE UNITS. United Kingdom Atomic Energy Authority. Research Group Report R 4214, 1963.

Difficulties were experienced with the original design of drive units and this was mainly centered around the gas lubricated journal bearings. Investigation showed that the design of the bearing was fundamentally wrong, because for maximum strength against displacement and torque the feed hole was too large, ratio of bearing length to diameter was too low, bearing was not self-aligning and the radial gap between shaft and journal was too large. A detailed description is given of the modifications incorporated in the bearing and mounting design, followed by performance figures for the new bearings showing their superiority over the original design.

63-026 Elrod, Jr., H.C.

THE THEORY OF PULSATING FLOW IN CONICAL NOZZLES. Trans. ASME, ... (J. Appl. Mech.), vol. 30 E, no. 1, pp. 1-6. (March 1963).

A knowledge of the dynamic characteristics of nozzles and orifices

is important in many control and stability analyses of engineering devices. It is usual to assume that the instantaneous flowrate, for a given set of inlet conditions and outlet pressure, is the same as the nontransient value for the same operating conditions. Recently, in connection with the stability analysis of an externally pressurized thrust bearing, the validity of this assumption was questioned. The analysis presented in this paper was undertaken to provide an answer. The present analysis applies to any fluid, liquid or gas flowing into a simple conical nozzle. The amplitude and phase of the mass-flux response to a sinusoidally time-varying pressure fluctuation at the nozzle exit are determined. An approximate formula is given for these quantities in terms of the nozzle throat area, the solid angle subtended by the cone, the velocity of the fluid at the nozzle throat, the acoustic velocity at the throat, and the frequency of the pressure fluctuation.

- 63-027 Eusepi, M.W.
EXPERIMENTS ON A PARTIAL ARC SELF-ACTING GAS JOURNAL BEARING.
Mechanical Technology Inc. Technical Report, November 1963.
Contract Nonr-3730(00).

Operational characteristics of a rotor when supported on self-acting gas lubricated journal bearings are reported. Experimental results for the evaluation of several parametric changes are noted. Some of these parameters included in the investigation are elevated ambient pressure up to 500 psig., clearance ratio, length-to-diameter ratio, bearing load, and bearing orientation.

- 63-028 Fox, G.R.
HYDROSTATIC BEARING. U. S. Patent 3,110,527. Applied October 29, 1959. Issued November 12, 1963.

This invention relates to externally pressurized gas lubricated bearings having inherent stiffness to respond quickly to changes in load. It also provides means for increased lubricant flow at increased bearing loads. The invention, briefly stated, is directed to an externally pressurized bearing including a journal, a bearing surface enveloping the journal, a plurality of passages connecting a plurality of openings in the bearing surface to a source of fluid and valve means associated with the passages for controlling the flow of fluid through the passages in response to changes in bearing loads. By incorporating special devices and structures in the bearing, fluids which may not possess what are commonly considered good lubricating characteristics may be employed. The use of certain fluids such as gases is often dictated by high temperature, high radiation environments, and by the need for a lubricant having inherent low friction characteristics or by the need for non-contaminating properties.

63-029 Fricker, H.W.

THE CHOICE OF GAS BEARING MATERIALS. O.E.C.D. High Temperature Reactor Project. Dragon Project Report 208, August 1963.

The influence of material properties on the performance of gas bearings in the fully gas-borne state and during stopping and starting were investigated. Metals, ceramics, cermets, and plastics were analyzed for possible applications in gas bearings, as well as for the effect of various surface treatments on the performance of these materials. It is suggested that good rubbing materials be adapted for use in gas bearings. The two most promising materials investigated were PTFE compounds and carbons or graphites. The latter have the advantage of higher temperature resistance and are little affected by atomic irradiation. Another possible development, which is suggested for more investigation, is the use of dry lubricant films, such as graphite, MoS_2 , and PTFE. For low temperature and short time applications, films of liquid lubricants might cure unsuccessful material combinations. A combination like tungsten carbide-CY132, properly cooled, would stand an unusual amount of overloading or underspeeding if used in a gas bearing, and its reliability would be similar to a good oil lubricated bearing.

63-030 Gross, W.A.

GAS BEARINGS: A SURVEY. Wear, vol. 6, no. 6, pp. 423-443. November/December 1963.

Previously (Internat. Sci. Technol., January 1963) the author has approached the subject in more general terms. In the present survey he addresses himself to the specialist. A gas can lubricate bearing surfaces just as a liquid can, but the unit loads that a gas film can support are much lower because the viscosity of the gas is several orders of magnitude lower than that of a liquid lubricant. Since low viscosity means low friction, bearings run on gas can move at tremendous speeds without overheating. Like liquid lubrication theory, gas lubrication theory is well developed; however, only recently have we had adequate mathematical tools and adequate experimental facilities for verifying it. Gas lubricants are used in three basic bearing types: self-acting, externally pressurized and squeeze-film. They are being applied in a variety of machines, from inertial guidance gyros to computer memory systems. Once the dynamic properties are more completely evaluated, gas film lubrication will be even more widely applied.

63-031 Gross, W.A.

EXTERNALLY PRESSURIZED BEARING LUBRICATION. International Symposium on Lubrication and Wear, Proceedings, Houston, June 1963. Mc Cutchan Publishing Corp., Houston, 1965. pp. 309-421.

Fundamentals of externally pressurized bearings are discussed, emphasizing the significant parameters. Limitations and complications involved are examined. The embodiments of externally pressurized bearings, and the specific design of such bearings are discussed. Special cases such as squeeze-film bearings and foil bearings are also treated.

Note: Two letters offer some constructive criticism on this article in the May 1963 issue of the same journal.

63-032 Gross, W.A.

GAS LUBRICATED BEARINGS. Naval Engrs' J., vol. 75, no. 4, pp. 737-43. October 1963).

This paper contains a description of gas bearings, and concentrates on the properties of steady gas lubricating films and on the dynamics of gas bearing systems. Types of films, bearings, configurations, and shapes are described. Operating conditions and environmental and material problems are discussed which bracket the region in which the properties of gas lubricating films need to be understood. Theoretical solutions for unsteady gas lubricating films are described and their use with bearing systems discussed.

63-033 Grossman, R.L.

APPLICATION OF FLOW AND STABILITY THEORY TO THE DESIGN OF EXTERNALLY PRESSURIZED SPHERICAL GAS BEARINGS. Trans. ASME (J. Basic Engng.), vol. 85 D, no. 4, pp. 495-502. (December 1963).

The first portion of the paper, defining the gas flow through externally pressurized spherical gas bearings, follows very closely the analyses and steps of the paper by Laub and Norton, except that a recess is cut into the socket, and the bearing and the socket are of the same radius. Next a relation for critical depth assuring stability is established following the procedure of Licht and others. Calculations giving a set of design curves to optimize the design of spherical bearings are indicated. Design of three cases, 6-in., 10-in., and 22-in. diam. air bearings, has been considered. Carefully designed experiments have been conducted in 6-in. and 10-in. bearings for verification of the flow and stability criteria. From the experimental results, area correction factors are suggested to modify the analytical equations.

- 63-034 Gunter, Jr., E.J., V. Castelli and D.D. Fuller.
THEORETICAL AND EXPERIMENTAL INVESTIGATION OF GAS-LUBRICATED,
PIVOTED-PAD JOURNAL BEARINGS. ASLE Trans., vol. 6, no. 4,
pp. 346-357. (October 1963).

This paper presents some of the theoretical predictions and experimental results for the steady-state characteristics of a gas-lubricated, pivoted-pad journal bearing of finite length. An analytical expression for the prediction of load-carrying capacity for these bearings is developed from numerical computer solutions. Sample calculations are presented to show how the theoretical data may be utilized in the design of an actual pivoted-pad bearing. Improvements over previous approximate theories are discussed.

- 63-035 Gunter, Jr., E.J., and D.D. Fuller.
RECENT PROGRESS ON THE DEVELOPMENT OF GAS-LUBRICATED BEARINGS
FOR HIGH SPEED ROTATING MACHINERY. USAF Aerospace Fluids and
Lubricants Conference, Proceedings, San Antonio, Texas,
April 16-19, 1963. pp. 487-508.

Problems that may be encountered when high-speed rotors are operated on gas lubricated bearings are reviewed. Although certain of these difficulties are peculiar to the type of bearing that is used, all gas lubricated bearings have common characteristics of low damping and relatively low spring rates. The influence of gas lubricated bearings on balance requirements, critical rotor speeds, and the susceptibility of the rotor system to external excitation, especially when near a critical speed, is discussed. The tilting-pad journal bearing shows much promise for high-speed rotor applications and a comparison between theoretical and experimental performance is given for load-carrying capacity and optimum pivot position. The agreement between measured and predicted values of film thickness was good.

- 63-036 Gunter, Jr., E.J., J.G. Hinkle and D.D. Fuller
THE APPLICATION OF GAS-LUBRICATED BEARINGS TO HIGH-SPEED,
TURBO-MACHINERY. Franklin Institute Laboratories. Quarterly
Technical Report Q-A2392-3-8, December 1, 1962 to February
28, 1963. February 1963. TID-18924.

Studies were made on the design and analysis of both self-acting and externally-pressurized gas-lubricated bearings. A review of the theoretical and experimental work performed on a self-acting, gas bearing rotor is presented. A four-inch diameter rotor was tested at speeds up to 20,000 rpm. Hydrodynamic film thickness measurements of the self-acting pivoted shoes were obtained for several conditions of shoe load and various equivalent pivot positions at design speed of 18,000 rpm. An observation of apparent half-fre-

quency whirl instability is presented and discussed. Preliminary test data are shown for tests performed with the small aspect ratio self-acting shoes, $L/B = 1.0$, which were externally-pressurized at the pivot location during start-up and at low rotational speeds. A discussion of the advantages of this type of bearing arrangement is given.

63-037 Hall, J. and R. Spies.

DETERMINATION OF WORKING FLUID LUBRICATION CAPABILITY IN JOURNAL BEARINGS, PART II. Rocketdyne. Technical documentary report ASD-TDR-62-640, Part II, May 1963. AF contract AF 33(616)-8328.

Gas bearings are used in the test equipment employed in this program. In the general purpose test rig, the radial support for the test shaft is provided by two externally pressurized inert gas bearings. The endurance test rig uses a similar drive turbine and externally pressurized gas support bearings. Several water lubricated test bearings have been run in this rig using a rotor support bearing incorporating the thrust and radial gas bearings in one piece. The basic characteristics of the test equipment are discussed in detail in ASD-TDR-62-640.

63-038 Jaffrey, W.G. and G.M. Boxall.

THE SUPPORT OF THIN STEEL STRIP ON AIR CUSHIONS. J. Iron Steel Inst., vol. 201, pt. 5, pp. 401-408. (May 1963).

The support of thin steel strip on air cushion bearings offers exciting possibilities for novel and compact forms of strip processing plants. The potential advantages are great in that the strip need not be under high tension, and its surface will not be marked by contact with rolls. A form of bearing whereby strip is supported on a cushion of air retained by annular jets has been developed and found to be both practical and economical. A labyrinth form of looping tower is described, and a full scale pilot plant handling 36 in. wide strip has been constructed. Equations for the performance of air cushion bearings have been derived and compared with experimental results.

63-039 Kao, H.C.

THEORY OF SELF-ACTING, GAS-LUBRICATED BEARINGS WITH HEAT TRANSFER THROUGH SURFACES. Trans. ASME (J. Basic Engng.), vol. 85 D, no. 2, pp. 324-8. (June 1963).

Use is made of the continuity, Navier-Stokes, energy, and state equations to develop the differential equations for gas lubrication problems. Heat transfer through the surface is allowed. The first approximation, not surprisingly, gives the Harrison equation

which is usually obtained by assuming the isothermal process. The error introduced by this assumption is shown up in the second approximation, when the isothermal condition is dropped. Under normal operational condition, this error is small enough to be neglected. However, the main purpose of developing the second approximation is to allow heat transfer through the surfaces such that the load capacity can be increased. Two curves of the pressure distribution for the infinitely long inclined plane slider bearing at various bearing numbers are plotted to show the effect of a temperature difference compared with the isothermal case given by Harrison's equation. These results suggest that merely by increasing the temperature difference between the surfaces, the load capacity of a self-acting, gas-lubricated bearing can be considerably increased.

63-040

Krementulo, V.V.

[SOME PROBLEMS IN THE MOTION AND STABILITY OF A SPHERICAL GYROSCOPE]. NEKOTORYE VOPROSY DVIZHENIYA I USTOICHIVOSTI SHAROVOGO GIROSKOPA. (in Russian). Izv. Akad. Nauk SSSR, Otd. Tekh. Nauk, Mekh. i Mashinostr., no. 2, pp. 120-125. (March-April 1963).

Various approaches are suggested for studying the motion and stability of a spherical gyroscope held in suspension by a thin film of gas (air cushion). The sphere of such a gyroscope can move within its casing as a result of the force of gravity in addition to the forces generated by the air support and by the stator. Since the ball, while in the casing hollow, can move translationally in any direction and can rotate around any axis that passes through its center of gravity, it must be examined as a mechanical system with six degrees of freedom. It is proposed to model the effect of the suspension on the ball by means of the elastic forces of springs. Using this model, the motion and stability of the ball are investigated in detail.

63-041

Ku, P.M., editor.

U.S.A.F. AEROSPACE FLUIDS AND LUBRICANTS CONFERENCE, PROCEEDINGS, San Antonio, Texas, April 16-19, 1963. September 1963. AF contract AF 33(657)-11088.

The purpose of this conference was to present unclassified results of Air Force internal and contractual research and development programs in the broad field of aerospace fluids and lubricants, as well as selected applicable topics from other government agencies and industry. Sessions included gas turbine lubricants, solid-film lubricants, aerospace lubricants, greases and advanced base stocks; liquid metal lubrication, gas bearings, aerospace bearings, and bearing fatigue; liquid metals, heat transfer and hydraulic fluids. Fifty-eight technical papers were presented. These papers range in scope from broad flight lubrication requirements to where fluid samples should be sent for evaluation, and from operational

problems of MIL-L-7808 to the synthesis of triphenyltriazine and to fractional frequency whirl of gas bearings. The proceedings attempt to provide the current state-of-the-art work in the above areas since the last conference in November 1960. The papers point out that although advanced fluid and lubricant materials have progressed considerably, there is still a substantial gap between requirements and available products. As a result lubrication techniques such as gas bearings, liquid metal bearings and magnetic bearings are taking on increased importance and endeavors.

63-042 Langlois, W.E.

A RECURSIVE APPROACH TO THE THEORY OF SLOW STEADY-STATE VISCO-ELASTIC FLOW. International Business Machines Corp. Research Report RJ 227, October 30, 1963. Navy contract Nonr 3448(00).

The slow, steady-state motion of an arbitrary Rivlin-Ericksen fluid is considered. By perturbing about a state of rest, equations governing the first, second, and third order flow fields are developed in such a way that the second order theory uses explicitly the first order results, etc. The first order equations are those of creeping viscous flow; the second order theory introduces two parameters associated with the viscoelasticity of the fluid; the third order theory brings in three more. Fluid inertia is neglected throughout. To facilitate application, the flow equations, derived in Cartesian tensor notation, are rewritten in general tensor notation; the equations are explicitly given both for cylindrical and spherical coordinate systems. Several elementary flow problems of technological importance are solved: flow between parallel plates; the Poiseuille problem; helical flow in an annular region; torsional flow between discs. It is shown that, in a rather fundamental sense, there is no fluid-film lubrication theory of viscoelastic flow. The components of stress differ among themselves, and vary across the film, by amounts comparable with the lubrication pressure. Hence, boundary conditions cannot be satisfied and it must be concluded that viscoelastic lubrication presents a fully three-dimensional flow problem.

63-043 Lehmann, R., R. Pich and A. Wiemer.

[FUNDAMENTALS FOR THE CALCULATION OF THE FLOW PROCESSES IN AIR LUBRICATED BEARINGS WITH SLOW SLIDING VELOCITY].
GRUNDLAGEN FÜR DIE BERECHNUNG DER STROMUNGS VORLÄGE IN LUFTGESCHMIERTEN GLEITLAGERN MIT GERINGER GLEITGESCHWINDIGKEIT.
(in German). Feingeratetechnik, vol. 12, no. 8, pp. 345-353. (August 1963).

Since no general data for construction and calculation of air-lubricated bearings were available, flow processes in low clearances were examined theoretically by the authors. Starting from

the equations of Navier-Stokes for stationary flow, non-turbulent flow in narrow clearances was investigated for rectilinear parallel flow and for diverging and converging radial flow. Besides, the corresponding equations for turbulent flow were established. In order to simplify further studies, three kinds of bearing surface elements were introduced, which were sufficient for the calculation of the various bearings. A bearing surface element consists of an inlet orifice, a chamber, and the corresponding part of the bearing clearance. Formulae were derived for the calculation of the connections between the individual parameters in the bearing surface elements.

- 63-044 Lemon, J.R.
 DYNAMICS OF GAS-LUBRICATED PLAIN JOURNAL BEARINGS. Dissert.
 Abst., vol. 23, no. 10, pp. 3845-6. (April 1963).

An expression is developed which describes in detail the dynamic performance of the fluid film. Linear ordinary differential equations, for the loads on the shaft of a journal bearing due to the fluid film, have been derived directly from the Reynolds equations. Several simplifying assumptions concerning the mechanical configuration of a journal bearing system have been verified through the experimental program. Also, it has been possible to separate experimentally the modes of vibration, to find techniques of balancing, and to simplify techniques for collecting data. The load expressions, when included in the equations of motion of the simplified system, are shown to describe the half frequency whirl and the lowest resonant whirl phenomena. The dynamic predictions from an analog computer study of the equations of motion closely resemble those obtained in testing. The resulting equations of motion are of a higher order than previously assumed equations, but they are still linear and in reality present little additional complexity.

- 63-045 Lewis, P., J.W. Lund and S.F. Murray.
 RESEARCH ON GAS LUBRICATION AT HIGH TEMPERATURE AND LOW
 FLOW RATES. Mechanical Technology Inc. Report MTI-63TR25,
 June 18, 1963. AF contract AF 33(657)-10694.

Load carrying capacity at minimum flow rates, stable rotor-bearing behavior, suitable material properties, geometry changes due to thermal gradients, growth and distortion, centrifugal growth, and deterioration of restrictor and flow passages due to high gas velocity and impingement for gas lubricated bearings are investigated and results reported where possible. This information will be used to design nitrogen gas-lubricated journal and thrust bearings that will have stable operation over temperatures of 80°F to 1900°F, at speeds of 0 to 60,000 RPM, and at pressures to 300 psig.

- 63-046 Lech, Erwin
[PNEUMATICALLY EXCITED VIBRATIONS IN STATIC AIR BEARINGS].
PNEUMATISCH ERREGTE SCHWINGUNGEN IN STATISCHEN GASLAGERN. (in
German). Konstruktion, vol. 15, no. 8, pp. 333-336. (1963).

In some designs of aerostatic (externally-pressurized) bearings, pneumatically excited vibrations cause difficulties which have been frequently investigated in the past. Previous efforts, of practical and theoretical nature, to design stable bearings had the object of tuning the characteristic parameters in such a way to each other that this vibration did not occur. The author claims however that this sacrifices economy. The present paper describes new methods for damping or removing these vibrations. Based on comparison and measurements, the relationship between bearing stability and vibration frequency, on the one hand, and equilibrium volume, feeding nozzles, pressure, and height of the clearance, on the other hand, is investigated. When the vibration frequency of the bearing system is known, an accurate tuning and design of resonators is possible. These resonators are arranged in the stationary parts of the bearing and represent efficient damping elements. Finally, vibrations of bilateral thrust bearings are investigated, including the possibilities for removal of these instabilities.

- 63-047 Los Alamos Scientific Laboratory
QUARTERLY STATUS REPORT ON ULTRA HIGH TEMPERATURE REACTOR
EXPERIMENT (UNTREX). Report LAMS-2894. TID-4500.
April 30, 1963. AEC contract W-7405-Eng. 36.

Mechanical Technology Inc. assembled and tested the small 8 hp. compressor for the UNTREX gas cleanup system. Fixed- and tilting-pad hydrodynamic gas bearings were tested and the tilting pad type was found preferable. Fabrication of the prototype large helium blower for the main coolant loops is underway also by MTI. The design is similar to that of the small compressor, that is the motor is located between the two hydrodynamic gas bearings, the compressor wheel is cantilevered on the end of the rotor and all mechanical components are canned within a He casing operating at the pressure of the working fluid (500 psi). The journal bearings are of the pivoted shoe (tilting pad) type. The bearing nearest the impeller has a diameter of $3\frac{1}{2}$ in. and the other bearing, $2\frac{1}{2}$ in. The thrust bearing is also of the tilting pad type and consists of two shoes of 60° arc.

- 63-048 Lund, J.W.
HYBRID GAS JOURNAL BEARING INSTABILITY. Mechanical Technology
Inc. Report MTI 63TR60, December 27, 1963. AF contract
AF 33(657)-10694.

The instability of the hybrid gas journal bearing is investigated

analytically. The bearing is supplied with pressurized air through orifices in the centerplane which is approximated by a line source. The gas film equation, Reynolds' equation, is solved by the linearized Ph-method including the hydrostatic pressure effect and used to generate the coefficients for the determination of the threshold of instability. The equations are solved by numerical integration. The results for threshold speed and frequency are given in the form of graphs. Comparison with experimental data shows qualitative agreement but quantitatively there are discrepancies of as much as 2:1. This is believed to be caused by too simple an orifice representation whereas the gas film in itself should be correctly treated. A method for correction is discussed.

63-049 McCann, R.A.

STABILITY OF UNLOADED GAS LUBRICATED BEARING. Trans. ASME (J. Basic Engng.), vol. 85 D, no. 4, pp. 513-18. (December 1963).

This paper deals with a perfectly cylindrical, self-acting, gas lubricated, and unloaded journal bearing. Complete stability criteria for the translational mode of oscillation are formulated and a method is given by which the ultimate stable operating speed may be found for arbitrary ambient pressure, viscosity, and bearing geometry. The nature of the stable motion is indicated. In addition, a simplified criterion and bearing motion are given for low-speed operation. Graphs which show the effect of design parameters on bearing forces are included as an aid in numerical calculations.

63-050 Maloney, R.E. and F.J. Jain.

GAS/BALL BEARINGS. A STUDY OF THEIR INHERENT DAMPING CHARACTERISTICS. USAF Aerospace Fluids and Lubricants Conference, Proceedings, Session IV-B, San Antonio, Texas, April 16-19, 1963. September 1963. AF contract AF 33(657)-11088. pp. 509-516.

A special type of self-acting gas lubricated ball bearing was investigated for the purpose of showing through optical displacement measurement, that the fixed mounting conditions assumed in the theoretical analysis of half-frequency whirl do not exist in the gas/ball bearings, and also to compare experimental results on gas/ball bearings with work done by others on conventional bearings. In the apparatus used for the tests, the rotors consisted of 0.5000 in. diameter shafts, 7.875 in. long, and a 1.2500 in. diameter aluminum turbine. The bearings used were nominal 0.5000 bore with a 0.3125 length and were round and taper-free, within 0.000005 in. Two basic types of test were conducted: (1) with the rotor vertical and (2) with the rotor at 45°. Conclusions

reached are that: (1) gas/ball bearings do not exhibit one half whirl at speeds substantially higher than the theoretical threshold of half-speed whirl in conventional gas bearings, and (2) the continuous following motion of the gas bearing acting on stiff springs (the balls) provides damping.

63-051 Mann, D.B.

REFRIGERATION ANALYSIS AND EXPANDER BEARING RESEARCH.

Fifteenth Progress Report on the Cryogenic Aspects of Project Sherwood. Nat. Bur. Stand. Rep. 7973, October 16, 1963.
pp. 5-9.

Self-acting tilting pad journal bearings and spiral groove thrust bearings were tested and may prove satisfactory for use with high speed turbo expanders. The spiral groove thrust bearing had an O.D. of 0.562 in., and I.D. of 0.32 in., and was 0.14 in. thick. It was made from free cutting phosphor bronze as were the tilting pads for the self-acting journal bearing. Stability, surface finish, balance problems, and cooling of the bearings are briefly discussed. It is noted that in cryogenic applications a small pad design and possibly larger radial clearance could be used to reduce friction HP loss.

63-052 Marsh, Harry.

THE STABILITY OF AERODYNAMIC GAS BEARINGS. Doctoral Dissertation. Cambridge University, England. August 1963.

This dissertation describes an analysis for the stability of aerodynamic gas bearings. The theory is based on only one major assumption, namely that a local linearization may be applied to the pressure field for small dynamic motions. This is a dynamic analysis of bearing behavior which leads to the formation of translational and conical dynamic stiffness matrices. For the aerodynamic gas bearing, these dynamic stiffness matrices can be calculated directly from Reynolds' equation for thin film lubrication. Stability criteria are then derived for translational and conical modes of whirl in both one and two bearing systems. The effect on the whirl onset speed of varying the bearing parameters is described in detail and it is shown that the theory unifies the existing knowledge of gas bearing instability for both modes of whirl. The analysis is then extended to systems with flexible rotors and flexibly mounted bearings, including such problems as the stability of a uniform flexible shaft supported in two aerodynamic gas bearings. To complete this study of bearing behavior, the matrix analysis is used to examine the effect of small dynamic loading. It is shown that a bearing system can give

a large response to dynamic loading not only at about one half of the rotational speed, but also at two other frequencies. The importance of these fluid film resonances is discussed and also their relationship to the phenomenon of inversion for a rigid unbalanced rotor. An experimental verification of the theory is described in detail, including the design of a new form of bearing apparatus. The experimental results confirm the theory and show that it underestimates the whirl onset speed by about four percent.

63-053 Meacher, J.S.

GAS LUBRICATION OF BEARINGS AT HIGH TEMPERATURES. Stratos Division, Fairchild Stratos Corp. Technical Documentary report ASD-TDR-62-634, February 1963. AF contract AF 33(657)8216.

Externally pressurized gas-lubricated journal bearings 1.5 in. in diameter and 2 in. in length and thrust bearings 1.5 in. in diameter were tested with nitrogen as the lubricant gas at temperatures to 1200°F. A variable-inductance type proximity system was applied to the measurement of bearing operating clearances at temperatures up to 1200°F. Clearances were measured under static nonrotating conditions for a wide range of lubricant-supply pressures and bearing loads. Shaft motion was observed during high-speed rotating tests indicating dynamic instability. The effects of lubricant-supply pressure, loading, and temperature on the threshold of instability were recorded. Correlation with theoretical predictions of bearing load capacity, clearance, and whirl threshold was examined.

63-054 Mech, Christian

THE PRIMARY CIRCUIT GAS BEARING CIRCULATORS FOR THE DRAGON REACTOR EXPERIMENT. Dragon Project Report 229. October 1963. Paper presented at: Dragon Project Engineering Symposium, Bournemouth, 21 - 23 October 1963.

Gas bearings developed by Rateau are mainly applied in the manufacture of leak-tight circulators. In the Rateau technique journal bearings with multiple pre-loaded pads and multi-pad thrust bearings with a self-aligning feature are used. The paper gives further an analysis of the circulators used, and a detailed description of their characteristics.

63-055 Michael, W.A.

SMALL TRANSIENT AND PERIODIC SQUEEZE MOTIONS IN PARALLEL GAS FILMS. International Business Machines Corp. Report RJ 197, September 25, 1963. Navy contract Nonr 3448(00).

A perturbation analysis is employed to find pressure in a thin gas film contained between two nearly parallel surfaces. The

method is sufficiently general to allow small but otherwise quite arbitrary time-dependent variations in the separation of the surfaces. Thus film forces and moments may be obtained for periodic or non-periodic motions of either rigid or flexible surfaces. No tangential motion is permitted, however. Special cases treated in detail are several different motions of finite (rectangular) and infinite gas bearings. Time constants for transient effects are estimated.

- 63-056 Michael, W.A.
 APPROXIMATE METHODS FOR TIME-DEPENDENT GAS-FILM LUBRICATION PROBLEMS. Trans. ASME (J. Appl. Mech.), vol. 30 E, no. 4, pp. 509-517. (December 1963).

Solution to the time-dependent Reynolds equation for compressible fluids by several different equation techniques is analyzed from the standpoint of computational stability and speed. The equation is rewritten in terms of a dimensionless variable $\mu = PH$ where P is dimensionless pressure and H is dimensionless film thickness, both functions of position and time. The author concludes that the Crank-Nicolson formula, solved using the Newton-Raphson method, is to be preferred because (1) it is always stable and (2) the computational speed is 40 times or more faster than other methods tested. Algorithms for applying this method to one-dimensional and two-dimensional slide bearings are given. Static, i.e. non-time-dependent, solutions are readily obtained as asymptotic solutions beginning with $P = 1$ at all points in the grid.

- 63-057 Moller, P.S.
 RADIAL FLOW WITHOUT SWIRL BETWEEN PARALLEL DISCS. Aeronaut. Quart., vol. 14, no. 2, pp. 163-186. (May, 1963).

Analysis and experiment are presented for flows of concern to radial diffuser and air bearings. Integral methods (both laminar and turbulent) prove quite adequate when comparison is made with experimental results. The inlet separation bubble and critical Reynolds number are discussed.

- 63-058 Montgomery, A.G.
 IMPROVEMENTS IN OR RELATING TO FREE PISTON COMPRESSORS WITH GAS BEARINGS. British Patent 923,732. (to United Kingdom Atomic Energy Authority). Applied May 26, 1961. Issued April 18, 1963.

This invention relates to free piston compressors incorporating gas bearings for a reciprocating piston and aims to provide a compressor of improved design having the majority of the working parts enclosed within the cylinder casing so as to be particularly suited to the

handling of toxic fluid. The invention comprises a free piston gas compressor in which a reciprocating piston is arranged to compress gas into a reservoir from which a proportion of compressed gas is continuously withdrawn to provide a hydrostatic gas bearing for the piston.

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63-059 Mori, Haruo

A THEORY OF AN EXTERNALLY PRESSURIZED CIRCULAR THRUST GAS BEARING WITH CONSIDERATION OF THE EFFECTS OF LUBRICANT INERTIA. Trans. ASME, (J. Basic Engng.), vol. 85 D, no. 2, pp. 304-310. (June 1963).

An approximate solution of the axisymmetric laminar flow of a viscous gas between two nearby parallel plates is developed. Compressibility is considered as well as inertia of the lubricant. The equation of state of a perfect gas is assumed. The result shows a velocity distribution in the clearance in the shape of an elliptic function rather than the parabolic distribution usually found in other approximate solutions. However little change is found in the load-carrying capacity. The paper is followed by discussion by V. N. Constantinescu.

63-060 Mori, Haruo, Yasunori Miyamatsu and Shigeru Sakata.

RESEARCH ON EXTERNALLY PRESSURIZED CIRCULAR THRUST GAS LUBRICATED BEARINGS. (in Japanese). Trans. Japan Soc. Mech. Engrs. vol. 29, no. 205, pp. 1475-82. (September 1963).

In externally pressurized gas lubricated circular thrust bearings, the occurrence of depression in the pressure profile is observed under some working conditions. Succeeding the previous paper on the theoretical investigation of the pressure depression, the pressure distribution in externally pressurized circular thrust gas bearings with a circular recess is investigated theoretically by assuming the generation of a normal shock wave in the bearing recess. Good quantitative agreement is found between the analytical results and available experimental data except the case of small bearing clearance height or deep recess. In order to prevent the pressure depression just after the gas supply hole, it is effective to make a round or tapered chamber at the entrance edge of the hole to the bearing clearance or to make the recess tapered doubly. By these alternations, the shape of pressure distribution becomes flatter so that the load capacity can increase remarkably.

- 63-061 Mori, Haruo, Toshiyuki Shibayama and Setsuo Kedo.
ELECTROLYTIC ANALOGY OF PRESSURE DISTRIBUTION IN EXTERNALLY-
PRESSURIZED GAS BEARINGS. (in Japanese). J. Japan Soc. Lub.
Engrs., vol. 8, no. 1, pp. 16-20. (1963).

In order to determine, accurately, such quantities as the load-carrying capacity and flow rate in an externally-pressurized bearing, it is necessary to clarify the nature of the pressure distribution. In the case wherein the flow within the bearing clearance is incompressible and viscous, the pressure distribution may be fundamentally expressed by the Laplace equation. Accordingly, the pressure distribution is obtained by the measurement of electric potential through electrolytic analogy. In this paper, the general Reynolds equation, which depends on the compressible lubricant and can take the change of bearing clearance into consideration, is reduced to the Laplace equation with an appropriate transformation, and the pressure distributions of: (1) Externally pressurized thrust collar bearing and (2) Externally pressurized journal gas bearing are obtained by electrolytic analogy, and discussed in comparison with the solution by complex potential theory. Moreover, by making two electrolytic layers of gelatin with different specific resistivities, the pressure distribution of (3) Externally pressurized porous thrust gas bearing is also obtained by electrical analogy. Electric experiments have produced results in good agreement with the solutions by hydrostatic theory.

- 63-062 Mori, Haruo, Toshiyuki Shibayama, I. Shizuma and T. Yamamoto.
RESEARCH ON EXTERNALLY PRESSURIZED JOURNAL GAS BEARINGS. (in English). Bull. JSME, vol. 6, no. 23, pp. 598-605. (August 1963).

In a previous paper by T. Sasaki and H. Mori, the experimental data used in the comparison with theoretical results were for a bearing with a single gas supply hole without restriction. However, it is common to use externally pressurized gas bearings with multiple gas supply holes arranged circumferentially and axially. In this paper, a gas bearing with multiple gas supply holes is designed theoretically and the pressure distribution, flow rate and optimum restriction are examined and compared with the complex potential theory. The experimental results show good agreement with the theoretical results.

- 63-063 Mori, Haruo and Hiroshi Yabe.
COMPLEX POTENTIAL THEORY OF EXTERNALLY-PRESSURIZED, THRUST-COLLAR GAS BEARINGS. (in Japanese). J. Japan Soc. Lub. Engrs., vol. 8, no. 1, pp. 11-15. (1963).

In practice there are many applications of externally-pressurized, thrust-collar gas bearings. It has been reported that a gas bearing with larger recess has higher load carrying capacity, but has

lower dynamic stability. Accordingly, it is preferable to use an externally-pressurized gas bearing of the thrust-collar type without a recess but with a number of gas supply holes arranged circumferentially thereabout. In this paper, the authors analyze externally-pressurized, thrust-collar gas bearings of the above type without a recess and obtain pressure distributions by using the complex potential theory.

- 63-064 Mori, Haruo and Hiroshi Yabe.
THEORETICAL INVESTIGATION OF EXTERNALLY PRESSURIZED THRUST COLLAR GAS-BEARINGS. ASLE Trans., vol. 6, no. 4, pp. 337-345. (October 1963).

Externally pressurized thrust collar gas-bearings with several supply holes are investigated theoretically. The gas supply holes are spaced circumferentially and communicate directly with the film without feeding into recesses. A complex potential function which satisfied the boundary conditions of the bearing is found, and the pressure distribution, quantity of flow, and load capacity are calculated for the two cases where there are or are not radial grooves between the holes. The theory is applicable for any number of gas supply holes.

- 63-065 Mueller, B.K.
A NOVEL GAS BEARING SPHERICAL-ROTOR GYROSCOPE FOR SPACE APPLICATIONS. Paper presented at the American Institute of Aeronautics and Astronautics, Summer Meeting, Los Angeles, Calif., June 17-20, 1963. Paper 63-214.

A gyroscope which deviates completely from the conventional design concept, but does not require exotic new developments or materials is described. The gyroscope element of the spinning-sphere gyroscope consists basically of a solid, homogeneous, spherical rotor, suspended with a spherical outer housing by means of a hydrostatic gas bearing. Discussed are the operating principles, design features, inherent advantages, and test results of the gas bearing spherical-rotor gyroscope with case rotation, and its possible use for vehicle orientation and stabilization in space, for the determination of the vehicle turn axis, and for directional orientation on a lunar surface.

- 63-066 Muster, D. and Beno Sternlicht, Editors.
INTERNATIONAL SYMPOSIUM ON LUBRICATION AND WEAR, Proceedings, Houston, June 1963. McCutchan Publishing Corp., Berkeley, Calif. 1965.

Papers included in this volume are "Inverse Hydrodynamics," by

Blok; "Theory of Turbulent Lubrication", by Constantinescu; "Thin Film Lubrication", by Dowson; "Boundary Lubrication", by Godfrey; "Lubrication of Externally Pressurized Bearings", by Gross; "Inertia Effects in Self-Acting Bearing Lubrication Theory", by Milne; "Influence of Bearings on Rotor Behavior", by Sternlicht; "Friction and Wear", by Tabor; "Thermal Effects and Elasto-Kinetics in Self-Acting Bearing Lubrication", by Vogelpohl; "Gas-Lubricated Bearings", by Ausman; "Design of Fluid Film, Hydrodynamic and Hydrostatic Thrust and Journal Bearings", by Fuller; "Computer Analysis of High-Speed Rolling-Element Bearing Systems", by Jones; "Lubrication in the Environment of Space", by Lewis and "High-Temperature Lubrication", by Peterson.

- 63-067 National Bureau of Standards.
ON THE CRYOGENIC ASPECTS OF PROJECT SHERWOOD. Thirteenth Progress Report, for the period December 31, 1962 to March 31, 1963. Nat. Bur. Stand. Rep. 7677, March 1963.

Aside from an analytical description of the Sherwood project, the report also discusses the successful testing of the redesigned gas-lubricated bearings of the low-pressure turbine system.

- 63-068 National Bureau of Standards.
ON THE CRYOGENIC ASPECTS OF PROJECT SHERWOOD. Fourteenth Progress Report, for the period April 1, 1963 to June 30, 1963. June 3, 1963.

This paper mentions the use of externally pressurized gas-lubricated bearings in a cryogenic turbine expander at speeds of 660,000 RPM.

- 63-069 Ng, Chung-Wah.
LINEARIZED PH STABILITY THEORY FOR FINITE LENGTH, SELF-ACTING, GAS-LUBRICATED, PLAIN JOURNAL BEARINGS. Mechanical Technology, Inc. Report MTI-63TR51, December 1963, Navy contract Nonr 3730(00) (FBM).

Use of Ausman's linearized PH method to determine the threshold of half frequency whirl for a rigid rotor in self-acting cylindrical journal bearings is extended to include finite length effects. Rotating polar coordinates are used to derive the governing equation. Results obtained are generally consistent with several previous works in wide ranges of all parameters. This method is judged to give conservative results and is suitable for studying dynamic problems of more complicated systems.

63-070 Orcutt, F.K.

EXPERIMENTAL INVESTIGATION OF TWO-PHASE FLOW IN THRUST BEARINGS.
Mechanical Technology, Inc. Report MTI-62TR40, January 1963.
Contract Nonr-3731(00) (FBM).

An analytical study is made of two-phase flow in thrust bearings. For all the operating conditions investigated, there is a sharply defined load-carrying limitation for the steam-lubricated bearing beyond which there is a sudden loss of stiffness leading to collapse of the bearing and contact of the surface. Bearing-load carrying capacity and stiffness are strongly dependent on the rate at which heat is withdrawn from the film by the bearing surfaces. Condensate in the form of droplets and streaks forms on the uncooled surface near the outer radius as the load approaches the critical load for collapse of the bearing. The performance of the experimental bearing lubricated with steam is compared with its theoretical performance using a single-phase lubricant having the properties of dry steam. Results indicate that, for a fixed inlet pressure and surface separation, a two-phase bearing has considerably lower carrying capacity. For the bearing configuration used there was very little dependence of bearing performance on rotor speed. Instability was observed occasionally when the shaft was stationary and conditions at onset were such that the bearing was close to the verge of collapse.

63-071 Pan, C.H.T.

GAS LUBRICATED SPHERICAL BEARINGS. Trans. ASME (J. Basic Engng.), vol. 85 D, no. 2, pp. 311-323. (June 1963).

This paper is based on a NASA-AEC supported study (MTI-62TR5, April 1962, 46 p.) of a derivation of the isothermal Reynolds equation. The gas lubricated hemispherical bearing is considered theoretically. First, the isothermal Reynolds equation for a thin film between arbitrary curved surfaces is derived. The equation is then applied to a hemispherical bearing. External pressurization is considered by assuming a "point" source at the pole. The self-acting effects are studied by a perturbation analysis assuming a small displacement ratio of the journal center. Extension to moderate values of displacement ratios is treated by means of the linearized ph method. Numerical results for comparison with other bearing configurations and an earlier analysis are given.

63-072 Parker, K.G.

SHAFT BEARINGS. U. S. Patent 3,110,528. Applied May 14, 1962.
Issued November 12, 1963.

This invention relates to bearings for shafts, more particularly shafts which are intended to be rotated at high speeds, and of the

kind where the shaft is supported within a bearing bush which in turn is rotatably supported within a relatively fixed body, the arrangement being such that when the shaft is rotated the bush will be rotated at a lesser speed (a floating ring bearing). An annular passage for lubricant is defined between the internal periphery of the body and the bush. The annular passage is in register with passages extending through the wall of the bush to the clearance between the latter and the shaft, and there is formed in the body an inlet to the circumferential passage and a substantially tangentially disposed restricted outlet from the passage, the arrangement being such that particles in lubricant entering the annular groove through the inlet will be caused to move outwardly by centrifugal forces and to be discharged through the outlet.

- 63-073 Pears, C.D.
EVALUATION OF TENSILE DATA FOR BRITTLE MATERIALS OBTAINED WITH GAS BEARING CONCENTRICITY. Southern Research Institute. Final Report, May 1963. Contract AF 33(657)-7685.

Using gas bearings to provide uniaxial loading the ultimate tensile strengths of an alumina and a graphite were investigated statistically at 70°F, 1000°F and 1600°F and the strengths correlated with volume, surface finish, and strain rate. Significant correlations were found for the parameters at most levels.

- 63-074 Powell, J.W.
UNBALANCE WHIRL OF ROTORS SUPPORTED IN GAS JOURNAL BEARINGS. Engineer, vol. 216, no. 5609, pp. 145-6. (July 26, 1963).

The resonant speed of cylindrical synchronous whirl of a rotor supported in externally pressurized gas journal bearings is often called the "inversion" speed. At inversion the rotor is said to change from rotation about its geometric axis to rotation about its mass axis. The author describes some experiments in which measurements were made of the amplitude of whirl and phase changes as a rotor was accelerated through its cylindrical synchronous resonance. The results suggest that a spin axis shift takes place which can be described as inversion in bearings of large clearance ratio.

- 63-075 Ramachandra, S.
SHORT BEARING APPROXIMATIONS FOR GAS LUBRICATED BEARINGS. Appl. Sci. Res., vol. 12 A, no. 1, pp. 1-8. (1963).

The Reynolds equation for gas lubricated bearings is solved for a finite journal bearing, applying the approximation of Dubois and Ocuvirk as in the case of normal journal bearings. The results agree with the experimental values for an L/D ratio of one, with the pressure and the load capacity independent of the ratio of specific heats.

- 63-076 Rice, J.R.
NOTE ON NUMERICAL SOLUTIONS FOR GAS-LUBRICATED JOURNAL BEARINGS.
Trans. ASME (J. Heat Transfer), vol. 85 C, no. 2, pp. 187-189.
(May 1963). (Tech. Briefs).

In two papers which appeared in 1961 on the numerical solution of Reynolds equation for finite-length, gas-lubricated cylindrical bearings under static loading, results are quoted which show discrepancies for certain ranges of parameters, where the calculations are more delicate (high eccentricity and bearing numbers). The author has painstakingly repeated the numerical work and looked for possible reasons of discrepancy. He finds that the results of Raimondi are more reliable, though Sternlicht's procedure is faster.

- 63-077 Richardson, H.H. and others.
BASIC APPLIED RESEARCH IN FLUID POWER CONTROL. Massachusetts Institute of Technology. Progress Reports 8998-5,-6 for the period February 1963 - September 1963. Contract AF 33(657)7535.

Technical results are presented and progress in several phases of continuing applied research and development of the design of high-performance fluid control devices for advanced aerospace systems are described. Continued emphasis was placed on pneumatic components and systems capable of performing in wide ranges of temperature and with intense radiation. Current research dealing with a new pneumatic pulse actuation servosystem, a gas-operated accelerometer, the dispersion of transients in fluid transmission lines, compressible dampers, negative stiffness flapper valves, and gas lubricated bearings are also discussed.

- 63-078 Rotron Manufacturing Co., Inc.
DESIGN MANUAL FOR SELF ACTING PLAIN CYLINDRICAL GAS JOURNAL BEARINGS AND THRUST BEARINGS FOR USE IN ELECTRICAL BLOWER MOTORS, FINAL DEVELOPMENT REPORT, PART II, FOR THE DEVELOPMENT OF GAS LUBRICATED BEARINGS FOR USE IN BLOWER AND FAN MOTORS. Report for the period June 7, 1962 - June 7, 1963, June 25, 1963. Navy contract NObsr-87522. AD-413 027.

This manual is a direct outcome of the requirements set forth in BuShips Contract NObsr-87522 and is intended for use in the design of unit type self-acting gas bearings applicable to electrically driven blowers in the 10 to 500 cfm range. The work of preparing the manual was accomplished by the Rotron Manufacturing Company with Prof. D.D. Fuller serving as a consultant on gas bearings. The information contained in the manual has been assembled utilizing the existing available literature for self-acting gas lubricated bearings. Insofar as possible, the data have been verified by additional test data accumulated at Rotron Manufacturing Co. This manual attempts to

provide the user with the latest state-of-the-art information on gas bearing design. The manual contains an analysis of bearing size and load capabilities and bearing stability characteristics. An example is given for each computation to assist the designer in making use of the information. Included in the manual is a section on motor magnetic load influences of a two pole alternating current motor to assist the designer in predicting actual loads.

- 63-079 Sagot, J.
[THEORY OF CYLINDRICAL GAS BEARINGS OF FINITE LENGTH]. SUR LA
THEORIE DU PALIER A GAZ CYLINDRIQUE DE LONGUEUR FINIE. (in
French). J. Mecan., vol. 2, no. 1, pp. 3-19. (March 1963).

An approximate analytical method for first-, second-, and third-order solutions of Navier and continuity equations of hydrodynamic lubrication is given. Values of the third-order solution obtained are in satisfactory agreement with those calculated with purely numerical methods and are valid in the relative bearing eccentricity range $0 < \epsilon < 0.5$, that is, in the working range of gas lubricated bearings.

- 63-080 Sasaki, Tokio, Haruo Mori and Toshio Teshima.
STIFFNESS OF EXTERNALLY PRESSURIZED JOURNAL BEARING. (in
English) Bull. JSME., vol. 6, no. 24, p. 866. (November 1963).

The use of the sliding bearing has been steadily decreasing since the development of commercial rolling contact bearings. But if it were possible to produce an externally pressurized bearing which possesses very high stiffness, then this bearing would have the following desirable characteristics: (1) low frictional torque, (2) very high stiffness, (3) load supportability when not rotating, and (4) smooth operation. Mayer has investigated the production of such a bearing. Research has been conducted on the improvement of static stiffness after his investigation, and the results obtained are as follows: The stiffness obtained from experimental research is qualitatively similar to, but smaller than that obtained from Mayer's theory. When the spool valve was used as the variable external restriction, the bearing stiffness is much greater than that with the fixed external orifice restriction.

- 63-081 Sasaki, Tokio, Haruo Mori and Ryuji Wada.
RESEARCH ON THE DYNAMIC BEHAVIOR OF EXTERNALLY PRESSURIZED AND
CONTROLLED BEARING. (in Japanese). J. Japan Soc. Lub. Engrs.,
vol. 8, no. 5, pp. 330-338. (1963).

Recently, externally pressurized and controlled bearings have been reported by Mayer and others. The bearing employs a variable

restriction in place of the fixed flow restriction in ordinary externally pressurized bearings. The automatic regulation of this variable restriction can improve greatly the static stiffness of the bearing. It is necessary to investigate the dynamic behavior and stability of the bearing for practical use. The dynamic stability should be examined by the Routh-Hurwitz stability criterion of the characteristic equation of the bearing system. In order to find out the fundamental properties of this bearing, the authors discuss the dynamic characteristics, static, initial and dynamic stiffnesses in this paper. Since the complete analysis of the controlled bearing is extremely difficult, lumped parameter analysis is used for the bearing system to analyze the dynamic behavior.

63-082 Schrader, E.W.

LAYER OF AIR ON ROTATING MEMORY DISC FLOATS MAGNETIC HEADS.
Design News, vol. 18, no. 23, pp. 8-9. (November 13, 1963).

Magnetic read/write heads float on a cushion of boundary layer air as the magnetic storage disc rotates. The shape of the multichannel heads maintains the same constant flying gap for each track on the disc. The gap between head and disc is a function of the disc surface speed. At the larger disc radii, where surface speed is greater, an increased force is applied to the head to compensate for the higher surface speed. Air pressure supplies this balancing force. The use of a fixed head for each track, rather than a head-positioning system typically used in other similar storage devices, reduces the access time to a function of rotational speed. Each disc rotates at 1500 rpm. The average access time to any segment of information is 20 msec., and the maximum access time is 40 msec. Each storage module is capable of storing 9.6 million, six-bit, alphanumeric characters. Each read/write head mounts on a flexible flat spring, which, in turn, is rigidly secured to the main head mount casting. The spring allows the head to align itself during landing. An air-actuated plunger pushes the head toward the disc. The spring supplies the force for retracting the head when the air pressure is released.

63-083 Schwartz, A.A.

LUBRICATION REVIEW - DEVELOPMENTS IN BEARINGS AND LUBRICANTS -
A DIGEST OF THE LITERATURE FOR 1960-1961. Trans. ASME, (J. Basic Engng.), vol. 85 D, no. 3, pp. 457-473. (September 1963).

This paper presents a review of developments in the field of gas lubricated journal bearings for the years 1960 and 1961. Articles on dynamic loads, whirl, sliders with liquid and gas films, externally pressurized bearings and bearing design are included.

- 63-084 Sneek, H.J.
 A SOLUTION FOR THE PRESSURE DISTRIBUTION IN A SHORT GAS JOURNAL BEARING. Trans. ASME, (J. Basic Engng.), vol. 85 D, no. 3, pp. 474-5. (September 1963).

It has been verified experimentally by Du Bois and Ocvirk that the short journal bearing ($L/D < 1.0$) with an incompressible lubricant may be analyzed accurately using a simplified Reynolds equation which neglects the flow caused by circumferential pressure gradient. Using the same assumption for short gas journal bearings the simplified Reynolds equation take the form:

$$\frac{\partial}{\partial y} (ph^3 \frac{\partial P}{\partial y}) = 6\mu\omega \frac{\partial}{\partial \theta} (ph).$$

It is generally agreed that an isothermal thermodynamic path-function relates pressure and density in a self-acting gas bearing. If the perfect gas law is used to describe this path, even the simplified equation becomes nonlinear in the dependent variable, P. However, if a certain degree of approximation is acceptable, this difficulty can be avoided. The significance of this analysis is twofold: It permits the computation of the pressure field in a bearing without recourse to the usual linearizations or numerical techniques. As a result, the influence of the various parameters λ , L/D and ϵ can be studied analytically within the limits stated in the analysis; and probably more important, the approximate path function removes the pressure nonlinearity from the Reynolds equation in its most general form; i.e., when the shaft center moves. In view of this, a reexamination of hitherto unsolvable problems in bearing dynamics may prove fruitful.

- 63-085 Snyder, W.T.
 THE NONLINEAR HYDRODYNAMIC SLIDER BEARINGS. Trans ASME, (J. Basic Engng.), vol. 85 D, pp. 429-434. (September 1963).

An analysis is presented of the influence of nonlinear inertia terms in the equations describing the slider bearing. A series solution is obtained which considers the local variation of the inertia terms across the film, as well as in the direction of motion of the slider.

- 63-086 Speen, G.B., and R.C. Turnblade.
 ANISOELASTICITY IN GAS LUBRICATED SUPPORT SYSTEMS. Lubrication Engng., vol. 19, no. 11, pp. 449-56. (November 1963).

The non-linear character of gas lubrication precludes the possibility of truly isoeleastic support. This paper examines a family of isoeleastic gas bearing support systems which are determined by linearizing the gas lubrication support equations. It is suggested that this

family of bearing configurations is minimally anisoelastic when bearing nonlinearity is taken into account. Analytical expressions are developed which obtain a measure of the anisoelasticity introduced by the nonlinearities in practical gas bearing support systems.

- 63-087 Sternlicht, Beno
COMBINED JOURNAL AND THRUST BEARING. U. S. Patent 3,110,525.
Applied November 1, 1960. Issued November 12, 1963.

This invention relates to a combination journal and thrust bearing having a relatively large load-carrying capacity for its size. The end of a shaft is provided with an external journal surface which is coaxial and concentric with the external bearing surface. The shaft is journalled in a bearing housing which envelops the end of the shaft and has both internal and external bearing surfaces operating in load-carrying relationship with both the external and internal journal surfaces on the shaft. New applications for bearings are presented where bearings utilizing low supply pressure lubricant films require large load-carrying areas to support the bearing load. A further requirement is that the improved bearing constructions be capable of withstanding both radial and thrust loading conditions.

- 63-088 Sternlicht, Beno
DYNAMICS OF GAS BEARINGS IN AEROSPACE MANEUVERS. Paper presented at the USAF Aerospace Fluids and Lubricants Conference, Session IV-B, San Antonio, Texas, April 16-19, 1963.

A review of the dynamics of rotor bearing systems for space applications is presented. Several types of system instability that originate in gas lubricated bearings are defined and the bearing fluid film forces are determined. The dynamic phenomena considered include critical speed, synchronous whirl, half-frequency whirl, fractional-frequency whirl, and pneumatic hammer oscillation in the flow system. Some effects of rotor-bearing geometry on instability are examined. Experimental results reported for synchronous whirl and half-frequency whirl agree with theoretical predictions. The conditions for initiation of destructive self-sustained whirl in hybrid bearings are established, and the effects of an increase in load on the onset of fractional-frequency whirl are related to high and low supply pressure.

- 63-089 Sternlicht, Beno and L.W. Winn.
ON THE LOAD CAPACITY AND STABILITY OF ROTORS IN SELF-ACTING GAS-LUBRICATED PLAIN CYLINDRICAL JOURNAL BEARINGS. Trans. ASME, (J. Basic Engng.), vol. 85 D, no. 4, pp. 503-512. (December 1963).

Good agreement has been found between theory and experiment for static

load-carrying capacity, eccentricity ratio, and attitude angle for plain cylindrical journal bearings (fitted with a single 0.020-in. diameter orifice, 3/32 in. long). With $L/D = 1$ and three bearing clearances, indication of minimum speed for the onset of instability has been obtained. Onset of HFW (= half frequency whirl) increases almost linearly with load. For a given rotor mass and bearing clearance the eccentricity ratio at the onset of instability remains virtually constant even though the bearing load is varied. As the bearing clearance increases, so does the eccentricity ratio at onset of instability. There is a clearance at which onset of HFW occurs at lowest speed. *(See General Electric Technical Report as AD-259 957, July 1961, 67 p.)

- 63-090 Stingelin, Valentin
 [THEORETICAL AND EXPERIMENTAL RESEARCH ON GAS BEARINGS].
 THEORETISCHE UND EXPERIMENTALLE UNTERSUCHUNGEN AN GASLAGERN.
 (in German). Zurich Eidgenossischen Technischen Hochschule.
Inst. fuer Aerodynamik. Mitt., no. 32. (1963).

The differential equation of self-acting lubricated bearings is derived. The known exact solutions of special cases of the equation are discussed. Solutions for the equation for the closed gas bearing (without slip-flow) and for the finite width gas bearing (with slip-flow) are derived and explained. Bearing reactions and characteristics are displayed graphically. Lubricating film changes-of-state and the influence of slip-flows on the bearing are discussed briefly. Experimental apparatus, procedures, and results are described.

- 63-091 Stoller, H.M.
 EXPERIMENTAL INVESTIGATION OF GAS LUBRICATED WATER BOUNDARY LAYERS. OTS Technical Report 007-3, May 1963. Navy contract
NOw-60-01111-c. AD-425 217.

Gas lubrication experiments were conducted on two-dimensional and three-dimensional models. Thin films of maximum length of four to six inches were observed on the two-dimensional flat plate model at low water speeds and air flow rates. Comparable length films were observed on the paraboloid-of-revolution model under approximately the same conditions. Additional observations on gas lubrication are presented.

- 63-092 Tipei, Nicolae
 THEORY OF LUBRICATION- WITH APPLICATIONS TO LIQUID AND GAS-FILM LUBRICATION, edited by William A. Gross. Oxford University Press. 1963. 566 pp.

This is an English edition of a book published in Roumanian in 1957

and acknowledged as a significant work on the theory of bearing lubrication, written by Professor Tipei, Head of the Machine and Mechanics Division of the Institute of Applied Mechanics, Bucharest. Dr. Gross, the Editor, is Director of Research Laboratories, Ampex Corporation. The English Edition includes new material and a new chapter on lubrication in turbulent flow. It presents a complete picture of hydrodynamic liquid lubrication and self-acting gas lubrication that will permit application by digital computer. It is illustrated by situations actually encountered in machine design and construction. Three general considerations on friction and the motion of viscous fluids are presented at the beginning, followed by a chapter on lubricants, in which data on different types of lubricants are given. The remaining chapters are concerned with fluid and gas lubrication between solid walls. Important results obtained by other investigators are included but, in the main, the material presented is the result of the author's own experience.

63-093 Turnblade, R.C.

THE MOLECULAR TRANSIT TIME AND ITS CORRELATION WITH THE STABILITY OF EXTERNALLY PRESSURIZED GAS-LUBRICATED BEARINGS. Trans. ASME, (J. Basic Engng.), vol. 85 D, no. 2, pp. 297-303. (June 1963).

In discussing the stability of externally pressurized gas bearings, the author introduced two dimensionless parameters: molecular transit number Δ and bearing Reynolds number N_R . The former, Δ , concerns the elapsed time for a molecule to traverse the bearing, or the time lag in the bearing response to an external perturbation. The latter, N_R , is a number similar to Reynolds number and concerns the rate of mass flow into the bearing. From experimental data, the author has proposed a stability-criterion involving these two parameters. Although some ambiguities remain in the theory because of its wide generality, the paper should be helpful for the researcher in the same field.

63-094 Wernick, R.J. and C.H.T. Pan.

STATIC AND DYNAMIC FORCES OF PARTIAL ARC SELF-ACTING GAS JOURNAL BEARINGS AT MODERATE COMPRESSIBILITY NUMBERS. Mechanical Technology Inc. Report MTI-63TR4, February 1963. Navy contract Nonr-3730(00).

The problem of lubricating self-acting cylindrical journal bearings with half-frequency whirl instability can be solved by an expansion of the fluid film pressure in terms of power series in Λ , where Λ is the bearing compressibility number. This paper extends the method of Galerkin in solving the steady state Reynolds equation for a variety of bearing configurations to include both time dependence and higher order effects of Λ . The results may be applied to the calculation of critical speed rotor response and stability of flexible rotors.

- 63-095 Whitley, Stanley and D.S. Allen.
JOURNAL AND JOURNAL BEARING ASSEMBLIES, U. S. Patent 3,079,203.
(to United Kingdom Atomic Energy Authority). Applied November
2, 1959. Issued February 26, 1963.

A gas lubricated journal and journal bearing assembly is described where the journal bearing has a cylindrical bearing surface having defined therein at each end of the assembly at least one ring of three or more circumferentially extending shallow grooves each having a width less than the arcuate length and each terminating abruptly to create a step. The grooves occupy corresponding arcuate positions in all the rings and have at corresponding ends thereof a hole providing free communication between the grooves and the atmosphere ambient to the assembly.

- 63-096 Wildmann, M.
THE GAS LUBRICATED STEPPED THRUST BEARING. A COMPREHENSIVE
STUDY. Ampex Corp. Report RR-63-2, April 1963. Contract
Nonr-3815(00).

The existing analytical solutions for gas lubricated stepped pads are reviewed and simplified. Experiments performed on gas lubricated stepped pads are described, and the experimental results are used to verify the analytical solutions. Design curves, based on a combination of analytical and experimental results, are presented and a design procedure, including sample calculations, is given.

- 63-097 Yeaple, F.D.
IN SEALED MACHINERY ROTORS RIDE ON GAS. Prod. Engng., vol. 34,
no. 21, pp. 116-23. (October 14, 1963).

Uses, design, advantages and disadvantages of gas bearings are described. Tables give operating requirements and specifications for typical machines. U.S. and foreign manufacturers are listed.

- 63-098 Zajac, Felix and David Small.
A LINEARIZED ANALYSIS AND DESIGN OF AN AUTOMATIC BALANCING
SYSTEM FOR THE THREE AXIS AIR BEARING TABLE. NASA TM X-50177,
April 25, 1963.

The design analysis of an automatic control system to reduce the mass unbalance (torque) of the air bearing table, so as to enable satellite attitude-control-systems testing is discussed. To balance the table to within 5000 dyne-cms or less the torque balance is first set manually in the horizontal position so that the pendulous table has a period greater than 2.0 minutes. Then the automatic balancing system is activated, correcting any imbalance by placing weights on the appropriate axis. In the same manner, the table is

balanced in roll and yaw axes. Analog computer results show the balancing system to be stable. Block diagrams are presented, showing the parameters of the system on all three axes (pitch, roll and yaw). The balancing time for total fine balancing is approximately 10 minutes.

- 64-001 Adams, C.R.
DESIGN AND FABRICATION OF IMPACT DOCKING SIMULATOR AIR BEARINGS.
Paper presented at the 1964 ASLE Annual Meeting, May 26 - 28,
Chicago, Ill. Reprint 64AM 4B4.

Externally pressurized air bearings for a space vehicle docking simulator are discussed. Design considerations for shallow recess step bearings are examined and preliminary design calculations made. Methods for machining the spherical and flat thrust bearings are also described.

- 64-002 Anonymous.
AIR LEVITATES MANEUVERING ASTRONAUTS. Compressed Air Magazine,
vol. 69, no. 1, p. 20. (January 1964).

A jet-propelled, land-based device called the Manned Docking Simulator that will enable space scientists to simulate and perfect techniques of carrying men between earth and orbiting space stations has been developed. The Manned Docking Simulator is built to carry two astronauts plus supplies. It weighs about 1000 pounds, is 7½ feet high and 5 feet wide. The supporting structure is mounted on air cushions, metal discs constructed so that air is expelled at supersonic velocities beneath them causing the simulator to lift a fraction of an inch from the floor. This simulates the frictionless environment of space, and is a close approximation of weightlessness. Test pilots operating the device can pitch, roll, twist, or yaw the vehicle as they go through rendezvous, approach, and connection to a space station.

- 64-003 Anonymous.
MOVING HEAVY LOADS - ON AIR. Engineering, vol. 198, no. 5135,
p. 359. (September 18, 1964).

An ingenious application of the ground effect principle, as used currently in hovercraft, has been made for the handling of freight in containers or on pallets. The system will enable loads weighing many tons to be transferred from vehicle to vehicle or from platform to trailer with just a push of the hands. The basic principle of the method of handling is that air cushions of a size proportional to the weight of the load to be transported are fixed under the container or pallet and fed with low pressure air. The cushions are molded in an oval shape from a durable plastics material. In use, a modest volume of air supplied either by a centrifugal or a positive displacement blower, feeds the center of each cushion; after inflating the cushion and effecting a seal against the supporting surface, excess air supplies the contained air layer that supports the weight of the load and allows easy movement.

64-004 Anonymous.

AIR BEARING CRINDING SPINDLES. Engineer, vol. 217, no. 5644, p. 584. (March 27, 1964).

A high speed grinding spindle with air bearings, which is principally intended for use in bore grinding machines, can be adapted for use on other machine tools. These spindles have an air turbine drive and consume about 9 s.c.f.m. of air at 75 lb./sq. in. and, due to the low viscosity of air, their bearings absorb comparatively little power. Bearing heating is stated to be negligible and no warming up period is required before the commencement of grinding. With air supplied at a pressure of 30 lb./sq. in. the spindle speed is 30,000 rpm, and at 80 lb./sq. in. it is 60,000 rpm.

64-005 Anonymous.

AIR BEARING TORQUEMETER AIDS DESIGN. Engineering, vol. 198, no. 5148, p. 787. (1964).

Accurate torque measurements on model agitators enable predictions to be made for the power requirements of full scale agitators of the type used in the chemical industry. An air bearing torquemeter has been developed by Imperial Chemical Industries Limited for this purpose. The torquemeter utilizes a flat circular table of 10 in. diameter, which floats on an air thrust bearing, and which acts as a support for the model agitator vessel. Concentric location of the table is provided by a vertical air column bearing which also permits the table to rotate about the vertical axis.

64-006 Anonymous.

HONER FLOATS ON AIR PADS TO GRAIN GRIND SMOOTHEST FLOOR.
Engng. News Record, vol. 173, no. 25, p. 119. (December 17, 1964).

General Dynamics engineers developed a honing machine that rides on cushions of air. They leveled two I-beams with polished steel plates on the top flanges to form tracks about ten feet apart. A gantry-like cross-beam rides the tracks on four air cushions. Polished steel plates on both flanges and both sides of the web of the cross-beam are used to form grinding surfaces for four air cushions that support the suspended honing machine.

64-007 Anonymous.

BEARING RESEARCH SPINS ALONG. Iron Age, vol. 194, no. 4, pp. 102-3. (July 23, 1964).

In nuclear power plants, the lubrication of coolant compressors and turbines is complicated by the threat of leakage across the seal between coolant stream and bearing lubricant. However, when the

bearings in a gas-cooled reactor are gas lubricated, they do not require elaborate seals. In fact, the lubricating gas can be the same as the cooling gas. Moreover, temperatures will not present problems. As temperatures soar, oil begins to break down. Gases, on the other hand, lubricate even better as a reactor's coolant stream temperature rises. An analysis was completed recently at The Franklin Institute for predicting the performance of self-acting (hydrodynamic) gas lubricated partial-arc, finite-length, journal bearings for steady-state conditions. The results "can be used for bearings of many types". This analytical work will be followed by experiments on a special test rig to verify underlying assumptions.

64-008 Anonymous.

AIR BEARING SPINDLE. Light Metal Age, vol. 22, no. 7-8, p. 31. (August 1964).

The Model 1300 Nano Stable Air-Bearing Spindle has the capability of turning, microdrilling, boring, and facing to within one micro-inch surface finish, and roundness to less than five millionths inch total indicator runout reading. The variable-speed 1/12-hp motor drives the spindle which is designed as a replacement headstock for the Leven Lathe or it may be mounted on any other suitable base.

64-009 Anonymous.

AIR-TURBINE ROTOR SPINS ON GAS BEARINGS AT 73,600 RPM. Mach. Design, vol. 36, no. 12, p. 8. (May 21, 1964).

A gas bearing speed record was established (it is claimed) with a rotor and supporting gas bearings developed by J.M. Tessarzik and R.C. Elwell of General Electric. The shaft journals are round to within 10-millionths inch of a perfect circle. A special film coating permits dry starts and protects the bearings and shaft until 1000 rpm is attained. At this speed a gas film is established which floats the shaft. The system is being integrated into a high-speed electric motor used to power a cryogenic refrigeration system.

64-010 Anonymous.

HUMAN ENGINEERING. Prod. Engng., vol. 35, no. 21, p. 68. (October 12, 1964).

An air cushion lawn mower weighing 30 lb. is powered by a 2-stroke, $2\frac{1}{2}$ hp Tecumseh engine that lifts the mower clear of the ground at 3100 rpm and holds it at $\frac{1}{2}$ in. above the ground at 3500 rpm. The secret is an impeller attached to the crankshaft above the rotary blade. The impeller raises air pressure under the mower's steel

housing which lifts the unit from the ground and simultaneously holds the grass upright for a smooth cut. Height of cut ranges from 5/16 in. to 1-7/16 in. and is easily altered by changing spacers on the crankshaft extension.

- 64-011 Anonymous.
LUBRICATING GYROSCOPE ROTOR (SPIN-AXIS) BEARINGS. Sci. Lub.,
vol. 16, no. 5, pp. 23-6. (May 1964).

Hydrodynamic gas spin bearings are being developed for flotation gyroscope rotors. Advantages and disadvantages are discussed briefly.

- 64-012 Anonymous.
LONG-LIFE SPACE DESIGNS ARE OUT OF THIS WORLD. SAE J.,
vol. 72, no. 11, pp. 76-85. (November 1964).

One of the most serious problems of gas bearing turbomachinery has been self-excited instability. In order to eliminate this problem as far as possible, the partial arc bearing and composite bearings made up of several fixed or pivoted arcs are generally used for high speed rotating machinery. These bearings either reduce or eliminate tangential forces which produce instability. When the eccentricity ratio is high, partial arc bearings have appreciable load capacity. Often, their threshold of instability more than compensates for the loss of load capacity when compared with the full 360-deg. bearing. The compressibility parameter and the dimensionless load contain gas viscosity as one of the parameters. Most gases have similar viscosities, which increase with temperature. Stability without appreciable loss in load carrying capacity can be enhanced still further by designing bearings that comprise a plain partial arc in the loaded region and that are grooved in the diverging part of the bearing. This grooving serves to eliminate subambient pressures and to generate an applied force that increases the threshold of instability. Experiments were conducted to study load capacity, attitude angle and rotor stability as functions of geometry, ambient pressure, rotor mass, bearing force, rotating unbalance, and other parameters. These experiments demonstrated how increased ambient pressure drastically reduces the whirl onset speed.

- 64-013 Astill, K.N.
STUDIES OF THE DEVELOPING FLOW BETWEEN CONCENTRIC CYLINDERS WITH THE INNER CYLINDER ROTATING. Trans. ASME, (J. Heat Transfer),
vol. 86 C, pp. 383-392. (August 1964).

The present paper is part of the third phase of an investigation of

the phenomena and variables which control the rate of heat transfer in the air gap of a rotating electrical machine. Experimental studies were made in the developing adiabatic flow of air in an annulus having a rotating inner cylinder and stationary outer cylinder. Experiments were made to determine when Taylor vortices, and/or turbulence occurred as a function of Reynolds number of the flow, rotational speed of the inner cylinder, and distance from the inlet. Lines of demarcation of the several modes of flow were established for positions along the axis of the annulus. Two length effects were present: the distance to the point where vortices occurred and the distance required for the vortices to develop. A criterion is presented for determining the point in a developing flow where Taylor vortices originate. The value is given in terms of the dimensionless parameter,

$$\frac{\omega r_1 \delta_0^*}{\nu} \sqrt{\frac{\delta_0^*}{r_1}} > 24$$

A discussion of the occurrence of vortices in well-developed flows is presented.

64-014

Ausman, J.S.

ON THE BEHAVIOR OF GAS-LUBRICATED JOURNAL BEARINGS SUBJECTED TO SINUSOIDALLY TIME-VARYING LOADS. Paper 64-Lub-27 presented at The ASME and ASLE International Lubrication Conference, Washington, D.C., October 13-16, 1964.

Linearized steady-state time-dependent solutions to the equations of journal motion for sinusoidally time-varying radial loads, derived by utilizing the "linearized ph" technique to approximate lubricant pressure forces are presented. An exemplary check for vibration at half-rotor frequency shows that the nonlinear terms can be neglected provided the total eccentricity ratio remains less than one half. A typical journal-bearing frequency response exhibits two distinct types of resonances; one at half-rotor frequency and another at a frequency given by $\sqrt{K/M}$, where K is the effective spring constant due to the bulk modulus of the gas lubricant and M is the mass of the supported rotor. As the static eccentricity ratio increases, the amplitude of the half-rotor frequency resonance decreases drastically, but the amplitude of the $\sqrt{K/M}$ resonance increases slightly. Rotating load response can be synthesized by superimposing the responses to two 90° out-of-phase radial loads acting along perpendicular axes. The resulting response is a nearly circular ellipse centered about the static equilibrium position.

- 64-015 Ausman, J.S.
GAS LUBRICATED BEARINGS. Advanced Bearing Technology,
National Aeronautics and Space Administration, 1964.
pp. 109-138.

A study is made of the problems that are presented by gas lubricated bearings. Analysis is complex because the compressibility of gases makes the Reynolds equation nonlinear. Because of this nonlinearity, no general analytical solution to this equation has been found, and approximate methods of solution invariably rely on some means of linearizing the equation. Some methods for obtaining approximate solutions are discussed. Results are presented in forms intended to illustrate the fundamental nature and behavior of gas lubrication. Typical design curves are also given to serve as guides.

- 64-016 Baldwin, R.G. and S.J. Korzenowski.
THE APPLICATION OF GAS BEARING SPIN MOTORS TO MINIATURE GYROS.
Bureau of Naval Weapons, Rotating and Static Precision Components Symposium, Proceedings, April 1964. pp. 64-92.

The application of gas spin bearings to miniature floated rate-integrating gyros is discussed in some detail. Included in the discussion are the following subjects: (1) basic principles; (2) instrumentation--steady loads and dynamic loads; (3) materials--wear resistance and surface finish; (4) fabrication and assembly; (5) test results--static data and dynamic data; and (6) gyro data--random drift, cool-down stability, run-up stability. It is concluded that the practical application of miniature gas spin bearings to gyroscopes has been demonstrated and documented; random drift characteristics have been improved by an order of magnitude; and mass stabilities have been improved by a factor of three.

- 64-017 Barlow, Edward
AXISYMMETRICAL FOIL BEARING - COMPRESSIBLE FLOW. Ampex Corporation. Res. and Engng. Pub. RR 64-6. June 1964. Navy contract Nonr-3815(00).

The axisymmetrical foil bearing is studied with effects of compressibility being included. The pressure and gap profiles are found by numerically integrating the governing equations. The results are compared with the corresponding results obtained in a previous report on an approximate solution of the same problem assuming incompressible flow.

64-018

Baumann, H.

DESCRIPTION AND PERFORMANCE OF THE PRIMARY CIRCULATORS FOR THE O.E.C.D. HIGH TEMPERATURE REACTOR PROJECT DRAGON, ENGLAND. Rotating Machinery for Gas-Cooled Reactor Application, Proceedings, Gatlinburg, Tennessee, November 4-6, 1963. TID-9690, May 1964. pp. 189-206.

The main coolant circulators for the OECD-High temperature-reactor Dragon at Winfrith in England are totally enclosed blowers with hydrodynamic gas-lubricated bearings. Multiple-wedge bearings with fixed wedges in a cylindrical shell or pad type bearings show a considerably lower load carrying capacity compared with cylindrical bearings with stabilizing wedges. For duties where a high bearing capacity or a large speed range is demanded, it is said that stabilized cylindrical bearings are to be preferred. The necessary manufacturing accuracy of wedge-stabilized cylindrical bearings offers no production difficulties, and permits, on the other hand, the free exchange of any bearing or shaft. The arbitrarily composed parts can be put into service fulfilling all the required conditions, especially the "touchdown" speed and running without signs of wear.

64-019

Baumeister, H.K.

A NOTE ON THE NOMINAL CLEARANCE OF THE FOIL BEARING. Paper presented at the 1964 ASLE Annual Meeting, May 26-28, Chicago, Ill. Preprint 5B5.

An investigation has been made of the magnitudes of the errors introduced into the analytical solution for the nominal clearance of the foil bearing by the assumptions that are usually made. From numerical integrations, it has been concluded that the exact method of specifying the clearance and the exact locations of the ends of the bearing are not critical, and that the assumption of various shapes for the foil will result in erroneous nominal clearance values.

64-020

Bayley, F.J. and L. Conway.

FLUID FRICTION AND LEAKAGE BETWEEN A STATIONARY AND ROTATING DISC. J. Mech. Engng. Sci., vol. 6, no. 2, pp. 164-172. (1964).

An investigation of the flow in a narrow gap between a rotating and a stationary disc with an arbitrarily imposed radial pressure difference is described. This system represents the conditions obtaining between the rotors and casings of many fluid machines. The investigation is mainly experimental, for although the equations of motion were derived for the fluid system in question, these were found not to be tractable for the conditions observed. Experimental results are reported from two separate test series. The first test series

yielded data on the frictional and pressure forces in the system which were obtained in sufficient detail for use in design calculations for fluid machinery. In the second series the flow between the discs was studied in detail in order to explain the nature and form of the results obtained in the first series of tests.

- 64-021 Beams, J.W., Beno Sternlicht and W.F. Hughes.
GAS, MAGNETIC, AND MHD BEARINGS FILLING NEW NEEDS. SAE J.,
vol. 72, no. 3, pp. 72-75. (March 1964).

A simplified explanation of how gas bearings work is presented. The operation of a self-acting compressible fluid (gas) bearing is shown schematically. A "hybrid" bearing (self-acting and externally pressurized) is described. Although a common journal bearing has been used for ease of explanation, many other configurations of gas bearings have been designed and are in use. Among present commercial applications of gas bearings are a high-speed drill, a 24,000 rpm electric fan for cooling electronic assemblies, and control gyroscope assemblies for guidance and control of ballistic missiles and aerospace vehicles. Magnetic bearings are described which offer many of the same advantages of the gas bearings. The basic characteristics of MHD bearings are also discussed.

- 64-022 Benatti, R.J.
GAS BEARINGS FOR GYROSCOPES. Sperry Engng. Rev., vol. 17,
no. 1, pp. 40-5. (Spring 1964).

This paper discusses the parameters affecting the performance of gas lubricated bearings designed to support gyroscope rotors. The gas bearing provides the exacting, positional stability required in the gyro spin axis. Its introduction has improved the long-term drift stability of the SINS gyroscopes by a factor of five.

- 64-023 Benatti, R.J.
GAS BEARINGS. U. S. Patent 3,146,036. Applied May 29, 1962.
Issued August 25, 1964.

This invention relates to an improvement in gas bearings of the hydrodynamic pressure type by which the condition known as half speed whirl is inhibited without a resulting loss in load carrying capacity. A further object of the invention is to provide a gas bearing with a moving element that accelerates through an operational range from lift speed to the design speed of rotation without experiencing the termed half speed whirl. To produce the additional lift provided, the respective end areas of one of the bearing elements includes a plurality of rocket providing channels

in its curved periphery with an open end and an interior end wall. As the rotating element of the primary bearing accelerates above lift speed, the gas compressed in the included end rockets exerts a radially directed secondary positive pressure on the rotating element that produces this result.

64-024

Benedict, R.P.

SOME COMPARISONS BETWEEN COMPRESSIBLE AND INCOMPRESSIBLE TREATMENTS OF COMPRESSIBLE FLUIDS. Trans. ASME, (J. Basic Engng.), vol. 86 D, pp. 527-537. (September 1964).

The degree of approximation made when various common parameters involved in an isentropic, compressible fluid flow are evaluated from incompressible relations is examined. First, compressible and incompressible solutions are derived and presented graphically. Then, ratios between these compressible and incompressible treatments are formed which define various expansion factors; these are tabulated and presented graphically. Several numerical examples illustrate the use of the tables and graphs.

64-025

Bisson, E.E. and W.J. Anderson.

ADVANCED BEARING TECHNOLOGY. NASA special publication SP-35. 1964.

Chapter 5, "Gas Lubricated Bearings", was written by J.S. Ausman. Gas lubricating films remain more nearly isothermal and more nearly laminar than do liquid lubricating films. The validity of the isothermal assumption is verified mathematically. There is a general discussion of self-acting bearings which is divided into two sections, journal bearings and thrust bearings. There is a table showing the optimum number of pads and location of step for maximum load at a compression ratio of 2. The section on externally pressurized bearings is divided into two parts, step bearings and orifice-restrictor bearings. There is also a section on stability. The chapter has 15 references.

64-026

Bowhill, A.J.

METHODS OF MANUFACTURING JOURNAL AND JOURNAL BEARING MEMBERS. U. S. Patent 3,158,924. (to United Kingdom Atomic Energy Authority). Applied May 17, 1962. Issued December 1, 1964. Applied Great Britain May 17, 1961.

This invention describes a method of manufacturing a journal and journal bearing assembly designed for operation with gas lubrication between the journal member and journal bearing member in which, by means of the application of clamping strain during machining, desired variations from true circular geometry may be achieved.

- 64-027 Castelli, V., C.H. Stevenson and E.J. Gunter, Jr.
STEADY-STATE CHARACTERISTICS OF GAS-LUBRICATED, SELF-ACTING,
PARTIAL-ARC JOURNAL BEARINGS OF FINITE WIDTH. ASLE Trans.,
vol. 7, no. 2, pp. 153-167. (April 196

This paper contains the description of a solution of the problem of self-acting, gas lubricated, partial-arc, finite length journal bearings for steady-state conditions. The results can be used for bearings of many types such as simple, fixed, partial-arc, journal bearings (tapered land), axial-grooved journal bearings, pivoted-pad journal bearings, and similar geometric shapes. Sample results are plotted, and their utilization for various bearing types is illustrated by examples.

- 64-028 Castelli, V. and H.G. Elrod, Jr.
SOLUTION OF THE STABILITY PROBLEM FOR 360 DEG. SELF-ACTING,
GAS-LUBRICATED BEARINGS. Paper presented at the ASME Lubrica-
tion Symposium, Cleveland, Ohio, April 28-30, 1964. Paper
64-LubS-10

This is an investigation of the stability of self-acting, gas-lubricating bearings. Two approaches to the solution are presented and their results are compared. The relation is discussed between the present work and other, more simplified, methods available in the literature. The particular case of a 360° journal bearing of infinite length is treated, and the changes necessary to use the same theories with other geometries are pointed out.

- 64-029 Chaboseau, J.P. and Christian Mech.
EXPERIENCE OF SOCIETE RATEAU IN THE CONSTRUCTION AND OPERATION
OF GAS-BEARING COMPRESSORS. Rotating Machinery for Gas-Cooled
Reactor Application, Proceedings, Gatlinburg, Tennessee,
November 4-6, 1963. TID-7690. May 1964. pp. 219-235.

General specifications of a typical gas circulator are given. The most frequently handled gases in such a machine are: helium, carbon dioxide, nitrogen, uranium hexafluoride. A brief survey is made of machines already built by Societe Rateau, those under construction, those undergoing acceptance tests, and those presently being designed. A brief review of engineering problems encountered in the development of the gas bearing system is included. From tests performed, the reliability of hydrodynamic gas-bearings of the tilting pad type has been demonstrated and some local improvements made. Optimum geometries of gas-bearing pads have been determined. As no jacking gas is used, friction resistant materials have been developed and used to improve start-stop conditions. Satisfactory results have been obtained. It is felt that this work provides insurance that high reliability can be obtained with sealed machines using the multi-pad, gas-bearing system and that such machines are now suitable for

industrial operation in a broad range of rotating speeds from 2,000 to 24,000 rpm and power up to 250 HP. No particular problems have been encountered in operating such bearings for pressures varying from 14.7 to 850 psi.

- 64-030 Chaboseau, J.P. and Christian Mech.
DEVELOPMENT OF PROSPECTS FOR MULTI-PAD GAS BEARINGS. Rotating Machinery for Gas-Cooled Reactor Application, Proceedings, Gatlinburg, Tennessee, November 4-6, 1963. TID-7690. May 1964. pp. 263-72.

The performance of gas bearings was explored. The range of bearing characteristics covered by the results is given. Tests on materials are being continued with a view of enlarging the range of gas-bearing applications. Future possibilities for industrial applications are discussed.

- 64-031 Cheng, H.S. and C.H.T. Pan.
STABILITY ANALYSIS OF GAS-LUBRICATED, SELF-ACTING, PLAIN, CYLINDRICAL, JOURNAL BEARINGS OF FINITE LENGTH, USING GALERKIN'S METHOD. Paper presented at the ASME Lubrication Symposium, Cleveland, Ohio, April 28-30, 1964. Paper 64-LubS-5.

This paper is based on a Navy supported study (MTI Technical Report, April 19, 1963, 62 p.) of gas bearings. It is essentially an extension of the work of Chang and Trumpler to the stability study of finite journal bearings using Galerkin's method. Galerkin's method provides an effective technique to solve the time-dependent, nonlinear Reynolds equation, and it lends itself very conveniently to determination of the stability for various operating conditions. Both equilibrium and stability results have been obtained.

- 64-032 Chironis, Nicholas
NEW DATA ON GAS BEARINGS. Prod. Engng., vol. 35, no. 25, pp. 98-101. (1964).

Some of the results of the International Lubrication Conference held in Washington, D.C. in October 1964 are described. Some operating problems continue to bother gas-bearing designers. At the meeting, two types showed exceptional promise in overcoming these obstacles; the herringbone groove type, which is a journal bearing capable of attaining high speeds without showing signs of instability, and the spiral groove type, which can take high thrust loads. The grooving in both of these bearings is very shallow - only a few thousandths of an inch (or less). The new design data, which were presented at the meeting will probably help to expand the range of applications.

- 64-033 Constantinescu, V.N.
[GAS-LUBRICATED BEARINGS SUBJECTED TO VARIABLE FORCES AND VELOCITIES]. SUR LES PALIERS LUBRIFIES A GAZ, SOUMIS A DES FORCES ET VITESSES VARIABLES. (In French). Rev. Roumaine Sci. Tech. Serie Mecan. Appl., vol. 9, no. 2, pp. 263-284. (1964).

Derivation of the equation of pressures for gas-lubricated bearings operating under conditions of variable velocities and forces. Some possible asymptotic solutions of the problem are analyzed. The effect of distances between the bearing surfaces on the lubricant compressibility is considered for the case of radial bearings.

- 64-034 Constantinescu, V.N.
[DETERMINATION OF PRESSURES IN GAS-LUBRICATED BEARINGS CONSISTING OF RECTANGULAR PLANE SURFACES]. DETERMINATION DES PRESSIONS DANS LES PALIERS COMPOSES PAR DES SURFACES PLANES RECTANGULAIRES, ET LUBRIFIES AUX GAZ. (In French). Rev. Roumaine Sci. Tech. Serie Mecan. Appl., vol. 9, no. 1, pp. 145-155. (1964).

The possibility of determining the pressures in bearings consisting of plane surfaces, by using a particular approximate differential equation is examined. For two-dimensional motions, the solutions are obtained in a simple form. The pressure distribution is also deduced in an explicit form for a bearing of finite length consisting of two inclined plane surfaces.

- 64-035 Constantinescu, V.N.
ON HYDRODYNAMIC INSTABILITY OF GAS-LUBRICATED JOURNAL BEARINGS. Paper 64-Lub-24 presented at ASME and ASLE, International Lubrication Conference, Washington, D.C., October 13-16, 1964.

The dynamic behavior of gas-lubricated journal bearings is discussed in the light of the author's general theory of small perturbations which provides equations for motion of two lubricated bodies in a system of Cartesian coordinates. The theory and the stability conditions of two gas-lubricated journal bearings are analyzed at length. A more elaborate theoretical approach is seen to be necessary to differentiate more precisely between different types of instability due to perturbations, oscillations, or their combined effects.

64-036

Constantinescu, V.N.

ON GAS LUBRICATION IN TURBULENT REGIME. Trans. ASME, (J. Basic Engng.), vol. 86 D, no. 3, pp. 475-482. (September 1964).

This paper first analyzes the transient conditions from laminar to turbulent regime for gas lubricated bearings. Then the pressure equation is deduced for self-acting gas lubricated bearings by using Prandtl's mixing length theory. A simple method for determining the pressure and the operating characteristics for bearings operating at high numbers H is given, based on an analogy with the corresponding laminar case. The pressure equation is also given for thrust and journal gas bearings under variable forces and velocities. The last two sections examine the influence of turbulence in externally pressurized gas bearings and the influence of inertia forces, respectively. The results obtained show that the turbulence does not qualitatively alter the operating conditions of gas lubricated bearings. Moreover, the influence of turbulence in self-acting gas bearings is less important than in the case of liquid film lubrication and even negligible when the bearing operates at high numbers H .

64-037

Constantinescu, V.N.

APPROXIMATE DETERMINATION OF THE PRESSURE DISTRIBUTION IN GAS LUBRICATED BEARINGS IN TURBULENT REGIME. (In English). Rev. Roumaine Sci. Tech. Serie Mecan. Appl., vol. 9, no. 4, pp. 771-784. (1964).

The equation of pressures for gas lubrication in stationary turbulent regime has been demonstrated previously to have the same form as in laminar regime, namely:

$$\frac{\partial}{\partial x} \left[\bar{h}^3 \bar{p}^{\frac{1}{x}} \frac{\partial \bar{p}}{\partial x} \right] + \frac{\partial}{\partial z} \left[\bar{h}^3 \bar{p}^{\frac{1}{x}} \frac{\partial \bar{p}}{\partial z} \right] = 6 \tilde{H} \frac{\partial (\bar{p}^{\frac{1}{x}} \bar{h})}{\partial x} \quad (1)$$

where p = pressure, h = thickness of the lubricant layer,
 x = polytropic exponent of the evolution of the lubricant gas,

$$H = \frac{\mu V_0}{p_0 h_m^2} \quad (2)$$

$$\tilde{H} = \frac{k_x}{12} H, \quad \tilde{z} = \frac{\tilde{h}}{h} = \sqrt{\frac{k_z}{k_x}} \quad (3)$$

$\tilde{h}$ = elongation for a great value of H . The present paper points out that with certain corrections the relations for determining pressures remain valid for any H number. This fact is demonstrated

by applying the method of linearizing the equation of pressures for the laminar regime. By means of the results obtained, the operating characteristics of gas lubricated bearings are determined, in relation to their corresponding characteristics in laminar regime.

- 64-038 Constantinescu, V.N.
ON SOME SECONDARY EFFECTS IN SELF-ACTING GAS-LUBRICATED BEARINGS.
ASLE Trans., vol. 7, pp. 257-268. (July 1964).

Analysis of some secondary effects which can influence the operation of self-acting gas-lubricated bearings, such as the effect of the inertia forces, thermal effects, turbulence, and the effect of the molecular character of the flow. In order to point out their qualitative influence, as well as the conditions in which such influences can be important, the case of infinitely long bearings is considered; however, for the computation of quantitative effects, the real case of finite bearings is used.

- 64-039 Crocker, W.S.
APPLICATIONS OF HYDROSTATIC AIR BEARINGS TO METROLOGY.
Massachusetts Institute of Technology, Report R-469,
October 1964. AF contract AF 04(694)-553.

Favorable characteristics of this type of bearing are illustrated by examples. Advantages illustrated are low torque, no stick-slip action, accuracy of rotation, support with negligible loading, stiffness at zero speed, higher range of stiffness under extreme loading, shock resistance, and nearly constant torque characteristics. The bearings are compared with ball bearings. There are two disadvantages: an air supply is required and seismic noise affects delicate readings.

- 64-040 Crowe, W.E.
GAS-BEARING BLOWER MANUFACTURED BY SOCIETE RATEAU FOR THE ULTRA HIGH TEMPERATURE REACTOR EXPERIMENT. Rotating Machinery for Gas-Cooled Reactor Application, Proceedings, Gatlinburg, Tennessee, November 4-6, 1963. TID-7690. May 1964. pp. 365-370.

A helium blower operating on hydrodynamic gas bearings has been manufactured by Societe Rateau for the Los Alamos Scientific Laboratory. This type of blower was selected for use in the Ultra High Temperature Reactor Experiment because of highly radioactive system contamination resulting from the investigation of unclad fuel elements. This blower is designed for the gas cleanup loop through which about one percent of the primary loop coolant will be diverted for the removal of fission products and other impurities. Each of the hydrodynamic journal bearings consist of three 115° arc, tilting pads, preloaded by means of a spring on one pad. The thrust bearing, which handles the major portion of the load, consists of three 60° arc tilting pads. Bearing surfaces

are coated with "Glacier DU", a eflon sintered bronze. All pads are pivoted on tungsten carbide points. Helium in the motor compartment is circulated by means of holes bored in the hollow shaft above the upper bearing. Design features for this blower are also described in report LADC 6093 issued by the AEC Division of Technical Information under contract W-7405-Eng-35.

- 64-041 Crowe, W.E., J.H. Russell and B. Sternlicht.
A REPORT ON THE STATUS OF GAS LUBRICATION FOR TURBOMACHINERY.
Rotating Machinery for Gas-Cooled Reactor Application, Proceedings, Gatlinburg, Tennessee, November 4-6, 1963.
TID-7690. May 1964. pp. 331-364.

Some of the reasons why gas bearings are being applied to specialized turbomachinery are discussed. Several of the factors that must be considered in selection and design are outlined. Also, attention is focused on the limitations of current knowledge and on a number of remaining problem areas. Illustrations are given for rotors supported in self-acting and in externally pressurized gas bearings. These rotors range from a fraction of a pound to several hundred pounds in weight.

- 64-042 Crowe, W.E. and Hans Schwarz.
DEVELOPMENT OF UHTREX GAS-BEARING COMPRESSORS. Rotating Machinery for Gas-Cooled Reactor Application, Proceedings, Gatlinburg, Tennessee, November 4-6, 1963. TID-7690.
May 1964. pp. 253-263.

Two helium blowers operating on hydrodynamic gas-bearings have been developed by Mechanical Technology Incorporated for the Los Alamos Scientific Laboratory. These blower designs were selected for use in the Ultra High Temperature Reactor Experiment because of the highly radioactive system contamination resulting from the investigation of unclad fuel elements. The smaller of the two blowers is designed for the gas cleanup loop through which about one percent of the primary loop coolant will be diverted for the removal of fission products and other impurities. Hydrostatic journal bearings, requiring an external source of 12 psi additional pressure, are used to raise the rotor assembly to avoid wear during stopping and starting intervals when the hydrodynamic bearings are not operating within their design range. Each of the hydrodynamic journal bearings consist of four 80° arc, tilting-pads, which become self-acting at 3600 rpm and have been proven stable up to 14,000 rpm. The thrust bearing has two stationary Whipple groove thrust plates pumping radially inward.

64-043

Dschen, Y.H.

[EXPERIMENTS WITH BEARINGS]. GASDYNAMISCHE LAGER. (in German).
Brown Boveri Mitt., vol. 51, no. 12, pp. 821-832. (December 1964).

New possibilities are given to the designer of machines in many fields by the development of safely operating gas lubricated bearings, especially bearings in high-speed medium weight shafts. A review of the fundamentals and problems of gas lubrication is given. The techniques used by Brown Boveri for the solution of these problems is illustrated by an example of the design of circulating compressors with helium for gas cooled high temperature reactors. For certain applications of thermal turbo machines, considerable simplifications of design and thus technological advantages can be achieved by gas lubricated bearings with the operating gas as lubricating agent. Experiments performed in the Brown Boveri Laboratories show that the principal problems of gas bearings, load capacity and stability, can be solved by the proper shape of the contact surfaces, appropriate design and accurate construction of the bearings. In future developments of gas bearings of larger dimensions, the trend will be towards higher load capacity and lower speed of contact rotation. There will be no change, in all likelihood, in the use of pressurized gas during the short periods of priming and shutdown, because of the increased circumferential speed and bearing load and since no other material can guarantee the same freedom from wear and unlimited working life as the lubricating film generated by the pressurized gas. Based on the experience gained in the construction and the development work of gas lubricated machines and the optimum utilization of the load capacity of the bearings, as explained in this paper, it can be concluded that it is feasible to design safely operating larger turbo machines with gas lubricated bearings.

64-044

Dworski, Juraj

HIGH-SPEED ROTOR SUSPENSION FORMED BY FULLY FLOATING HYDRODYNAMIC RADIAL AND THRUST BEARINGS. Trans. ASME, (J. Engng. Power), vol. 36 A, pp. 149-160. (April 1964).

A hydrodynamic suspension for a 44,000 rpm gas turbine rotor, with emphasis on the interaction between the flexible rotor and its supports is described. Bearings with relatively large clearances are shown to allow continuous operation at the rotor's first critical speed of 22,000 rpm. The apparent absence of hydrodynamic system instabilities is attributed to the use of simple floating-sleeve bearings. A parametric study of the influence of bearing clearance upon vibrational excitation relief is presented, as are test data obtained on actual system hardware.

- 64-045 Dziedzic, J.
[SLOT MEASUREMENT OF A GAS BEARING]. POMIAR SZCZELINY W.
LOZYSKU GAZOWYM. (in Polish). Polish Institute of Nuclear
Research. Report PAN-520/IX. May 1964.

The electronic method of the measurement of the shaft position within the bush is presented. In the case considered, the lubrication of the bearing is performed by use of the gas. The transducers of the throttle type are used to measure the shaft position. Shaft movements cause variations in the impedance of inductive transducers which in turn cause the unbalancing of the a-c bridge of which they are part. The bridge output, in the form of an amplitude-modulated carrier, is supplied to an a-c amplifier and then demodulated and transferred to the plates of a cathode-ray oscilloscope. A plot of shaft movement can be obtained by monitoring the shaft position with respect to the bush in two diameters at right angles and by supplying the demodulator outputs to the X- and Y-plates of oscilloscope. The Telec camera is used to record the shaft movement in the time domain. The record is obtained on the oscillograph film with a time resolution of 0.01 sec. The apparatus can be used for shaft diameter of 2 in. and for rotation of 20,000 rpm.

- 64-046 Ertaud, Andre, Jean Friberg and Pierre Maginot.
AERODYNAMIC BEARING. U. S. Patent 3,143,382. Applied May
29, 1962. Issued August 4, 1964.

This invention relates to aerodynamic (self-acting) bearings comprising a rotary shaft rotating in a bushing with a slight clearance being provided between these two parts. The clearance is fed with a gas under pressure which supports the movable shaft through a "gas wedge" effect similar to the "oil wedge" effect which occurs in plain oil-lubricated bearings. The invention comprises in combination, on the one hand a fine groove provided in the central portion of the internal surface of the stator and on the other hand pumping means permitting exhaustion to be effected at one end of the bearing in such a manner as to subject the end to a "low pressure".

- 64-047 Ertaud, Andre, Jean Friberg and Pierre Maginot.
AIR BEARING. U. S. Patent 3,152,845. Applied May 23, 1962.
Issued October 13, 1964.

This invention consists of a rotatable disc supported by externally-pressurized gas-lubricated bearings in conjunction with an externally-pressurized sphere. Other mechanical refinements are also included. It is claimed that this design results in a low turbine torque and minimum flow rates.

- 64-048 Eshel, A. and H.G. Elrod, Jr.
THE THEORY OF THE INFINITELY WIDE, PERFECTLY FLEXIBLE SELF-ACTING FOIL BEARING. Ampex Corporation. Res. and Engng.
Pub. RR 64-14. December 1964.

The differential equations applicable to the film thickness beneath an infinitely wide, perfectly flexible self-acting tape are derived in this paper. Accurate numerical solutions are obtained for the film thickness in both the entrance and exit regions. These solutions have general applicability to situations where the entrance and exit regions are separated by a third region of uniform thickness.

- 64-049 Eusepi, M.W. and P. Lewis.
RESEARCH ON GAS LUBRICATION AT HIGH TEMPERATURE AND LOW FLOW RATES. Mechanical Technology, Inc. Fifth Quarterly Progress Report, Report MTI-64TR53. September 15, 1964.
AF contract AF 33(657)-10694.

The objective of the program is to develop nitrogen, gas-lubricated, journal and thrust bearings that have the best potential for stable operation over the ranges: Temperature: 80 F to 1900 F; Speed: 0 to 60,000 RPM. This report summarizes the complete experimental work on the 360 degree hybrid bearing including both the inherent and orifice compensation cases. Also included in this report is a summary of experimental work currently in progress on the flex pad bearing.

- 64-050 Eusepi, M.W. and P. Lewis.
RESEARCH ON GAS LUBRICATION AT HIGH TEMPERATURE AND LOW FLOW RATES. Mechanical Technology, Inc. Sixth Quarterly Progress Report, Report MTI-64TR70, December 15, 1964. AF contract AF 33(657)-10694.

The objective of the program is to develop nitrogen, gas-lubricated, journal and thrust bearings that have the best potential for stable operation over the ranges: Temperature: 80 F to 1900 F; Speed: 0 to 60,000 RPM. This report summarizes the experimental work to date on the flex pad bearing. Described also are the efforts which were devoted to readying the equipment for high temperature operation and the start of the high temperature evaluations on the 360 degree hybrid bearing.

64-051

Eusepi, M.W., J.S. Meacher and P. Lewis.

RESEARCH ON GAS LUBRICATION AT HIGH TEMPERATURE AND LOW FLOW RATES. Mechanical Technology, Inc. Fourth Quarterly Progress Report, Report MTI-64TR-35, June 25, 1964. AF contract AF 33(657)-10694.

In the program to develop nitrogen, gas-lubricated, journal and thrust bearings with stable operation over a speed range, two bearing concepts were selected for experimental work--the 360° inherently compensated hybrid bearing and the flexure-mounted hybrid pad bearing. The test program and the results of tests completed to date are given for the inherently compensated bearing, and the assembly drawings for the pad bearing are presented. A complete description of the test facility is included.

64-052

Evans, J.L.

MODIFIED GAS BEARING IS ADJUSTABLE TO OPTIMUM STIFFNESS RATIO. NASA Tech. Brief 64-10050. August 1964.

The problem was to provide a rapid, inexpensive means for accurately adjusting the radial-to-axial stiffness ratio of a spherical gas bearing conventionally used in certain instruments. This type of bearing consists of a rotor with concave spherical inner surfaces that are positioned by a layer of gas in a small annular gap around the convex surface of a sphere. Pressurized gas is fed into the gap by two series of orifices located at equal latitudes on each side of the equatorial plane (perpendicular to the bearing spin axis) through the sphere. The stiffness, or resistance to change in gap width as the load varies, is provided by the regulating effect of gas-pressure variations in the gap. The restoring forces tending to maintain a uniform gap around the sphere can be resolved into radial and axial components, which in many instrument applications must be kept nearly equal. In the unmodified bearing, the stiffness ratio is primarily a function of the bearing geometry, and changes in this ratio can be made only by precise machining of these parts. The solution of the problem was to add a series of gas passages in the equatorial plane of the sphere which feed into orifices that can be readily changed in size to provide the desired stiffness ratio. The gas passages and orifices are machined at uniform intervals along the equatorial section of the sphere. The effect of the equatorial orifices is to increase the stiffness ratio by changing the radial stiffness without changing the axial stiffness. The magnitude of this effect can be varied by plugging some of the equatorial orifices or by changing

their size. Both methods of changing the orifices may be used simultaneously to provide considerable flexibility in adjusting the stiffness ratio of the bearing.

54-053 Feldmeier, J.R.

BEARING RESEARCH SPINS ALONG. Iron Age, vol. 194, no. 4. pp. 102-3. (July 23, 1964).

Research work on hydrostatic, gas-lubricated, and partial fluid film bearings, rolling element bearings and metal-elastomer bearings is briefly reported. At the Franklin Institute Laboratories, Philadelphia, digital computer programs which require fewer assumptions were developed to provide design data for hydrostatic bearings. Analysis was completed for predicting performance of self-acting (hydrodynamic) gas-lubricated, partial-arc, finite-length journal bearings at steady-state conditions.

64-054 Ford, G.W.K.

THE PLACE AND SCOPE OF GAS LUBRICATION. Gas Lubricated Bearings, edited by N.S. Grassam and J.W. Powell. Butterworths, 1964. pp. 3-24.

Topics discussed include classes of gas bearings, advantages, and size limitations.

64-055 Ford, G.W.K.

GAS LUBRICATION IN SPECIALIZED MACHINES. Engineering, vol. 198, no. 5135, pp. 369-371. (September 18, 1964).

The two main classes of fluid film bearings are described. Gaseous lubricants score over liquids mainly because of the almost unlimited usable temperature range and their low viscosities. Since gas viscosities increase with temperature, and bearing performance consequently improves, the converse of liquids, the upper temperature limits depend only upon the bearing material. The self-acting bearing has usually been selected for application as a gas circulator because it avoids the need for compressing the gas for the bearing feed and for disposing of the exhaust. Other applications, such as in liquid pumping, machine tools and digital computers are discussed.

64-056 Foster, D.J.

AN ANALYTIC DESCRIPTION OF MEANS FOR STABILIZING A HYDRODYNAMIC GAS BEARING. Paper 64 - Lub-23 presented at ASME and ASLE, International Lubrication Conference, Washington, D.C., October 13-16, 1964.

A bearing design which introduces damping at the half-rotational

frequency is described. Hydrodynamic plain journal bearings with compressible lubricants have failed under smaller dynamic loads than those that were predicted by static analysis. Perturbation of the time-dependent Reynolds' equation shows that, for the plain journal bearing, there are two principal resonant frequencies in the cylindrical mode, and three in the conical mode. The lowest resonant frequency in both modes, which occurs at one-half rotational speed, makes the plain journal bearing unsuitable for application in vibration environments. General performance curves for the new bearing are shown for the static load-carrying capacity and damping factor as functions of the bearing's parameters. Data for these plots were obtained from a two-speed analog-computer study, in which pressure distribution around the bearings was repeatedly calculated while motion of the rotor was continuously simulated.

64-057

Freeman, A.P.

CONSTRUCTION AND TESTING OF GAS BEARING GYROSCOPES.
Massachusetts Institute of Technology. Informal Monthly Letter Report No. 45, for the period June 1-30, 1964.
Contract NObs-78136, July 15, 1964.

The major effort of the program was directed toward constructing and testing of gas-bearing gyroscopes. Special effort was made to increase the slew capability of the fifth gyroscope wheel package by grooving two chrome oxide inners 0.014 in. wide. An alternative method of heat exchange for the oil in the E-test station was adopted. It consists of tapping chilled water (28°F) from a nearby air-conditioning unit and piping it directly into the heat exchanger.

64-058

Fricker, H.W.

DRY FRICTION IN GAS BEARINGS AND SHAFT SEALS. Rotating Machinery for Gas-Cooled Reactor Application, Proceedings, Gatlinburg, Tennessee, November 4-6, 1963. TID-7690.
May 1964. pp. 106-120.

Various materials for gas bearings were tested for frictional properties and start-stop performance. Sintered bronze impregnated with PTFE gave low friction and wear at medium temperatures. Carbon, lubricated with MoS_2 , gave low wear and friction up to high temperatures (600° C) and freedom from seizure. Start-stop performance was determined by continuous running plain bearing tests. Hard chrome against cast iron (Meechanite) gave very unsuccessful results. K-monel against hard chrome showed some improvement and S-monel-hard-chrome gave acceptable performance. The best performance was given by sand or vapor blasted, MoS_2 -treated nitrided steel against nitrided steel. These tests were carried out in an inert atmosphere, mostly helium, of high purity. Water vapor concentrations were between 10 and 20 volume parts/million (vpm) and oxygen below 10 vpm.

64-059

Fricker, H.W.

THE CHOICE OF BEARING MATERIALS. Gas Lubricated Bearings,
edited by N.S. Grassam and J.W. Powell. Butterworths, 1964.
pp. 181-202.

The need for a material combination with a good rubbing behavior is stressed since it is not possible to guarantee contact-free running at all times. Design and operation factors must be taken into account as well as material properties such as machinability, physical and metallurgical stability, strength and elasticity, thermal conductivity and expansion, chemical stability, and gas permeability. These are discussed. Suitability of various materials, surface treatments, and material combinations are investigated. Promising materials include: Glacier, DU, PTFE, carbon, and dry lubricant films.

64-060

Grassam, N.S., Editor.

GAS LUBRICATED BEARINGS. Edited by N.S. Grassam and J.W. Powell.
Butterworths, 1964. 309 pp.

This work is based on a three day course of lectures and discussions on the design, manufacture and operation of gas lubricated bearings organized by the editors in the Department of Mechanical Engineering of the University of Southampton in March, 1963. But this is not merely a reprint of the papers then presented. The lecturers at this course have co-operated with the editors and have expanded and developed their subject matter, while also obviously taking note of points raised in the discussions. Chapter 1, by G.W.K. Ford (U.K. A.E.A., Winfrith) deals with the Place and Scope of Gas Lubrication. Chapter 2, by D. Pantall (U.K.A.E.A., Winfrith) deals with the Design of Aerodynamic Bearings and includes calculations of load-carrying capacities, tilted pad journal bearings, disc thrust bearings, safety factors, etc. Chapter 3, by S. Whitley (U.K.A.E.A., Capenhurst) deals with Instabilities in Self-acting Bearings and covers synchronous shaft vibrations, etc. An appendix dealing with the stability of aerodynamic bearings has been included in this chapter. This outlines new theoretical work by Dr. H. Marsh at the University of Cambridge and represents a breakthrough in the problem of half-speed whirl. Chapter 4 by G.L. Shires (U.K.A.E.A., Winfrith) on the Design of Externally Pressurized Bearings covers theory and discusses the influence of jet configuration on journal bearings, effect of expansion and deceleration on pressure profile near the jet, etc. Chapter 5 on Dynamic Characteristics of Externally Pressurized Bearings, by J.W. Powell (Micro-Turbines Developments Ltd.) deals with such subjects as synchronous unbalance whirl, fractional speed whirl, measurement of radial stiffness and damping, pneumatic instability, etc. Chapter 6, by the same author, covers the Hybrid Gas Journal Bearing covering load capacity and stability. The second section of the book is devoted to Manufacture and Development. Chapter 7, by H.W. Fricker (O.E.C.D. Dragon Project) deals with the influence of

material properties, material combinations and selection. Chapter 8 by D. Pantall concerns itself with General Production Methods, including inspection methods. Chapter 9 by K.R. McLachlan (University of Southampton) on Techniques of Measurement discusses transducers, and electronic equipment. The third section is devoted to Some Specialized Applications. Chapter 10, by A.G. Patterson (Admiralty Compass Observatory) on Precision Bearings for Gyros, and Chapter 11 on the Applications of Externally Pressurised Air Bearings to Measuring Instruments and Machine Tools, by H.L. Wunch (East Kilbride) cover between them, typical practical examples of the use of these bearings. To avoid overweighting the book with mathematics, the fundamental equations have been given but the often lengthy intermediate derivations have been omitted. The book is profusely illustrated with photographs, graphs, and line drawings. The bibliography refers to 375 papers and articles on gas bearing lubrication.

64-061

Gray, D.L.

TESTS USING HYDROSTATIC GAS BEARINGS. Rotating Machinery for Gas-Cooled Reactor Application, Proceedings, Gatlinburg, Tennessee, November 4-6, 1963. TID-7690. May 1964. pp. 303-312.

Two requirements led to the present hydrostatic gas bearing experiment. One was the need for a very sensitive balancing method for rebalancing the Bristol Siddeley rotary assemblies after maintenance activities. The successful design and operation of the balancing machine gave confidence that a circulator for the now defunct Pebble Bed Reactor Experiment could be designed and built on ORNL. The test bed was assembled before procurement was stopped. Experimental apparatus is described and there is a section on experimental results. There are five figures.

64-062

Grossman, N., J.P. McGee, H. Schwarz and Beno Sternlicht.

GENERAL CONSIDERATIONS IN THE APPLICATION OF GAS BEARINGS TO LONG LIFE TURBOMACHINERY. Paper 871E presented at SAE and ASME Air Transport and Space Meeting, New York, N.Y., April 27-30, 1964.

The application of gas bearings to turbomachinery, in particular the mechanical considerations and test results for a high-temperature gas bearing compressor, is discussed. The advantages of using gas bearings in turbomachinery are: no contamination of the system environment by the lubricant, operation over a wide temperature range, resistance to thermal break-down of the lubricant, resistance to damage by radioactivity, high reliability and long life, elimination of lube oil systems, and increased overall efficiency. Turbomachinery employing gas bearings is necessary in nuclear and space fields where high reliability, long life, and zero contamination

requirements prevent the use of ball bearings, liquid lubricants, and seals. The two categories of gas bearings, self-acting (hydrodynamic) and externally pressurized (hydrostatic), are discussed and compared on the basis of load-carrying capacity, maximum stable speed, starting torque, materials compatibility, and necessary auxiliary equipment.

- 64-063 Gunter, Jr., E.J.
THE STABILITY OF A FLEXIBLE ROTOR SUBJECTED TO ROTARY DAMPING.
Rotating Machinery for Gas-Cooled Reactor Application, Proceedings,
Gatlinburg, Tennessee, November 4-6, 1963. TID-7690.
May 1964, pp. 313-330.

One aspect of the problem of rotor stability and certain system characteristics which influence rotor motion are discussed. This analysis shows the effect of foundation or bearing housing flexibility on rotor stability. In the original experimental investigation, it was found that decreasing the foundation flexibility and introducing damping into the foundation has an extremely beneficial effect on the whirl threshold. From a stability plot, it is seen that a reduction in the foundation flexibility will increase the flexibility ratio, R , and reduce the system critical speed. If the damping parameter, D , is less than 2, the effect of increased foundation flexibility will increase the whirl threshold speed.

- 64-064 Gunter, Jr., E.J., J.G. Hinkle and D.D. Fuller.
THE EFFECTS OF SPEED, LOAD, AND FILM THICKNESS ON THE PERFORMANCE OF GAS-LUBRICATED, TILTING-PAD JOURNAL BEARINGS.
ASLE Trans., vol. 7, pp. 353-365, (1964).

This paper deals with the effects of lubricant compressibility on the pressure profile and total load capacity in a partial journal bearing; pivot pressure as a measure of shoe load capacity; shoe friction characteristics; and optimum shoe clearance ratios for various speeds. The parameter Λ is used as an indicator of the compressibility effect of gas in the bearing clearance.

- 64-065 Gunter, Jr., E.J., J.G. Hinkle and D.D. Fuller.
AN INVESTIGATION OF PRESSURE DISTRIBUTION IN GAS-LUBRICATED, TILTING-PAD, JOURNAL BEARINGS FOR HIGH-SPEED ROTORS. Rotating Machinery for Gas-Cooled Reactor Application, Proceedings,
Gatlinburg, Tennessee, November 4-6, 1963. TID-7690. May 1964.
pp. 273-302.

One phase of the research program involving both theoretical and experimental aspects of the performance characteristics of pivoted-pad bearings is reported. Two experimental rotor test rigs were

developed: the one of concern here involves self-acting, gas-lubricated bearings. The basic theoretical background for the partial journal bearings has come from an associated program sponsored by the Office of Naval Research. This has produced a computer program for partial journal bearings, the results of which have been used for the analysis of the tilting-pad journal bearing. The paper covers experimental apparatus, theoretical foundations, a discussion of pressure distribution in the bearing, effect of compressibility on pressure profile, pivot pressure, and finally, a correlation of experimental and theoretical performance characteristics.

- 64-066 Gunter, E.J., J.G. Hinkle and D.D. Fuller.
DESIGN GUIDE FOR GAS-LUBRICATED TILTING-PAD JOURNAL AND THRUST BEARINGS WITH SPECIAL REFERENCE TO HIGH-SPEED ROTORS. Franklin Institute Research Laboratories. Report I-A2392-3-1, NYO-2512-1, November 1964. AEC contract AT(30-1)-2512.

This report contains the results of a theoretical and experimental program of investigation conducted at The Franklin Institute on high speed rotors supported by gas-lubricated, tilting-pad journal and thrust bearings. Detailed field maps of performance characteristics of the tilting pads are included along with associated design aspects of the problem to permit the analysis and optimization of a rotor support system. The text contains 94 figures and design charts and 18 numerical examples.

- 64-067 Herrman, A.L., R.E. Beyer and H.K. Naumann.
GASEOUS BEARING. U. S. Patent 3,137,531. Applied August 14, 1961. Issued June 16, 1964.

This invention relates generally to gaseous bearings and especially to a gaseous bearing of the ball and cup type. The bearing described is designed for use in the support of loads where minimum friction is desired. The angular freedom of motion of the spherical air bearing is ± 120 degrees in the pitch and roll axis and unlimited freedom in the yaw axis. The support housing contains a vertically movable cup of a pedestal configuration. Metallic contact between the ball and cup are substantially eliminated by employing a support ring for carrying the weight of the ball when the air pressure is turned off. A means is provided for greater stability in an air bearing by having an air outlet port at or near the center of the bearing cup.

64-068 Hirs, G.G.

THE LOAD CAPACITY AND STABILITY CHARACTERISTICS OF HYDRODYNAMIC GROOVED JOURNAL BEARINGS. Paper 64 LC -24 presented at ASLE and ASME, Lubrication Conference, Washington, D.C., October 13-16, 1964.

The resultant pressure components and the stability characteristics of three grooved-bearing types are determined. The determination is made for the case of near-center operation and noncompressible lubricants. Bearing parameters are optimized in search for the best stability characteristics. Behavior at greater eccentricities and the use of gaseous lubricants are dealt with qualitatively. The experimental results are found to agree with theory. Grooved journal bearings are found to have good and predictable stability characteristics. It is concluded that the grooved bearings can be stable at center and near-center operations, while plain journal bearings are not stable for that case.

64-069 Johnson, H.I. and O.A. Wobig.

PNEUMATIC POWER IS TRANSMITTED THROUGH AIR BEARING. NASA Tech. Brief 64-10141. July 1964.

There was a problem in providing an efficient system for simultaneously delivering high-pressure air to an air bearing and to pneumatic equipment mounted on a structure supported by this bearing. Conventional methods for supplying pneumatic power to a movable structure on an air bearing require compressed-air bottles on the structure or the piping of air from a remote location using a flexible hose or rigid passages with rotary seals. The use of air bottles adds excess bulk to the structure and also causes time to be lost when it is necessary to replace the bottles. Flexible hoses restrict the amount of freedom of the structure, and sealed rotary joints introduce undesirable friction. The solution to the problem was a system employing a conventional air bearing and an air-supported sphere with a central passage that channels high-pressure air to pneumatic equipment housed on the sphere.

64-070 Laub, J.L. and Frank Batsch.

ELASTIC ORIFICE AUTOMATICALLY REGULATES GAS BEARINGS. NASA Tech. Brief 63-10123. June 1964.

Recent trends in machine-tool and instrumentation technology have placed increasing emphasis on the development of externally pressurized liquid bearings to obtain performance characteristics that are difficult to achieve with rolling contact bearings. Liquid bearings are inherently capable of providing smoother operation than rolling-contact bearings, and eliminate the need for special lubricants that must remain effective in extreme environments (e.g., under high

temperatures or vacuum). They have many limitations, however, among which is a high frictional resistance at high speeds. Gas lubricated bearings, on the other hand, have low frictional resistance at high operating speeds, but their use has been limited because of their relatively high power consumption (gas pressure x orifice area x gas velocity) and low stiffness, especially at higher bearing loads. A further limitation is that these bearings have high efficiencies and optimum characteristics only at the loadings for which they were designed, since at high loads not enough gas flows for lubrication and at low loadings flows are excessive. Thus, a method for automatic control of gas flow was sought in order to permit bearings to be operated over wide ranges of loadings and speed. The solution to the problem was the use of an elastic, pressure-sensitive orifice to regulate the rate of gas flow into the bearing under varying loads. Orifices of this kind, in comparative tests with fixed orifices, appear to be more stable and provide greater bearing stiffnesses (especially at higher loads), lower power consumption, and greater load-carrying capacity per unit of power consumption.

- 64-071 Lewis, P. and J.S. Meacher.
 RESEARCH ON GAS LUBRICATION AT HIGH TEMPERATURES AND LOW FLOW RATES. Mechanical Technology, Inc. Technical documentary report APL TDR 64-56. March 1964. AF contract AF 33(657)-10694.

This report describes the first year's effort to develop nitrogen, gas-lubricated, journal and thrust bearings that have the best potential for stable operation at temperatures to 1900°F and speeds to 60,000 rpm with low flow rates. The report summarizes materials selection, bearing types, equipment design, instrumentation, and experimental work. Pivoted pad hybrid and flexible mounted hybrid pad bearings seemed most suitable. Load capacity and gas flow are considered and stability studies are described. Growth and changes in geometry are examined. Design procedure for a flexure mounted bearing pad is described. Materials were evaluated and the molybdenum alloy T2M was selected from standpoints of cost, machinability, and possibility of making minor changes after finishing. Boron nitride was selected as a possible sacrificial bearing material.

- 64-072 Licht, Lazar and J.W. Cooley.
 DYNAMICS OF EXTERNALLY PRESSURIZED SLIDERS WITH INCOMPRESSIBLE AND COMPRESSIBLE FILMS. Trans. ASME, (J. Basic Eng'g.), vol. 86 D, no. 2, pp. 396-404. (June 1964).

The ability of an externally pressurized slider to follow faithfully the runout, or waviness of a rotating disk, or drum are investigated. The response and the stability of the slider are considered in terms of small displacements from the equilibrium gap width. The first

part of the analysis treats the case of an incompressible lubricant. The dynamic Reynolds equation is integrated with respect to the space coordinate and the relative displacement of the slider is described by a nonlinear, second-order differential equation. Perturbation solutions are obtained, which permit successive approximations of small deviations from the equilibrium gap width. The second part of the analysis treats the case of a gaseous lubricant. A quasi-static variation of the pressure field is assumed and the problem is stated in terms of lumped parameters. The continuity equation and the equation of motion are linearized, yielding a third-order differential equation for small displacements of the slider from the equilibrium gap width. Results are discussed, with particular reference to the effect of the squeeze number, σ , on the response of the slider.

- 64-073 Licht, Lazar and K.K. Kaul.
EFFECT OF MISALIGNMENT ON A CIRCULAR, EXTERNALLY PRESSURIZED GAS LUBRICATED BEARING. Trans. ASME, (J. of Appl. Mech.), vol. 31 E, no. 1, pp. 141-143. (March 1964).

In their brief note the authors develop an intensive mathematical analysis as a way of furnishing means of estimating effects of misalignment of externally pressurized bearings. It is recognized that the problem is mathematically complex and that, so far, attempts have been made to predict the dynamic response from static bearing characteristics. However, the problem finds frequent applications in systems where the prediction of their dynamic response is of great importance. To analyze this prediction was the scope of the authors brief note.

- 64-074 Lindner, B.M.
BEARINGS. U. S. Patent 3,140,853. (to Alvac International, Inc.). Applied March 28, 1960. Issued July 14, 1964.

This patent deals with a form of hemispherical, externally-pressurized, gas-lubricated bearing incorporating a number of novel mechanical configurations.

- 64-075 Lord, R.G.
THE AERODYNAMIC RESISTANCE TO A ROTATING SPHERE IN THE TRANSITION REGIME BETWEEN FREE MOLECULE AND CONTINUUM CREEP FLOW. Proc. Roy. Soc. London (A), vol. 279, no. 1376, pp. 33-49. (May 12, 1964).

An experimental and theoretical study has been made of the aerodynamic drag torque on a sphere rotating in a rarefied gas. The drag torque on a magnetically suspended polished steel sphere rotating in air was measured over a wide range of Knudsen numbers

from continuum to free molecule flow and for several different Mach numbers up to Mach 1. The drag under free molecule conditions was found to be consistent with the assumption of perfectly diffuse reflection of molecules at the surface of the rotor. An approximate theory is derived which is analogous to Millikan's solution to the problem of plane Couette flow and is valid for low Mach and Reynolds numbers. Theory and experiment are found to agree to within 10% in the range investigated, for Reynolds numbers less than 20.

64-076

Los Alamos Scientific Laboratory.

QUARTERLY STATUS REPORT ON ULTRA HIGH TEMPERATURE REACTOR
EXPERIMENT (UHTREX) FOR PERIOD ENDING MARCH 20, 1964.
Report LAMS-3069. April 1964.

Performance data on the bearings operating in the prototype coolant loop blower for an ultra high temperature reactor are included in this report. After 138 hours of operation, a few minor scratches were observed on the front shaft bearing and journal pads, but there was no significant wear on any bearing surface. After one start, the rotor began to whirl immediately and caused the shaft to bounce against the journal pads. Attempts to stabilize the hydrodynamic film by hydrostatic jacking and speed change were unsuccessful. After the rotor had stopped a subsequent start was successful. It appears that starts must be monitored with bearing orbit instrumentation and that hydrodynamic film instability cannot be cured while the blower is running. After the third test the following observations were made: the thrust runner had scraped and shorted out one of the probes used for determining separation distances, this left a scratch on the surface of the runner; the journal pads were scratched through the "electrofilm" plating in several places and the two front bottom pads were worn through the plating to bare metal at the leading edges. Most of this damage probably occurred when a stable hydrodynamic film failed to form during the start.

64-077

Lund, J.W.

THE HYDROSTATIC GAS JOURNAL BEARING WITH JOURNAL ROTATION AND VIBRATION. Trans. ASME, (J. Basic Engng.), vol. 86 D, no. 2, pp. 328-336. (June 1964).

This paper analyzes the load-carrying capacity of the externally pressurized gas journal bearing, including the effect of journal rotation and vibration. The analysis assumes small eccentricity ratio and small vibration amplitude such that a first-order perturbation solution is obtained. The gas is fed to the bearing through orifice-restricted feeding holes around the circumference in one or two feeding planes. The number of feeding holes is sufficiently large to permit treating the feeding planes as line sources. Results are given for the load-carrying capacity and the attitude angle.

64-078

Lynch, R.J.

EVALUATION OF THE STRATOS MODEL GBN100-1 AIR CONDITIONING TURBINE FAN ASSEMBLY (PART 103430) INCORPORATING AIR LUBRICATED BEARINGS. Naval Air Engineering Center. Final Report, Report NAEC-AEL-1771, July 29, 1964.

The objective of this evaluation was to determine the feasibility of air lubricated bearings for service use in aircraft air-conditioning turbine fan assemblies as an improvement in reliability over the conventional ball bearings currently in use. A turbine fan assembly developed for, but since discontinued for use in, the A-6 aircraft, was employed. A limited evaluation program indicated the air bearing configuration used in the assembly would require considerable additional development work before an adequate determination of the feasibility of air-lubricated bearings would be possible. The design maximum assembly speed was 80,000 rpm, but failure occurred at 58,000 rpm after a brief operating period. It is recommended that additional development work be discontinued pending the outcome of current gas-lubricated-bearing investigations noted in this report.

64-079

McLachlan, K.R.

TECHNIQUES OF MEASUREMENT. Gas Lubricated Bearings, edited by N.W. Grassam and J.W. Powell. Butterworths, 1964. pp. 219-238.

Electronic techniques are discussed. Transducers suitable for gas bearing work are examined. Included are displacement transducers - capacitance and inductance type, force transducers, piezo-electric type force transducers, velocity and acceleration transducers, and force generators. Electronic equipment discussed includes Wayne Kerr Vibration Meter, cathode follower, photo-electric circuits, speed measurement, and phase measurement. Examples illustrating use of the various techniques and equipment are included.

64-080

Ma, J.T.

AN INVESTIGATION OF SELF-ACTING FOIL BEARINGS. Ampex Corporation. Res. and Engrg. Pub. RR 64-3. March 1964. Navy contract Nonr-3815(GO).

Experimental results on the interior and exit region film thickness measurements of self-acting foil bearings are presented and discussed. These measurements were made with capacitive sensors and conductive foils. The measured and predicted values agree very well within the range of non-dimensional parameters, h_0/R , from 10^{-4} to 10^{-3} and, $T/\mu U$, from 10^5 to 10^6 . The agreement deviates for values beyond these ranges. Empirical expressions for predicting the constant and minimum film thickness applicable beyond these ranges are also presented. They are valid within the range of h_0/R .

from $5(10)^{-5}$ to 10^{-2} and $T/\mu U$ from 10^4 to 10^6 . The validity of a growing sinusoidal film thickness in the exit region first predicted by Gross is clearly evidenced from the photographs. The measured wave lengths checked with Barlow's calculated values within 6 percent. For a constant relative velocity, the effect of increasing tension is to decrease the film thickness; while for a constant tension, the effect of increasing speed is to increase the film thickness. The effect of gas compressibility becomes important for high relative velocity; and the effect of surface roughness greatly influences either the predicted or measured values for thin film thickness. The data presented in this report cover a range of drum linear speeds from 30 to 1942 in/sec and tape tension from 0.054 to 3.24 lb/in.

64-081 Maas, M.A.

TORSION WIRE IN LOW-ORDER FORCE FIXTURE MEASURES ONE-QUARTER DYNE. Design News, vol. 19, no. 6, pp. 32-3. (March 18, 1964).

The fixture, designed by E.B. Sciulli, of the General Electric Co., was built to determine the supporting forces in a magnetic bearing. The bearing, designed for space application, will operate in zero g field. The force fixture is supported on a stone surface plate. Fastened to the plate is a welded frame of aluminum I-beams. A gas bearing mounted on the frame supports the weight of the magnetic bearing rotor and suspension system.

64-082 Mahoney, J.W.

HIGH PURITY AIR COMPRESSOR SUPPLIES PERSHING AIR BEARINGS. Hydraulics and Pneumatics, vol. 17, no. 9, pp. 121-5. (September 1964).

The air compressor assembly is a 4-stage radial piston type with accessory equipment that enables it to operate efficiently and reliably for missile ground support systems. It is rated at 12 scfm discharge at 3000 psig and 4000 ± 100 rpm with inlet air at 125°F and 29.92 in. Hg. It operates in a temperature range from -65°F to 125°F. Air outlet temperature is 25°F above ambient.

64-083 Malanoski, S.B. and C.H.T. Pan.

THE STATIC AND DYNAMIC CHARACTERISTICS OF THE SPIRAL-GROOVED THRUST BEARING. Paper 64-Lub-9 presented at the ASME-ASLE International Lubrication Conf., Washington, D.C., October 13-15, 1964.

A generalized analysis for spiral-grooved thrust bearings is presented. The effects of local radius are considered. For the same grooving geometry and the same inside-to-outside radius ratio, the inflow design is shown to be superior in both stiffness and load

capacity. The analysis also treats a relative, transverse, oscillatory motion of the bearing surfaces. Both the magnitude and phase angle (in the temporal sense) of the bearing reaction are dependent on the frequency of the motion. The results for the oscillating motion reveal the possibility of a self-excited, rotor-bearing instability. The criterion for determining the onset of this type of instability is given.

- 64-084 Mann, D.B., M.T. Norton and T.R. Strohbridge.
CRYOGENIC MAGNET REFRIGERATION. Boulder Labs. Nat. Bur. Stand.
Rep. 8239, February 1, 1964.

Refrigeration processes (Joule-Thomson expansion, Brayton cycle, Stirling cycle, and Claude cycle) were investigated, together with the reheat concept. The applicability of conventional turbine design methods to refrigeration systems was demonstrated. Efficiencies of 80% in a turbine supported by gas-lubricated bearings were achieved. A pulsed refrigeration system for cooling a magnet with pressurized helium gas was studied extensively. A proposed steady-state refrigeration system to remove heat from the circulating system is discussed. Refrigerant properties were also put into readily usable, up-to-date form.

- 64-085 Marsh, Harry.
THE STABILITY OF AERODYNAMIC GAS BEARINGS. PART II, NON-CIRCULAR BEARINGS. Cambridge University, England. June 1964.

This report extends the linearized theory (see Ref. #63-052 in this bibliography) of bearing behavior to systems with non-circular bearings, or rotor. The main interest is in the stability of these non-circular systems, but the problem of vibration capacity is also discussed. It is shown that a system with a non-circular bearing or rotor can be stable when unloaded, provided that certain conditions are satisfied. There is a marked difference in the behavior of a two lobed bearing and a three lobed bearing. For these two geometries, the effect of varying the bearing parameters leads to completely different forms for the regions of stable operation. A few experimental results are given for a system with a three lobed rotor and these show good agreement with the theoretical prediction of a region of instability at low rotational speeds. The theory of bearing stability for flexibly mounted bearing systems is extended to include the effect of damping in the bearing mounting. A few experiments are described for a bearing mounted in a piano wire mesh and the results show close agreement with the theoretical regions of stability. From these experimental results, it is possible to derive the criterion for whirl cessation in a flexible system. In some applications it is important that the bearing system should be able to withstand vibration over a wide range of frequencies without the rotor coming into contact with the bearing wall. The most severe

condition is often a vibration at the critical frequency, this being about one half of the rotational speed. For vibrations at the critical frequency, it is possible to obtain a simple estimate for the vibration capacity based on the linearized theory of bearing behavior. The effect of a synchronous rotating load is described for an arbitrary lubricant and a few experimental results are given for the stabilizing effect of an out-of-balance rotor. Non-dimensional parameters are widely used in lubrication theory and a short discussion is included of the conditions which must be satisfied for complete similarity between two bearing systems. If similarity can be achieved, then this may allow a more reliable test apparatus to be designed. The theory of gas-bearing similarity should be particularly useful when used in conjunction with the proposed apparatus for determining the stability parameters of any bearing system operating with any lubricant.

63-086

Meacher, J.S.

EXPERIMENTAL INVESTIGATION OF A STEAM LUBRICATED JOURNAL BEARING. Mechanical Technology, Inc. Report MTI 64TR40, August 1, 1964. Navy contract Nonr-3731(00) (FBM).

Apparatus and preliminary testing for the experimental investigation of a steam lubricated journal bearing is described. The test bearing is an externally pressurized, double-row, orifice compensated type, 3.0 inches in diameter and 3.0 inches in length. This work is a continuation of a study of process fluid lubrication wherein the performance of a steam lubricated thrust bearing has previously been investigated and reported. The work is directed toward the development of process fluid lubricated bearings for shipboard application. Steam was therefore considered to be the lubricant fluid with most potential for practical application. The choice of an externally pressurized test bearing, rather than a hydrodynamic type, was based on the load capacity requirements of probable shipboard applications. Preliminary tests were conducted at room temperature and at 400° F using nitrogen instead of steam as lubricant. A base line of bearing performance was thus established for comparison with future performance with steam at various conditions.

- 64-087 Mech, Christian, J. Poulain and H.W. Fricker.
EXPERIMENTAL STUDY OF TILTING PAD GAS BEARINGS, PART I,
RADIAL PADS. O.E.C.D. High Temperature Reactor Project.
Dragon Project Report 306, Part I. December 1964.

An experimental investigation into the behavior of gas lubricated single radial pads was carried out on special test equipment. A radial pad consists of a segment of a cylindrical shell, pivoted in one point, in which the shaft is running. The influence on gas film thickness and shape of the parameters load, speed, size, clearance and pivot location was studied.

- 64-088 Mech, Christian and H.W. Fricker.
EXPERIMENTAL STUDY OF TILTING PAD GAS BEARINGS, PART 2,
AXIAL PADS. O.E.C.D. High Temperature Reactor Project.
Dragon Project Report 306, Part 2. December 1964.

An experimental investigation into the behavior of single, gas lubricated, axial pads has been carried out using special test equipment. The test pad consisted of an annular sector running against the axial face of a rotor. Both running surfaces were plane. The influence of load, speed and pivot location on gas film thickness was studied and the results compared with various lubrication theories.

- 64-089 Mech, Christian.
[GAS BEARINGS]. LES PALIERS A GAZ. (In French). Mem. Soc. Ingen. Civils Fr., vol. 117, no. 12, pp. 44-52. (December 1964).

The development of the technology of gas-lubricated bearing is discussed. The subjects treated are: (1) historical review, (2) characteristics of gas bearings, (3) hydrostatic bearings, (4) hydrodynamic bearings, (5) mixed systems, (6) orders of magnitude of operating parameters, and (7) applications. It is concluded that the use of gas-lubricated bearings is anticipated in the fields of nuclear and aerospace technologies.

- 64-090 Modrey, Joseph.
GREEN'S FUNCTIONS FOR JOURNAL BEARINGS. Union College.
Mechanical Engineering Department Research Report. August 1964.
Navy contract Nonr(G)-00028-62.

The Green's Function $G(Q;D)$ for a journal bearing is an influence coefficient defining the pressure at point Q due a unit of dimensionless flow strength fed into point D of the bearing clearance. Because this concept is directly analogous to the fluid mechanics of hydrostatic bearings, the Green's Function has its most direct appli-

cation in this area. On the other hand, hydrodynamic bearings can be pictured as hydrostatic bearings with a distributed external pressurization defined by the self-acting effects. Green's Functions are therefore applicable to this area as well. Linearity of the Reynolds equation is assumed in the application of Green's Functions; therefore, non-linear systems must be made piecewise linear before the Green's Functions may be used. The Green's Functions are given as the sum of a closed form function and a Fourier Series. The coefficients of the Fourier Series are given as functions of peripheral source location and journal eccentricity. With these data it is shown how the Green's Function for any L/D and source offset can be generated. Data assumes full 360° journal bearings but transformations are given for generating the Green's Functions for 180° bearings as well. The data given is applicable to both compressible and incompressible fluids. By the use of Green's Function the bearing problem is reduced from one of solving partial differential equations to one of simple integrations. The computer programming for integration is considerably simpler than that for differentiation. This simplicity enables designers not deeply versed in field equations and their convergence to perform their own analysis with minimum restrictions on geometry.

- 64-091 Modrey, Joseph.
SOME APPLICATIONS OF JOURNAL BEARING GREEN'S FUNCTIONS. Union College. Mechanical Engineering Department Research Report. November 1964. Navy contract Nonr(G)-00012-63.

The fundamental Green's Function for journal bearings derived in a previous report are applied to both externally pressurized bearings and self-acting bearings. The Green's Function solution agrees very well with the theoretical solution of a self-acting bearing with Sommerfeld conditions. Small discrepancies between the Green's Function solution and experimental hydrostatic bearing data exist at the higher eccentricities. Differences arise from errors in estimating orifice discharge coefficients, neglect of local turbulent conditions in the Green's Function solution and tolerances in the real clearances of experimental models. All three of these factors seem equally important in an error analysis, hence the accuracy of Green's Function solutions is compatible with the realities one must recognize in applying the theory of lubrication.

- 64-092 Mori, Haruo, Yasunori Miyamatsu, and Shigeru Sakata.
THEORY OF THE PRESSURE DEPRESSION IN EXTERNALLY PRESSURIZED THRUST GAS BEARING WITH CONSIDERATION OF THE GROWTH OF BOUNDARY LAYERS. (In Japanese). J. Japan Soc. Lubr. Engrs, Tokyo, vol. 9, no. 2, pp. 113-118. (1964).

In order to investigate the fundamental characteristics of externally

pressurized gas bearings, a theory of the pressure distribution in the clearance space is introduced by using a mathematical model of the flow in a circular thrust bearing as the simplest case. The flow model used in this report is advanced from a previous report. That is, the region II of subsonic flow with the growth of boundary layers after the concentrated normal shock wave is added after the region I of supersonic flow which is from a central gas-supply hole to the shock wave. The region III of fully viscous and isothermal flow follows the region II. Comparing the results of the theoretical solution for the pressure distribution with experimental results, it was found that the flow model is suitable for indicating the pressure distribution, especially the pressure depression, for this gas bearing when the supply pressure is sufficiently high.

- 64-093 Mori, Haruo and Hiroshi Yabe.
ANALYSIS OF EXTERNALLY PRESSURIZED CIRCULAR THRUST GAS-BEARING WITH MULTIPLE SUPPLY HOLES. ASLE Trans., vol. 7, pp. 269-276. (July 1964).

This is a theoretical investigation, by means of the complex potential theory, of an externally pressurized thrust gas-bearing with multiple supply holes and no recesses. By using a suitable potential function which satisfied the boundary conditions, the pressure distribution and volume rate of flow for both an incompressible fluid and a compressible fluid, and the load capacity for an incompressible fluid are obtained theoretically. The optimum radial position of supply holes, which gives the largest load capacity, is then found. It is noted that the theory can be extended to any number of supply holes.

- 64-094 Mori, Haruo, Hiroshi Yabe and Takayuki Ono.
THEORY OF EXTERNALLY PRESSURIZED CIRCULAR THRUST POROUS GAS BEARING. Paper 64 - Lub-19 presented at ASME - ASLE International Lubrication Conference, Washington, D.C., October 13-16, 1964.

The externally pressurized circular-thrust gas bearing with a porous bearing surface is analyzed. A "permeability coefficient" is used to characterize the properties of the porous media. The concepts of "equivalent clearance" and "effective restricting thickness" of a porous layer are introduced which permit an analysis of the porous material in both axial and radial directions considering flows in both the porous material and the bearing clearance as being interconnected. The analytical and experimental results on pressure distribution and load capacity are in good qualitative and quantitative agreement.

- 64-095 Mori, Haruo, Hiroshi Yabe and T. Shibayama.
THEORETICAL SOLUTION AS A BOUNDARY VALUE PROBLEM FOR EXTERNALLY PRESSURIZED POROUS GAS-BEARINGS. Paper 64 - Lub-26 presented at ASME - ASLE International Lubrication Conference, Washington, D.C., October 13-16, 1964.

This paper is based on an analysis previously described, in Japanese, in the J. Japan Soc. Lub. Engrs. [9(1):35-42 (1964)]. It attempts to solve the problem of the externally pressurized porous gas-bearing, treating the flow in the bearing clearance in terms of a boundary value problem for a three-dimensional flow in a porous medium. The approach is found to allow investigations of the characteristics for different bearing configurations, taking into account the anisotropy of the porous material. An assumption is made that the flow in the bearing clearance is laminar and completely viscous, and the flow in the porous medium conforms to Darcy's law. These theoretical results are found to yield a more reasonable prediction of porous gas-bearing performance than those reported in an earlier paper by these authors.

- 64-096 Muijderman, E.A.
NEW FORMS OF BEARING: THE GAS AND THE SPIRAL GROOVE BEARING.
Philips Tech. Rev., vol. 25, no. 10, pp. 253-274. (October 2, 1964).

Types of bearings are discussed in which friction and wear are reduced to very small proportions by the agency of a viscous fluid (lubricant) that serves to maintain a small and more or less constant clearance between the bearing surfaces. A "contactless" bearing of this kind does not necessarily have to be lubricated with a liquid, such as oil; a gas is also effective. Particular attention is given to gas lubricated bearings, which have been a practical possibility for the past 15 years or so. A distinction is made between two classes of "contactless" bearing, the externally pressurized types and the self-acting types. In a comparative account of the two classes some indication is given of the applications for which each is most suitable. Examples of gas bearing applications may be found in turbo-jet engines, gyroscopic compasses, nuclear reactors, dentists' drills, etc.

- 64-097 Mullan, P.J. and H.H. Richardson.
JOURNAL BEARING - ANALYSIS AND COMPARISON WITH EXPERIMENTS.
ASLE Trans., vol. 1, pp. 277-287. (July 1964).

Consideration of the aspect of the dynamic response of externally pressurized gas journal bearings concerning the plane vibration without rotation of a rigid shaft supported by inherently compensated bearings. Lumped and distributed parameter analyses of the inherently compensated gas journal bearing are developed for small eccentricity ratios. Curves are presented for static and dynamic

gas film forces and for bearing gas flow requirements. Experimental results are compared with the theories for the case of plane vibration. The results are said to agree reasonably well with the analyses, considering the difficulty of isolating the gas bearing and shaft system from external sources of damping.

- 64-098 Ng, Chung-Wah.
LINEARIZED PH STABILITY THEORY FOR FINITE LENGTH, SELF-ACTING GAS-LUBRICATED, PLAIN JOURNAL BEARINGS. Paper 64 - Lub.-28 presented at ASME - ASLE International Lubrication Conference, Washington, D.C., October 13-15, 1964. Navy contract Nonr-3730(00)(FBM).

Ausman's linearized PH method is applied to the determination of the finite length effects in self-acting cylindrical gas-lubricated journal bearings. Rotating polar coordinates are used to derive the principal equation. The results obtained are generally consistent with those obtained previously for a wide range of the parameters involved. The method is believed to yield conservative figures and to be suitable for handling dynamic problems of more complex systems.

- 64-099 Oak Ridge National Laboratory.
ROTATING MACHINERY FOR GAS-COOLED REACTOR APPLICATION, PROCEEDINGS, Gatlinburg, Tennessee, November 4-6, 1963. TID-7690. May 1964.

Representatives of the U.S. Atomic Energy Commission, the Oak Ridge National Laboratory, and installations throughout the United States and foreign countries discuss progress in the development of rotating machinery for gas-cooled reactors. The equipment covered in the papers presented include main blowers, shaft seals, gas turbines, gas bearing compressors, and other types of special compressors for reactor or experimental applications.

- 64-100 Obrzut, J.J.
FIGHTING FRICTION'S DRAG ON MOTION. Iron Age, vol. 193, no. 21, pp. 133-40. (May 21, 1964).

Gas and magnetic bearings are briefly discussed in this general article. Uses and advantages are described.

- 64-101 Orcutt, F.K.
EXPERIMENTAL INVESTIGATION OF CONDENSING VAPOR LUBRICATED
THRUST BEARING. ASLE Trans., vol. 7, no. 2, pp. 168-179.
(April 1964).

The results of an exploratory experimental investigation of externally pressurized, condensing vapor lubricated, thrust bearing behavior are described. The results indicate that bearing load-carrying capacity using vapor lubricant is somewhat lower than would be expected from a comparable single-phase compressible lubricant. Bearing performance is strongly dependent on the rate at which heat is removed from the lubricant film by the bearing surfaces because of progressive condensation of the lubricant flowing over the cooled surfaces. Interaction of thermodynamic and fluid flow processes results in a well-defined load capacity for the vapor lubricated bearing and leads to an abrupt collapse of the bearing if the load limit is exceeded.

- 64-102 Ott, Hans.
GAS-LUBRICATED JOURNAL BEARINGS. U. S. Patent 3,129,037.
Applied December 26, 1961. Issued April 14, 1964.

This invention relates to a gas-lubricated journal bearing which is especially suited for operation in a dust-laden environment. The bearing is of the self-acting type in that the gas is put into circulation by rotation of the shaft rather than by use of extraneous pump devices, which requires no filter and which guarantees continual operation without supervision in a dust-laden environment, it being of simple construction. It is characterized by circumferential grooves which are arranged at both lateral ends of the bearing bushing, and by connections through which the lubricating gas is conducted into the axial grooves of the bearing bushings.

- 64-103 Pan, C.H.T.
SPECTRAL ANALYSIS OF GAS BEARING SYSTEMS FOR STABILITY
STUDIES. Mechanical Technology, Inc. Report MTI 64TR58.
December 15, 1964. Navy contract Nonr-3730(00).

A stability map for a gas-bearing supported rotor can be constructed from the periodic dynamic perturbation solution of the gas bearing equation about the equilibrium condition. A complete frequency range of the perturbation solution is required. Effective system stiffness and damping can be defined in terms of the perturbation solution of the gas bearing. The condition of neutral stability corresponds to the vanishing of the effective damping, yielding the characteristic frequency, and resonance at the characteristic frequency with the equivalent stiffness, yielding the

critical mass. An excess of rotor mass causes instability if the effective damping increases with frequency, at the characteristic frequency, and conversely. For unloaded journal bearings possessing rotational symmetry, the stability map can be constructed from their steady-whirl solutions. An example illustrating the latter case is given in terms of a herringbone-grooved journal bearing. This method of stability analysis is applicable to both thrust and journal bearings for both whirl and pneumatic-hammer instabilities.

64-104 Pan, C.H.T. and others.

THE INFINITELY LONG PARTIAL ARC SELF-ACTING GAS BEARING - A METHOD OF SOLUTION FOR THE FULL RANGE OF THE COMPRESSIBILITY NUMBER. Mechanical Technology Inc. Report MTI 64TR50. November 30, 1964. Navy contract Nonr 3730(00).

Modifications which must be made to Galerkin's method in treating the static solution of an infinitely long partial-arc, self-acting gas bearing are described. A simplified mathematical procedure for calculating quickly and with reasonable accuracy the loads and center of pressure for the bearing described is given in detail. The use of the parameter M (which contains both Λ and the exit film thickness) rather than Λ alone is justified by the results. Lower values of M require fewer terms but high values may require more than 6 terms. Stability calculations can be performed using results obtained from this procedure. The results obtained by use of the procedure discussed are more accurate for values of Λ lower than about 10.

64-105 Pan, C.H.T. and B. Sternlicht.

COMPARISON BETWEEN THEORIES AND EXPERIMENTS FOR THE THRESHOLD OF INSTABILITY OF RIGID ROTOR IN SELF-ACTING, PLAIN-CYLINDRICAL JOURNAL BEARINGS. Trans. ASME, (J. Basic Engng.), vol. 86 D, no. 2, pp. 321-327. (June 1964).

The threshold of half-frequency whirl for a rigid rotor in self-acting, plain-cylindrical journal bearings is analyzed by several methods, and the results are compared. The correlation among the various approaches appears to be good. The simplest method of analysis is, therefore, used for comparison with experimental data. Experimental results showing the effect of bearing length and bearing load are compared with theory. The influence of bearing length on the threshold speed follows closely the trend of the calculated results; however, the experimental threshold speeds are always a little higher. In comparing the effect of bearing load it is seen that the calculated threshold speeds are consistently somewhat over-pessimistic, but the influence of rotor inclination is in very good

agreement with experimental data. The methods presented in this paper can be used readily in design to insure stable operation with plain-cylindrical journal bearings.

64-106

Pantall, D.

GENERAL PRODUCTION METHODS. Gas Lubricated Bearings, edited by N.S. Grassam and J.W. Powell, Butterworths, 1964. pp. 203-218.

Both actual physical manufacture and inspection are discussed with emphasis on self-acting bearings and closely toleranced externally-pressurized bearings. Methods for 360° cylindrical journal bearing surfaces, oval bearings, shafts, tilting pad journal bearings, thrust bearings, surface finish, pockets, spiral grooves and steps, heat treatment, diaphragms, feed holes, assembly and balancing are discussed. Inspection techniques discussed include those for journal surfaces, thrust surfaces, groove or pocket depth, surface finish, material specification, and feed hole diameter.

64-107

Pantall, D.

THE DESIGN OF AERODYNAMIC BEARINGS. Gas Lubricated Bearings, edited by N.S. Grassam and J.W. Powell. Butterworths, 1964. pp. 27-84.

The theory of aerodynamic (self-acting) bearings is discussed, particularly the source of load-carrying capacity. Importance of knowing all applied loads is discussed. Factors determining choice of bearing type are examined. To determine bearing size, the load-carrying capacity must be calculated. Design charts are given for friction and attitude angle of 360° cylindrical journal bearings and information is given for load-carrying capacity of modified bearings. Load carrying capacity and other design data for tilting pad journal and thrust bearings and disc thrust bearings is also examined. Sample load carrying capacity calculations are included. Safety factors and installation considerations are discussed.

64-108

Patterson, A.G.

PRECISION BEARINGS FOR GYROS. Gas Lubricated Bearings, edited by N.S. Grassam and J.W. Powell. Butterworths, 1964. pp. 241-262.

The basic considerations involved in designing, making, and testing of gas bearings developed primarily for flotation gyros are outlined. Bearings for this application must be designed with various specifications unique to gyros in mind, such as miniaturization operational conditions, size conformity, attitude versatility, and inside-out operation. Other design conditions for both journal and thrust bearings are discussed, as well as machining accuracy and bearing materi-

als. Various dynamic measurement and test methods are discussed. Special problems such as friction, 'wringing', and debris are examined. Work is described that was done on aerodynamic bearings for gyroscopes having wander rates of the order of 5°/hr. This was conducted at the Admiralty Surface Weapons Establishment.

64-109

Pears, C.D. and F.J. Digesu.

GAS-BEARING FACILITIES FOR DETERMINING AXIAL STRESS-STRAIN AND LATERAL STRAIN OF BRITTLE MATERIALS TO 5500°F. Paper presented at the Annual Meeting of ASTM, Chicago, June 1964.

Facilities have been developed for the determination of axial stress-strain and lateral strain of brittle materials to 5500°F. This paper describes those facilities and presents performance data that confirm the improved capabilities. Gas-bearings were developed that permit the application of uniaxial loads to specimens in tension and compression, and specimens with shear gage sections. Also, optical strain analyzers were developed that follow the axial and lateral strains with an uncertainty of no more than 20 μ in., thus permitting precise measures of modulus of a ceramic such as alumina or beryllia. Both graphite and tungsten furnaces were developed that can be used to heat the specimen radiantly to temperatures in excess of 5000°F.

64-110

Pelech, Ivan and A.H. Shapiro.

FLEXIBLE DISK ROTATING ON A GAS FILM NEXT TO A WALL. Paper 64-APM-14 presented at the Summer Conference of the ASME, Applied Mechanics Division, Boulder, Colo., June 9-11, 1964.

The flow generated by the rotation of a flexible disk next to a wall is analyzed for small Reynolds numbers. A nonlinear differential equation for the radial variation of the pressure and the gap width is solved simultaneously with the equation governing the deflection of a spinning circular membrane under axial pressure load. Optical methods are used to measure the gap width experimentally. The theory agrees well with the measurements.

64-111

Pietsch, Anthony.

SOLAR BRAYTON-CYCLE POWER-SYSTEM DEVELOPMENT. Paper 64-726 presented at the American Institute of Aeronautics and Astronautics, Society of Automotive Engineers, ASME, Inter-agency Advanced Power Group, and Electron Devices Group of the Institute of Electrical and Electronics Engineers, Biennial Aerospace Power Systems Conference, 3rd, Phila., Penna., September 1-4, 1964.

A Brayton-cycle space power system is described. The system, which is illustrated, consists of: (1) a solar energy collector; (2) a heat-receiver/storage unit; (3) a recuperator; (4) a combined rotating unit; and (5) a radiator. This is a single-phase working-fluid cycle using inert gas in a closed power-conversion loop. Also shown is a conceptual illustration of a complete Brayton-cycle space power system. The development work performed on heat receivers, compressors, turbines, gas bearings, recuperators, and radiators is described.

64-112

Powell, J.W.

DYNAMIC CHARACTERISTICS OF EXTERNALLY PRESSURIZED BEARINGS.

Gas Lubricated Bearings, edited by N.S. Grassam and J.W. Powell. Butterworths, 1964. pp. 140-161.

Methods for recognizing various forms of instability are given and remedies for instability are discussed. Synchronous unbalance whirl is examined, equations for various types are given, and inversion speed and whirl at resonance are discussed. Fractional speed whirl is examined, whirl onset speeds, factors affecting them, and running through whirl are discussed. Methods of measuring radial stiffness and damping before a machine is run for the first time are investigated. Methods include static loading, shock loading and forced vibration. Pneumatic instability is also discussed. Pneumatic hammer occurs in bearings in which gas is fed through a small feed hole into a pocket of relatively large volume and self excited resonance is associated with choked, or nearly choked, feed hole conditions, and the frequency of vibration is always close to the natural frequency of the rotor mass and the bearing stiffness.

64-113

Powell, J.W.

THE HYBRID GAS JOURNAL BEARING. Gas Lubricated Bearings, edited by N.S. Grassam and J.W. Powell. Butterworths, 1964. pp. 162-178.

Load capacity, design, economic factors, stability and applications are discussed. The load capacity can be considered to be derived from the two sources of externally-pressurized pressure and the self-acting pressure. Prediction of load capacity is complex but some

progress can be made by considering externally-pressurized and self-acting effects as independent and by combining the effects by the addition of load vectors. Clearance ratio, the ratio of the mean radial clearance to the bearing radius, is an important design parameter. Other design factors such as eccentricity ratio, bearing pressure factor, feed hole diameter, externally-pressurized stiffness, self-acting load vector, and length-to-diameter ratio are discussed. Gas consumption and pumping power requirements are important economic factors. Methods of reducing costs by improved bearing design are discussed. Self excited half-speed whirl occurs in hybrid bearings at a speed approximately equal to twice the synchronous resonance speed. Methods of preventing this are discussed.

64-114

Powell, J.W.

EXPERIMENTS ON A HYBRID AIR JOURNAL BEARING. Paper 64-WA. LUB-11, presented at ASME, Winter Annual Meeting, New York, N.Y., November 29 - December 4, 1964.

This paper consists of a description of quasi-static load experiments to obtain performance data for externally-pressurized hybrid air journal bearings. Measurements were made on externally-pressurized stiffness and stability, and on the variation of the self-acting load increase with speed, clearance, and gage pressure ratio. The results are compared with those of a linear superposition theory, and it is found that, while the theory is of some value for a qualitative description of the load-carrying performance of the bearing, it seriously underestimates the load capacity. Therefore, if used for design purposes, the theory requires empirically derived corrections.

64-115

Powell, J.W.

GAS BEHAVIOUR AND LOAD CAPACITY OF HYDRODYNAMIC GAS JOURNAL BEARINGS. Lubrication and Wear Convention, Proceedings, Bournemouth, England, May 23-25, 1963. Lubrication and Wear Group of the Institution of Mechanical Engineers, 1964. pp. 113-125.

When Harrison formulated the basic theory of hydrodynamic gas journal bearings he assumed that the gas lubricant obeyed the isothermal law. Ausman deduced a generalized form of Harrison's equation to take account of any index of expansion of the gas lubricant between unity and the adiabatic constant $\gamma = C_p/C_v$. Ausman deduced that the gas lubricant obeyed the adiabatic law. Although Ford, Harris and Pantali obtained experimental results in four different gases with three different values of γ , no definite conclusions were drawn regarding the effect of γ on load capacity. A paper by Katto and Soda concludes that under certain conditions the gas behaviour can differ substantially from the isothermal law. In the present work

of the recess, is described. The part-spherical recess is formed in the bottom of a relatively spacious chamber of the socket and means are provided for the supply of lubricating fluid to the chamber and the discharge of the fluid through the passage. At high rotational speeds, the lubricating fluid splutters away from the equator of the pintle globe so violently that the supply of lubricating fluid to the bearing is hampered or cut off. The prevent this, grooves in the wall of the part-spherical recess of the socket are recommended. These grooves are in direct communication with the chamber. The positions, direction, and/or shapes of the grooves so differ from those of grooves lying in meridian planes of the pintle globe that the resultant of the forces exerted on the lubricating fluid in the grooves by the rotation of the pintle has a downward component.

64-118 Rice, J.R.

MISALIGNMENT TORQUES OF HYDRODYNAMIC GAS-LUBRICATED JOURNAL BEARINGS. Paper 64 LubS-9 presented at ASME Lubrication Symposium, Cleveland, Ohio, April 28-30, 1964.

Recently Ausman has made a perturbation analysis of the torques produced by the misalignment of gas-lubricated journal bearings. The results of such an analysis are adequate for engineering design work only if the eccentricity ratio is something less than 0.5. In this paper, design curves for misalignment torques are presented which are valid for high eccentricity ratios. These design curves are computed by numerically solving the governing Reynolds equation by a difference equation technique. Only conditions of zero net load are considered.

64-119 Richman, Jay

AIR BEARING. U.S. Patent 3,136,589. Applied March 6, 1963. Issued June 9, 1964.

This invention relates to an air bearing and more particularly, to vacuum apparatus where an element is supported with an air bearing. An ultra-high vacuum system includes an evacuated container having a bottom wall. The container is evacuated by means of a conduit communicating with the chamber inside the container. A vacuum pump is placed in the conduit. This invention is of general application and may be utilized in a wide variety of different ultra-high vacuum systems. For example, the system may be a laboratory device for testing and determining the effect on a rotatable member under evacuated conditions. The container may be part of a system simulating conditions in outer space designed to determine the effect on a rotatable element which will be rotating in a substantial vacuum with minimum frictional resistance.

- 64-120 Rood, L.H. and G.J. Erickson.
DYNAMIC BEHAVIOR OF SELF-ACTING GAS-LUBRICATED THRUST BEARINGS.
Paper presented at the 19th ASLE Annual Meeting, Chicago,
Illinois, May 26-28, 1964. Preprint 4B1.

Measurements of gas thrust bearing film thickness under sinusoidal loading are discussed. The results show the effects on film thickness of spiral groove pattern changes. The instrumentation used is also discussed. Experimental results from the vibration of gas bearing spinmotors for gyroscopes show the change of the gas film thickness with vibration frequency. The effects of spiral groove thrust bearing parameter variation are shown. The instrumentation used employs capacitance probe techniques to sense the small deflections occurring under sinusoidal loading.

- 64-121 Salbu, Erik
COMPRESSIBLE SQUEEZE FILMS AND SQUEEZE BEARINGS. Trans. ASME, (J. Basic Engng.), vol. 86 D, no. 2, pp. 355-366. (June 1964).

Experimental agreement with a finite-difference solution of the isothermal squeeze film equation was obtained for steady-state sinusoidal squeeze motion of parallel, coaxial disks. At low squeeze number, the film force is in phase with the velocity; at high squeeze number, with the displacement. Compressibility effects at high squeeze number introduce a superambient mean film pressure, so that it is possible to operate a gas bearing on squeeze effects alone. Thrust bearings, spherical bearings, and journal bearings have been successfully operated as squeeze bearings, using both electromagnetic and piezoelectric devices to generate the squeeze motion.

- 64-122 Schively, D.P.
OPERATING CHARACTERISTICS OF THE GAS BEARING COMPRESSORS OF THE PRTR GAS-COOLED LOOP FACILITY. Rotating Machinery for Gas-Cooled Reactor Application, Proceedings, Gatlinburg, Tennessee, November 4-6, 1963. TID-7690. May 1964. pp. 245-252.

A brief description of the compressors is given, including assembly data and operating limits. The compressors are of the hydrodynamic gas bearing type, single stage, with radial vaned impeller. Test results indicate that these machines appear fully reliable and suitable for circulation of carbon dioxide or other compatible gas in the PRTR Gas Cooled Loop Facility at inlet conditions of 660F and 465 psia. The possibility of larger, higher-temperature-rated machines appears attractive even though scale-up of designs for

smaller machines has proven difficult. Limiting items on the PRTR Gas Loop compressors are the bearing material and stator insulation. The temperature limitations imposed by these materials suggest further developmental investigation in this area.

- 64-123 Schubert, E.
BEARINGS. German Patent 1,177,878. (to United Kingdom Atomic Energy Authority). Applied October 17, 1958. Issued October 12, 1964.

This describes a gas-lubricated journal bearing which may be used in a nuclear plant and is modified for increased load capacity. In sequence from one end, the bearing has a ring of orifices for admitting pressurized gas, a circumferential groove for venting gas, and a special arrangement which may create a circumferentially asymmetric pressure. This arrangement comprises a pressurizable pocket in the bearing surface, and an adjacent opening(s) such as rows of vent holes.

- 64-124 Schwarz, Hans and J.P. McGee.
DEVELOPMENT OF A HIGH-TEMPERATURE HELIUM COMPRESSOR. Rotating Machinery for Gas-Cooled Reactor Application, Proceedings, Gatlinburg, Tennessee, November 4-6, 1963. TID-7690. May 1964. pp. 236-244.

The components of a hot gas circulator, using gas bearings, designed by Mechanical Technology Inc. are briefly described. The specifications are as follows: gas- helium; ambient pressure - 500 psia; inlet temperature - 1000F; flow rate - 450 lbs/hr.; pressure rise - 10 psi. The bearings are identical 4-pad tilting shoe type, $2\frac{1}{2}$ " diameter with an L/D of 0.65. Radial adjustment means are provided. The thrust bearing is a 4-1/8" O.D., 1-7/16" I.D. carbon-graphite ring with an inward pumping 'Whipple' groove pattern. The running film thickness was measured at 800 micro-inches. Shaft jacking is obtained from two 120° arc fixed pads adjacent to the main bearings. Instrumentation used to observe and measure the bearing gas film thickness is described. Future trends are noted.

- 64-125 Shevchenko, R.P. and G.S. Reichenbach.
LUBRICATION REVIEW.-DEVELOPMENTS IN BEARINGS AND LUBRICANTS,
A DIGEST OF THE LITERATURE FROM 1961-1962. Trans. ASME, (J.
Basic Engng.), vol. 86 D, no. 2, pp. 367-386. (June 1964).

This 1961-1962 lubrication digest reviews developments in fluid-film and rolling-element bearings, lubrication for bearings, gears, and automobiles; and covers basic work done in the general areas of friction and wear; elastohydrodynamic, boundary, and full film lubrication; and lubricant properties. The authors cover specific areas of lubrication literature and it is recommended that the reader, even the specialist, peruse related areas since the years of effort in this field have exposed more of the fundamentals; and the conclusions drawn, and the basic laws formulated in one area are important to all areas.

- 64-126 Shilling, W.F.
THE ROLE OF GAS BEARING CIRCULATORS IN THE DRAGON REACTOR.
Rotating Machinery for Gas-Cooled Reactor Application, Pro-
ceedings, Gatlinburg, Tennessee, November 4-6, 1963. TID-
7690. May 1964. pp. 207-218.

The development of gas bearings for the cooling circuits of the Dragon Reactor is discussed and test results are given. The influence of gas temperature at shutdown on the differential temperatures experienced by the journal bearings in the motor compartment are investigated. It is essential that the differential temperature between either end of a journal bearing should not exceed 40°C . It was found that when tripping out with a gas temperature in excess of 300°C , this temperature differential could be exceeded after an interval of time. At any gas temperature in excess of this value the interval of time between stop and restart must be carefully controlled. It is felt that the results of this development work have given a better understanding of problems such as bearing instabilities in helium, material compatibility and importance of temperature distribution.

- 64-127 Shires, G.L. and D. Pantall.
AEROSTATIC JACKING OF A VENTED AERODYNAMIC JOURNAL BEARING.
Lubrication and Wear Convention, Proceedings. Bournemouth,
England, May 23-25, 1963. The Lubrication and Wear Group of
the Institution of Mechanical Engineers. 1964. pp. 87-96.

An attempt is made to predict the load-carrying capacity of pressure-fed journal bearings, designed primarily for aerodynamic (self acting) operation, to explain changes in performance and to

provide a method of predicting the effects of changes in gas conditions or bearing geometry. The principal object was to determine the reasons for observed differences in behavior of bearings with different gases. Mathematical models are discussed, and short and long self-acting journal bearings and vented self-acting journal bearings are investigated. The performance of a typical bearing configuration is predicted and compares reasonably well with the experimental differences in performance between bearings in air and in helium. The shaft locks-up against the top of the bearing operating at some conditions in helium but not in air. The top vent in the bearings being tested had been cut away to prevent instability when the bearing is not used statically, but the shaft is turning.

64-128

Shives, G.L.

THE DESIGN OF EXTERNALLY PRESSURIZED BEARINGS. Gas Lubricated Bearings, edited by N.S. Grassam and J.W. Powell. Butterworths, 1964. pp. 110-139.

Topics discussed include theory and design of thrust and journal type bearings, influence of jet configuration on journal bearings and the effect of expansion and deceleration on pressure profile near the jet. A simple journal bearing is shown and mechanisms involved in balancing restoring forces so there is no net force on the shaft are described. The effect of jet type and number of jets on the load coefficient of a journal bearing is discussed. For thrust bearings, the cases of circular bearing with a central jet and with a ring of jets are discussed and designing for maximum stiffness is described.

64-129

Sixsmith, Herbert and W.A. Wilson.

THEORY OF STABLE HIGH-SPEED EXTERNALLY PRESSURIZED GAS LUBRICATED BEARINGS. J. Res., Nat. Bur. Stand., (Engng. Instrum.), vol. 68 C, no. 2, pp. 101-114. (April-June, 1964).

Externally pressurized gas lubricated bearings have been used successfully to support the shaft of a miniature, high-speed expansion turbine. The bearings incorporate stabilizing cavities to suppress whirl at high speeds. The theory of the bearing design is presented in detail.

64-130

Sneck, H.J. and K.T. Yen.

THE EXTERNALLY PRESSURIZED, POROUS WALL, GAS-LUBRICATED JOURNAL BEARING. I. ASLE Trans., vol. 7, pp. 288-298. (July 1964).

The externally pressurized, gas-lubricated journal bearing consisting of a porous bushing, through which gas enters the clearance space is analyzed. The classical Reynolds equation for laminar, isothermal, compressible flow in a finite journal bearing is modified to allow for the local mass flow through the porous bushing into the clearance space due to the difference between the constant supply pressure within the bearing. At low mass flow rates, it is assumed that the flow in the porous bushing obeys the Darcy equation for isothermal, compressible "creeping flow". The analysis is extended to include bearings with higher flow rates by a simple modification of the Darcy equation. The modified Reynolds equation is solved for the case where the shaft does not rotate by perturbing the mass flow rate through the bearing, using the eccentricity ratio as a small parameter. An asymptotic solution for the "short bearing" and the "maximum load-carrying capacity" is determined independently of the perturbation technique. The results of this technique are compared numerically with the results of the asymptotic solution, and they are found to be in agreement.

64-131

Snyder, W.T.

THERMAL ASPECTS OF MAGNETOHYDRODYNAMIC LUBRICATION. Paper 64-WA/LUB-9 presented at ASME, Winter Annual Meeting, New York, N.Y., November 29-December 4, 1964.

This paper consists of the analysis of the temperature distribution in the lubricant film of an MHD slider bearing. A solution is obtained for the conditions of adiabatic surfaces, neglecting axial conduction, and assuming a constant mean viscosity. It is found that the thermal aspects of MHD lubrication will always be significant in the range of electric and magnetic field strengths for which favorable MHD pressurization can occur. It is shown that, for certain conditions of electrical loading, the temperature rise of the lubricant with a magnetic field present can be as much as two orders of magnitude larger than the temperature rise without the magnetic field.

64-132

Sochacka, Zofia.

[AIR-LUBRICATED HYDROSTATIC BEARINGS]. LOZYSKA HYDROSTATYCZNE SMAROWANE POWIETRZEM. (In Polish). Prace, Instytut Lotnictwa, no. 23, pp. 63-72. (1964).

Brief review of the theory of air-lubricated thrust and journal

bearings, and its application to bearing design. Tests conducted to verify the theoretical computations of such bearings are described.

64-133 Speen, G.B.

GAS BEARINGS IN PRECISION INSTRUMENTS. Electromech. Components Systems Design, vol. 8, no. 4, pp. 40-3. (April 1964).

The features of gas lubricated bearings significant in precision instrument applications are discussed. Advantages and disadvantages are listed, as well as general rules for the basis of an intelligent approach to the application of gas lubricated bearings. If these rules are all satisfied, a successful design improvement is virtually assured. If not, the design can easily fall into the trap of overenthusiasm and obtain lower reliability, poorer performance, or more expensive design. A few typical examples (gyroscopes, accelerometers, inertial platform gimbal bearings) are given to illustrate the advantages of applying gas bearings, the penalties paid for their use, and some of the thinking used in the evaluation.

64-134 Spies, R.

INVESTIGATION OF CONDENSING VAPOR LUBRICATED SELF-ACTING JOURNAL BEARINGS. Rocketdyne. Final Report for period October 1, 1963 - June 15, 1964, Report R-5741. July 1, 1964. Navy contract Nonr 3617(00).

A test program on steam-lubricated journal bearings has been completed. Grooved and ungrooved bearings have been operated over a range of superheat. Performance data have been obtained and the effects of clearance, geometry, load, and speed are discussed.

64-135 Stahler, A.F.

FURTHER COMMENTS ON THE PRESSURE DEPRESSION EFFECT IN EXTERNALLY PRESSURIZED GAS-LUBRICATED BEARINGS. ASLE Trans., vol. 7, pp. 366-376. (October 1964).

The work of several authors on the pressure-depression effect in externally pressurized gas-lubricated bearings is presented. Improved mathematical formulas and experimental evidence are introduced. The use of the free-surface water-table analog as an aid in the visualization and study of the pressure-depression effect is presented. The basis of the analogy lies in the similarity of the equations of motion for the two-dimensional, frictionless isentropic flow of a perfect gas with specific heat ratio $K = 2.0$,

and the two-dimensional frictionless flow of an incompressible liquid in a horizontal channel with a free surface. Pressure waves in the gas flow correspond to gravity waves in the liquid flow. Although the water undergoing flow under the action of gravity is incompressible, it has the option to change its depth, and by this means it gains the characteristics of compressibility. Good qualitative agreement was found between this analog and the available experimental data. It is considered that future work on the free-surface water table should be directed toward obtaining quantitative values for the analogous friction factors.

- 64-136 Sternlicht, Beno
NEW FRONTIERS IN GAS BEARINGS. SAE Paper 810B for meeting
January 13-17, 1964.

Reasons for the growth in gas bearing applications are presented using as an example journal bearings to show the influences of several parameters on performance. These are dimensionless force, attitude angle, friction force, and flow. Self-acting, externally-pressurized, and hybrid bearings are compared; bearing instabilities and dynamic forces are discussed; and examples of present and future gas bearing applications and tabulation of problem areas are given.

- 64-137 Sternlicht, Beno
GAS BEARINGS. Mach. Design, vol. 36, no. 9, pp. 162, 164,
166, 168-169, 170-171. (April 1964).

This article discusses some of the reasons why gas bearings are being applied and outlines several of the factors that must be considered in selection and design. Examples are given of equipment supported by self-acting and externally pressurized gas bearings, ranging from a fraction of a pound to several thousand pounds in weight. Some of the advantages cited for gas bearings are (1) no contamination of the system environment by the lubricant, (2) operation over a wide temperature range, (3) resistance to thermal breakdown of the lubricant, (4) resistance to damage by radioactivity, (5) high reliability and long life, (6) low and constant friction, (7) close position control and low vibration. The article gives a fair description of how gas bearings work and reviews operating requirements for self-acting and externally-pressurized bearings. Practical illustrations give a review of the present state of the art and lists give areas where gas bearings can be applied. Some of the examples are high-speed motor driven spindles for grinding or synthetic fiber winding, gyros and accelerometers, attitude control simulators and man-carrying motion

generators. All applications utilize the above-mentioned advantages. Several future applications of gas bearings in the more exotic areas are predicted.

- 64-138 Sternlicht, Beno and L.W. Winn.
GEOMETRY EFFECTS ON THE THRESHOLD OF HALF-FREQUENCY WHIRL IN
SELF-ACTING GAS-LUBRICATED JOURNAL BEARINGS. Trans. ASME, (J.
Basic Engng.), vol. 86 D, no. 2, pp. 313-320. (June 1964).

This article is based on an investigation sponsored by Navy contract Nonr 2544(00)(General Electric Company report, AD-266 016, published October 16, 1961). Variations in geometry include a fine orifice in the bearing vented to atmosphere, two or three axial grooves in the bearing (groove orientation varied), and combinations of grooves and orifices. Plain bearing results are given for comparison. Details are also presented of computer solutions for steady-state load capacity for the grooved bearings. Conclusions draw attention to the need for theoretical analysis of the half-speed whirl condition. The analysis of Marsh, "The stability of aerodynamic gas bearings," [Cambridge University Ph.D. thesis, March 1963],*although not available to the authors at the time of publishing their article, will predict the whirl threshold speed of the axial grooved bearings to approximately 10% accuracy and is capable, with minor modifications, of predicting the results for bearings with orifices. (See Ref.#63-052).

- 64-139 Strass, Wilfried and Bernhard Schreiber.
[GAS-LUBRICATED, STATIC JOURNAL BEARING]. GASGESCHMEIRTES
STATISCHES GLEITLAGER. (in German). German patent 1,183,744.
(to Linde's Eismaschinen A.G.). Applied June 24, 1960.
Issued December 17, 1964.

This particular journal bearing is designed for radial and/or axial thrust with at least one restrictor between gas inlet and bearing gap. One bearing-half consists of single components whose contact face runs at least partly in the direction of the bearing gap. The restrictor is a shim mounted between the bearing-halves and has slits open to the bearing gap to form inlet nozzles for the gas.

- 64-140 Togo, Shinichi.
STUDY ON HYDROSTATIC AIR BEARINGS. PART II. (in Japanese).
J. Japan Soc. Prec. Engng., vol. 30, no. 6, pp. 468-474.
(June 1964).

This paper describes the method for determining the pressure distribution and the load capacity of hydrostatic air bearings using the conducting sheet analogy. For bearings of constant film thick-

ness, the pressure distribution and the bearing mean pressure of thrust bearings (the single pocket square type and the thrust ring type) are investigated. For bearings of variable film thickness, the pressure distribution of the journal bearing under eccentric condition is obtained for eccentricity $\epsilon = 0.2$.

64-141 Trugman, L.A.

SOME TESTS ON HYDRODYNAMIC GAS BEARINGS AT NORMAL AND ELEVATED TEMPERATURES. Paper presented at the 19th ASLE Annual Meeting, Chicago, Ill., May 26-28, 1964.

In order to develop a miniature rate gyroscope capable of operating at extremely high temperatures, a gas bearing spin motor assembly was required. Some of the efforts to achieve this goal are presented in this paper. Gas bearing test results are presented for various bearings operating at temperatures as high as 1000 F and speeds as high as 275,000 rpm. Rotors fabricated of tungsten carbide, nickel base alloy (Ni-Cr-Fe) and 440 C stainless steel were evaluated during this study.

64-142 Civian, C.H.

AERODYNAMICS IN VERY SMALL SPACES. Compressed Air Magazine, vol. 60, no. 4, pp. 11-15. (April 1964).

A brief history of the development of research in gas lubricated bearings is given. The two principal classes of gas lubricated bearings, self-acting and externally pressurized, are defined. Advantages and shortcomings are listed. Applications of gas lubricated bearings include precision grinders, centrifuges, turboexpanders, gas circulators, rotors for closed-type gas turbines, air-cycle refrigeration machines, motors for refrigeration defrost fans, yarn spindles, precision measuring instruments, gyroscopes and related devices, elements of computing machines, memory storage drums, jigs, tools, and fixtures of various types. A short summary of the state-of-the-art is included.

64-143 Vohr, J.H. and C.Y. Chow.

CHARACTERISTICS OF HERRINGBONE-GROOVED GAS-LUBRICATED JOURNAL BEARINGS. Paper 64-Lub-15 presented at the ASME-ASLE International Lubrication Conference, Washington, D.C., October 13-16, 1964.

This paper is based on an investigation at Mechanical Technology, Inc. sponsored by Navy contract Nonr-3730(00) [Reports MTI64TR15, AD-436 263, (April 2, 1964) and MTI63TR52 (January 1964)]. A differential equation is obtained for the smoothed overall

pressure distribution around a herringbone-grooved, gas-lubricated journal bearing operating with a variable film thickness. The equation is based on the limiting case of an idealized bearing for which the number of grooves approaches an infinite number. A numerical solution to the differential equation is obtained valid for small eccentricities. This solution includes the case where the journal is undergoing steady circular whirl. In addition to the usual plain bearing parameters L/D , A , and whirl speed ratio $\omega_3/(\omega_1 + \omega_2)$, the behavior of a grooved bearing also depends on four additional parameters: The groove angle β , the relative groove width α , the relative groove depth H_0 , and a compressibility number, A_s , which is based on the relative speed between the grooved and smooth numbers of the bearing. Results are presented showing bearing radial force and attitude angle as functions of β , α , H_0 , A_s , A , and whirl speed ratio.

64-144

Vohr, J.H. and C.H.T. Pan.

ON THE SPIRAL-GROOVED, SELF-ACTING, GAS BEARING. Mechanical Technology, Inc. Report MTL-63TR52, January 1964. Navy contract Nonr-3730(00).

A differential equation is derived for the smoothed overall pressure distribution around an arbitrarily-shaped, grooved, journal bearing operating with a variable film thickness. The equation is based on the limiting case of an idealized bearing in which the number of grooves approaches infinity, but it is expected that the equation would apply quite well to a bearing with a large but finite number of grooves. An analytical solution is obtained for the pressure distribution around a spiral-grooved, cylindrical journal bearing valid for small eccentricities and incompressible lubricant. The analysis shows that appropriate grooving of journal bearings can result in a significant improvement in radial stiffness and a significant decrease in attitude angle for the bearing. These results indicate that grooving could be used to enhance the stability of journal bearings.

64-145

Walkling, E.S.

JACKING SYSTEM FOR GAS BEARINGS. U.S. Patent 3,162,492. (to Bristol Siddeley Engines Limited). Applied October 27, 1961. Issued December 22, 1964.

This patent refers to an externally-pressurized means for jacking a rotor, normally supported on self-acting bearings, and creating separation of bearing and rotor at starting and under other conditions when the self-acting film is inadequate to support the load.

- 64-146 Warnock, Lyle.
SQUEEZE-FILM TECHNIQUE SUSPENDS INERTIAL GYROS, ACCELEROMETERS.
Aviation Week, vol. 81, no. 18, pp. 48 and 52. (November 2, 1964).

Lear Siegler's Instrument Div. has developed a technique which involves air suspension of an accelerometer mass or a gyro's precession axis but, unlike previous air bearings, it does not require an external air source nor does it require motion of the supported member to develop the suspension forces.

- 64-147 Wernick, R.J. and C.H.T. Pan.
STATIC AND DYNAMIC CHARACTERISTICS OF SELF-ACTING, PARTIAL-ARC, GAS JOURNAL BEARINGS. Trans. ASME, (J. Basic Engng.), vol. 86 D, no. 2, pp. 405-413. (June 1964).

The Reynolds equation applicable to a self-acting partial-arc gas journal bearing is perturbed in terms of the compressibility number Λ . The resulting set of equations is then put into a standard form and Galerkin's method is used to obtain bearing loads and stability derivatives. These results are expressed in a power series in Λ .

- 64-148 Whitley, Stanley
INSTABILITIES IN SELF-ACTING BEARINGS. Gas Lubricated Bearings, edited by N.S. Grassam and J.W. Powell. Butterworths, 1964.
pp. 85-109.

Topics discussed include vibrations of the thrust plate, synchronous shaft vibrations and half-speed whirl. Experimentally determined values of dynamic stiffness are presented for plain bearings, bearings with holes or axial slots, with circumferential pumping grooves, and pad bearings. An appendix deals with the stability of self-acting bearings and outlines new theoretical work by H. Marsh dealing with half-speed whirl.

- 64-149 Wilcock, D.F.
DESIGN AND PERFORMANCE OF GAS-PRESSURIZED, SPHERICAL, SPACE-SIMULATOR BEARINGS. Paper 64-Lub-76 presented at ASME and ASLE International Lubrication Conference, Washington, D.C. October 13-16, 1964.

This paper consists of a consideration of space-simulator bearings of the externally-pressurized, gas-lubricated type and of the stringent requirements they must meet. Of primary importance is that they contribute as nearly as possible zero error torque to the supported simulator structure, and that changes in this torque, as the structure is rotated as desired about all three axes, be

extremely small. The bearing must be stable and free of vibration under all conditions and, under the more sophisticated simulators, the bearing must sustain lateral as well as vertical loads with close control of film thickness. Bearing-design parameters and equations are established. A detailed computer analysis explains why these bearings cannot be operated below a certain minimum film thickness. Error torques resulting from flaws or scratches in the bearing and sphere surfaces are analyzed and found to increase with film thickness. Bearing-error torque is found to increase as the square of the load.

64-150 Wildmann, M.

FOIL BEARINGS - THEIR GENERAL BEHAVIOR WITH PARTICULAR EMPHASIS ON THE EXTERNALLY PRESSURIZED BEARING. Ampex Corporation. Res. and Engng. Pub. RR-64-13. (December 1964).

The equations describing the behavior of foil bearings are set forth. Linearized solutions to these equations are obtained. These solutions are used to examine the effects of foil stiffness and lubricant compressibility. Finally, the behavior of a foil of finite stiffness in the vicinity of a pressurizing groove is analyzed in detail, and the results of this analysis are used to design externally pressurized foil bearings.

64-151 Wildmann, M.

GROOVED PLATE GAS LUBRICATED THRUST BEARINGS, WITH SPECIAL REFERENCE TO THE SPIRAL GROOVE BEARING. Paper 64-Lub-25 presented at ASME-ASLE International Lubrication Conference, Washington, D.C., October 13-16, 1964.

The basic equations governing the behavior of spiral-groove, gas-lubricated thrust bearings are derived, and the assumptions made during this derivation are stated and explained. From these equations expressions for load of spiral groove thrust-bearings are obtained and optimum performance curves are presented.

64-152 Wildmann, M., J. Glaser, W.A. Gross, D.E. Moors, L. Rood and S. Cooper.

GAS-LUBRICATED STEPPED THRUST BEARING - A COMPREHENSIVE STUDY. Paper 64-LubS-6 presented at the ASME Lubrication Symposium, Cleveland, Ohio, April 28-30, 1964.

The theoretical part of this paper is based on Ausman's analysis of gas-lubricated stepped slider bearings, but presented in simpler form. Experimental data in this paper verify Ausman's solution. A correlation is attempted, and the design procedure given here is based upon a combination of the Ausman theoretical method and these experimental studies.

64-153 Wildmann, M. and A. Wright.

THE EFFECT OF EXTERNAL PRESSURIZATION ON SELF-ACTING FOIL BEARINGS. Paper 64-Lub-20 presented at the ASME-ASLE International Lubrication Conference, Washington, D.C., October 13-16, 1964.

The effects of introducing a small amount of lubricant under pressure into a self-acting foil bearing film are investigated. Foil shape and pressure distribution under the foil are obtained by combining the equilibrium equation with the Reynold's equation and solving the resulting equation. The results show that the effect of even small external pressurization in a self-acting foil bearing is very important.

64-154 Wilhoeft, W.W. and A.H. Mankin.

AIR BEARING. U.S. Patent 3,158,412. (to IMC Magnetics Corp.).
Applied October 16, 1962. Issued November 24, 1964.

This patent refers to (small) electric motors where the rotating cylindrical element is supported by a sleeve type journal bearing and is restrained from axial motion by a double-acting thrust bearing.

64-155 Wunsch, H.L.

THE APPLICATION OF EXTERNALLY PRESSURIZED AIR BEARINGS TO MEASURING INSTRUMENTS AND MACHINE TOOLS. Gas Lubricated Bearings, edited by N.S. Grassam and J.W. Powell.
Butterworths, 1964. pp. 263-280.

Design features and performance data for various applications are given. The devices discussed are a pneumatic roundness measuring machine, rotary measuring table, feed screw measuring bench, transmission dynamometer, high speed ball-bearing test rig, vibration equipment, and slideways. Work described was performed by the National Engineering Laboratory.

64-156 Wunsch, H.L. and W.M. Nimmo.

THE ROTATIONAL ACCURACY OF AIR JOURNAL BEARINGS. Mach. Shop, no. 11, pp. 526-529. (1964).

What is the effect of dimensional inaccuracies of the shaft and housing of an air journal bearing on its truth of rotation at slow speed and negligible radial loading? To answer this question the National Engineering Laboratory (British) carried out experiments on a vertical air journal bearing. The results indicate that the effect of the air film is to increase the rotational accuracy beyond that to be expected from the dimensional accuracy of the component parts of the bearings.

* The following list is an index of those periodicals, of the 2500 periodicals screened, found to contain papers pertinent to gas-lubricated bearings.

LIST OF PUBLICATIONS ABSTRACTED *

Aeronaut. Quart.	Aeronautical Quarterly, London.
Aerospace Engng.	Aerospace Engineering, New York.
Amer. J. Phys.	American Journal of Physics, New York.
ASLE Trans.	American Society of Lubrication Engineers Transactions, New York.
Appl. Mech. Rev.	Applied Mechanics Reviews.
Appl. Sci. Res. (A)	Applied Scientific Research, section (A) mechanics, heat, The Hague
Atomkernenergie	Atomkernenergie
Atomwirtschaft	Atomwirtschaft
Aviation Week	Aviation Week and space technology, New York.
Brown Boveri Mitt.	Brown Boveri Mitteilungen.
Bull. JSME	Bulletin of the JSME. Tokyo
Certif. Engr.	Certificated Engineer.
Chartered Mech. Engr.	Chartered Mechanical Engineer, London.
Chem. Week	Chemical Week.
Compressed Air Magazine	Compressed Air Magazine.
Compt. Rend. Acad. Sci., Paris	Comptes Rendus de l'Academie des Sciences, Paris.
Control Engng.	Control Engineering, New York.
Design News	Design News.
Dissert. Abst.	Dissertation Abstracts.
Electromech. Components Systems Design	Electromechanical Components and Systems Design.
Engineer	Engineer, London.
Engineering	Engineering, London.
Engng. Mats. and Design	Engineering Materials and Design.
Engng. News Record	Engineering News Record.

Feingeratetechnik	Feingeratetechnik, Berlin, D.D.R.
Feinwerk Tech.	Feinwerk Technik.
Groove	Groove.
Hydraulics and Pneumatics	Hydraulics and Pneumatics, Cleveland, Ohio.
Instrum. Prac.	Instrument Practice.
ISA Trans.	Instrument Society of America Transactions.
IBM Tech. Disc. Bull.	International Business Machines, Technical Disclosure Bulletin.
Internat. J. Mach. Tool Design Res.	International Journal of Machine Tool Design and Research, Oxford.
Internat. Sci. Technol.	International Science and Technology.
Iron Age	Iron Age.
Izv. Akad. Nauk SSSR, Otd. Tekh. Nauk, Mekh. i Mashinostr.	Izvestiya Akademiia Nauk SSR, Otdeleni Tekhnicheskikh Nauk, Mekhanika i Mashinostroenie, Leningrad.
J. Aerospace Sci.	Journal of the Aerospace Sciences, New York.
J. Appl. Phys.	Journal of Applied Physics, New York.
J. Iron Steel Inst.	Journal of the Iron and Steel Institute, London.
J. Japan Soc. Lubr. Engrs.	Journal of Japan Society of Lubrication Engineers, Tokyo. (Junkatsu).
J. Japan Soc. Prec. Engng.	Journal of Japan Society of Precision Engineering.
J. Mecan.	Journal de Mecanique, Paris.
J. Mech. Engng. Sci.	Journal of Mechanical Engineering Science, London.
J. Phys. Rad., Phys. Appl.	Journal de Physique et le Radium, Physique Appliquee.
J. Refrig.	Journal of Refrigeration.
J. Res. Nat. Bur. Stand. (Engng. Instrum.)	Journal of Research, National Bureau of Standards, Section C (Engineering and Instrumentation), Washington, D.C.
J. Sci. Instrum.	Journal of Scientific Instruments and of physics in industry, London.

Konstruktion	Konstruktion.
Light Metal Age	Light Metal Age
Lubrication Engng.	Lubrication Engineering, Chicago.
Mach. Design	Machine Design, Cleveland, Ohio
Mach. Shop	Machine Shop.
Mach. Market	Machinery Market
Maschinenbautechnik	Maschinenbautechnik, Berlin.
Matls. in Design Engng.	Materials in Design Engineering.
Matls. Res. Digest	Materials Research Digest.
Mech. Engng.	Mechanical Engineering, New York
Mem. Soc. Ingen. Civils Fr.	Memoires de la Societe des Ingenieurs Civils de France, Paris
Military Sys. Design	Military Systems Design.
Mill and Factory	Mill and Factory.
Missiles and Rockets	Missiles and Rockets, Washington, D.C.
Modern Matls. Handl.	Modern Materials Handling.
MPB Engng. News	MPB Engineering News.
Nat. Bur. Stand. Tech. News Bull.	National Bureau of Standards Technical News Bulletin, Washington, D.C.
Nat. Bur. Stand. Tech. Note	National Bureau of Standards Technical Note, Washington, D.C.
Naval Engrs'. J.	Naval Engineers' Journal, Washington, D.C.
New Scientist.	New Scientist.
Philips Tech. Rev.	Philips Technical Review, Eindhoven.
Phil. Trans. Roy. Soc. London	Philosophical Transactions of the Royal Society of London, series (A)
Prace, Instytut Lotnictwa	Prace, Instytut Lotnictwa.
Proc. Inst. Mech. Engrs.	Proceedings of the Institution of Mechanical Engineers, London.
Proc. Roy. Soc. London, (A)	Proceedings of the Royal Society of London, series (A) mathematical and physical sciences.
Prod. Engng.	Product Engineering, New York.
Progr. in Nuclear Ener.	Progress in Nuclear Energy.
Rev. Mecan. Appl.	Revue de Mecanique Appliquee, Bucharest

Rev. Roumaine Sci. Techn., Serie Mecan. Appl.	Revue Roumaine des Sciences Techniques, Serie de Mecanique Appliquee (formerly Revue de Mecanique Appliquee). Bucharest
Schmieretechnik	Schmieretechnik.
Sci. Lub.	Scientific Lubrication.
SAE J.	Society of Automotive Engineers Journal.
Sperry Engng. Rev.	Sperry Engineering Review.
Steel	Steel.
Studii si Cercetari Mecan. Apl., Inst. Mecan. Apl., Acad. Republ. Pop. Romine.	Studii si Cercetari de Mecanica Aplicata, Institutul de Mecanica Aplicata, Academia Republicii Populare Romine, Bucharest.
Sulzer Tech. Rev.	Sulzer Technical Review, Winterthur.
Trans. ASME, (J. Engng. Power)	Transactions of the American Society of Mechanical Engineers, Series (A), (Journal of Engineering for Power), New York.
Trans. ASME, (J. Engng. Industry)	Transactions of the American Society of Mechanical Engineers, Series (B), (Journal of Engineering for Industry), New York.
Trans. ASME, (J. Heat Transfer)	Transactions of the American Society of Mechanical Engineers, Series (C), (Journal of Heat Transfer), New York.
Trans. ASME, (J. Basic Engng.)	Transactions of the American Society of Mechanical Engineers, Series (D), (Journal of Basic Engineering), New York.
Trans. ASME, (J. Appl. Mech.)	Transactions of the American Society of Mechanical Engineers, Series (E), (Journal of Applied Mechanics), New York.
Trans. Japan Soc. Mech. Engrs.	Transactions of the Japan Society of Mechanical Engineers, Tokyo.
Trenie Iznos Mash.	Trenie i Iznos v Mashinakh.
Trudy Leningr. Politekh. In-ta.	Trudy Leningradskogo Politekhnikheskogo Instituta.
Wear	Wear, Amsterdam
Werkstatt u. Betrieb	Werkstatt und Betrieb, Munich.
Western Metalworking	Western Metalworking.
Zurich. Eidgenossischen Technischen Hochschule. Inst. fur Aerodynamik. Mitt.	Zurich. Eidgenossischen Technischen Hochschule. Institut fur Aerodynamik. Mitteilungen.

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<u>UNITED STATES</u>		
2,670,146	00-018	WINDING MACHINE.
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2,862,385	00-054	VIBRATION TABLE.
2,864,552	00-002	SHAFT OR LIKE BEARINGS.
2,869,901	00-014	BALL AND SOCKET COUPLING HAVING AIR BEARING MEANS.
2,884,282	00-040	BEARINGS FOR ROTATING SHAFTS WHICH ARE LUBRICATED BY GAS.
2,886,651	00-047	AIR HEAD.
2,888,878	00-010	NEUTRONIC REACTOR FUEL PUMP.
2,889,474	00-024	AIR SUPPORTED ROTOR.
2,899,260	00-015	MAGNETIC DISC RECORDER.
2,905,768	00-012	AIR HEAD.
2,908,164	00-006	BEARINGS WITH FORCE INDICATING MEANS.
2,915,358	00-037	RECORDING MEMBER ASSEMBLY FOR COMPUTER OR THE LIKE.
2,915,902	00-008	AUXILIARY BEARINGS FOR SENSITIVE INSTRUMENTS.
2,928,960	00-025	DYNAMOELECTRIC DEVICE.
2,929,548	00-013	TURBOCOMPRESSOR.
2,929,671	00-045	COMPUTER DRUM CONSTRUCTION.
2,937,294	00-026	DYNAMOELECTRIC DEVICE WITH FLUID SUPPORTED ROTOR.
2,942,385	00-030	APPARATUS FOR MOVING PARTS OF MACHINERY ON A SUPPORT.
2,951,729	00-041	GAS BEARING.

<u>Patent No.</u>	<u>Abstract No.</u>	<u>Patent Title</u>
3,006,697	61-043	GAS LUBRICATED BEARING.
3,012,827	61-022	GAS SUPPORTED BEARING.
3,013,845	61-027	SUPPLYING SUPPORTING GAS TO A GAS PRESSURE BEARING.
3,026,150	62-021	AIR BEARINGS.
3,034,635	62-011	AIR BEARINGS.
3,034,837	62-012	GAS LUBRICATED JOURNAL BEARING ASSEMBLIES.
3,039,830	62-119	JOURNAL BEARINGS.
3,042,460	62-044	SLIDE BEARING CONSTRUCTION.
3,049,363	62-070	DAMPING VIBRATIONS IN A GAS BEARING.
3,053,583	62-099	AIR BEARING.
3,058,785	62-107	GAS LUBRICATED BEARINGS.
3,070,406	62-075	AIR BEARINGS.
3,070,407	62-058	AIR BEARING.
3,079,203	63-095	JOURNAL AND JOURNAL BEARING ASSEMBLIES.
3,107,129	63-013	GAS LUBRICATED BEARING SYSTEM.
3,110,525	63-087	COMBINED JOURNAL AND THRUST BEARING.
3,110,527	63-028	HYDROSTATIC BEARING.
3,110,528	63-072	SHAFT BEARINGS.
3,129,037	64-102	GAS-LUBRICATED JOURNAL BEARINGS.
3,136,589	64-119	AIR BEARING.
3,137,531	64-067	GASEOUS BEARING.
3,140,853	64-074	BEARINGS.
3,143,382	64-046	AERODYNAMIC BEARING.
3,146,036	64-023	GAS BEARINGS.
3,152,845	64-047	AIR BEARING.

<u>Patent No.</u>	<u>Abstract No.</u>	<u>Patent Title</u>
3,158,412	64-154	AIR BEARING.
3,158,924	64-026	METHODS OF MANUFACTURING JOURNAL AND JOURNAL BEARING MEMBERS.
3,162,492	64-145	JACKING SYSTEM FOR GAS BEARINGS.
<u>FRANCE</u>		
1,307,545	62-037	OPERATING PROCESS FOR A MOTIVE POWER INSTALLATION COMPRISING A NUCLEAR REACTOR, AND DEVICE FOR PERFORMING THIS PROCESS.
<u>GREAT BRITAIN</u>		
870,829	61-016	IMPROVEMENTS IN OR RELATING TO CENTRIFUGAL PUMPS AND APPARATUS FOR SAMPLING RADIO-ACTIVE LIQUIDS.
876,136	61-006	IMPROVEMENTS IN OR RELATING TO GAS BEARING SYSTEMS.
877,555	61-047	IMPROVEMENTS IN AND RELATING TO BEARINGS.
884,061	61-002	GYROSCOPES, GYROSCOPE STABILISED SYSTEMS AND GAS BEARINGS FOR THE SAME.
887,695	62-121	IMPROVEMENTS IN OR RELATING TO THRUST BEARINGS.
891,039	62-120	IMPROVEMENTS IN OR RELATING TO GAS LUBRICATED JOURNAL AND JOURNAL BEARING ASSEMBLIES IN PUMPS.
893,045	62-035	IMPROVEMENTS TO FLUID BEARINGS.
895,328	62-100	IMPROVEMENTS IN DYNAMIC GAS BEARINGS.
901,004	62-040	IMPROVEMENTS IN AND RELATING TO GAS BEARINGS.
903,055	62-018	IMPROVEMENTS IN FLUID FILM DYNAMIC BEARING-SYSTEMS.
905,647	62-013	IMPROVEMENTS IN OR RELATING TO JOURNAL AND BEARING ASSEMBLIES.
911,490	62-019	IMPROVEMENTS IN OR RELATING TO GYROSCOPES.
923,732	63-058	IMPROVEMENTS IN OR RELATING TO FREE PISTON COMPRESSORS WITH GAS BEARINGS.

<u>Patent No.</u>	<u>Abstract No.</u>	<u>Patent Title</u>
930,813	63-017	IMPROVEMENTS IN AND RELATING TO AIR LUBRICATORS.
950,967	64-117	IMPROVEMENTS IN AND RELATING TO PINNLE THRUST BEARINGS.
<u>WEST GERMANY</u>		
1,177,878	64-123	BEARINGS.
1,183,744	64-139	[GAS-LUBRICATED, STATIC JOURNAL BEARING]. GASGESCHMIERTES STATISCHES GLEITLAGER. (in German).