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SUMMARY OF GAS BEARING APPLICATIONS IN THE FIELD OF SPACE ELECTRIC POWER SYSTEMS

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ABSTRACT

The NASA-Lewis Research Center is investigating the technology of closed Brayton cycle electric power systems for space. The turbine-alternator-compressor power conversion unit for such a system is designated Brayton Rotating Unit (BRU). In parallel to power system testing, a BRU improvement effort was initiated. The objectives of this effort are to improve the BRU reliability, potential life and ability to accept shock and vibration. A major portion of this effort involves the testing and evaluation of different bearing systems. A description of each bearing is presented along with results of the evaluation to date and a comparison of the merits and limitations of each bearing.

THE NASA-LEWIS RESEARCH CENTER is investigating the technology for closed Brayton cycle electric power systems for space (1)*. One system presently under test was designed to produce 2- to 15-kW net continuous electric power for at least five years. The testing to date has demonstrated that the system meets or exceeds design performance objectives. Insufficient test time has been accumulated to demonstrate the five-year operational goal; however, the test results do indicate that there is no apparent time limitation on operation.

The turbine-alternator-compressor power conversion unit in this system is designated Brayton Rotating Unit (BRU). The BRU has gas bearings which consist of a double-acting Rayleigh-step, thrust bearing and two tilting-pad journal bearings with the pads pivoted on full conforming ball-and-socket pivots. The bearings are lubricated by the system working fluid.

Four BRU's have been tested and have accumulated in excess of 12 000 hours of running time (10 500 hours on one unit). Post-test inspections of these units have shown that there is no apparent limitation on the life and that the journal bearings are extremely tolerant to high-speed rubs and the ingestion of particles larger than the bearing clearance. Post-test inspection of three units is reported in reference (2). Environmental testing has shown that the ability of the unit to accept shock and vibration is limited only by the bearing mounting system.

During the design and fabrication of the BRU, many questions were raised concerning the reliability and life of the bearing system. Of particular concern were the effects of light high-speed shaft-to-shoe contacts, the ingestion of hard particles into the bearing clearance space, the wear or life characteristics of the fully-conforming pivots, and the tolerance of the required shock and vibration environment. The original bearings were, therefore, backed up by several different gas-bearing programs. These programs consisted of the design, fabrication and testing of a spiral groove thrust bearing; nonconforming, pivoted-pad journal bearings; a flexure-supported pad journal bearing and a foil-type journal bearing.

In parallel with the power system testing and as a part of the Brayton cycle technology program, a BRU improvement effort was initiated. The objectives of

*Numbers in parentheses designated References at end of paper.

this effort are to improve total system reliability, BRU potential life, and the ability of the BRU to accept shock and vibration. A major portion of this effort involves the testing and evaluation of alternate bearing systems. A description of each bearing is presented along with results of the evaluation to date and a comparison of the merits and limitations of each bearing.

BRU DESCRIPTION

The BRU, designed and fabricated by the AiResearch Manufacturing Company, is shown in figure 1 and described in reference (3). The rotating assembly which operates at a design speed of 36 000 rpm includes a radial-outflow single-stage compressor, a four-pole modified-Lundell alternator and a radial-inflow single-stage turbine. The severe axial thermal gradient resulting from the turbine inlet temperature of 1600° F and the compressor inlet temperature of 80° F, the extended range of operation (2.0 to 15 kWe), and the rotational speed that requires operation between the second and third system critical speeds presented a difficult problem in the design of the rotor-bearing system.

The rotating assembly is supported by two pivoted-pad gas journal bearings and a double-acting thrust bearing. At design speed the bearings operate in the hydrodynamic mode. External pressurization is provided for hydrostatic operation during startup and shutdown. A journal-bearing assembly is shown in figure 2. Each of the three pads in each journal bearing is pivoted on a lapped ball-socket joint of 0.2500 in. radius and fabricated from solid tungsten carbide (K 96). The ball end of one pivot of each bearing is flexibly supported radially with respect to the bearing carrier on a resilient mount having a nominal spring rate of 2000 lb/in. This low spring rate makes it necessary to assemble the bearing with an 8- to 10-pound preload. A fully conforming ball-and-socket pivot was selected because the total-area contact provides a good seal for the hydrostatic gas which is supplied to the pad through the pivot. This configuration does, however, result in pure sliding at the contacting surface.

The thrust bearing assembly consists of a flat-disc runner (integral with the rotor) and a pair of mirror-image Rayleigh-step stator plates. The thrust bearing assembly is shown in figure 3. To facilitate alignment of the stator faces with the thrust rotor, the stator assembly is mounted on a flexure-pivoted gimbal. The motion about each gimbal axis is damped by two lightly-loaded friction pads shown in figure 4.

BEARING DESCRIPTION AND TEST RESULTS

The Brayton technology program has included in addition to the original BRU bearings the testing of three pivoted-pad journal bearing configurations, two foil-type journal bearings, Rayleigh-step and spiral-groove thrust bearings. The pivoted-pad bearings all have the same hydrodynamic or pad design but incorporate different pivot designs. These include a fully-conforming and a nonconforming ball and socket pivot and a cruciform flexure pivot.

ORIGINAL BRU BEARINGS - The fully-conforming pivoted pads and the Rayleigh-step bearing described above were designed as a part of the BRU and are the bearings that have been used in all BRU component and system testing. Four BRU's have accumulated in excess of 12 000 hours of operation. The unit presently on endurance test has accumulated 10 500 hours.

Testing and inspection of these units after 700, 3000, and 5700 hours reveal the following results. After initial pivot wear-in, which occurs in less than 700 hours, additional pivot wear cannot be detected for operation to 5700 hours. A system malfunction resulted in particle contamination of the bearing cavity of BRU #4. Some of these particles were ingested by the journal bearings, causing severe scoring of the shaft and shoe surfaces. This particle ingestion also resulted in high-speed shaft-to-shoe contacts. The thrust bearing, except for surface discolorations, was in the as-built condition. Prior to disassembly there was no indication that this damage had occurred. Rotor dynamic performance observed throughout the test was normal.

Vibration tests with a BRU simulator demonstrated that this bearing system has a low tolerance level to input random vibrations. This appears to be the result of the relatively low spring rate of the flex beam in each journal.

NONCONFORMING PIVOTS - The nonconforming pivots were introduced very early in the program as a backup to the fully-conforming pivots. There was concern that excessive wear would limit the life of the fully-conforming pivot. A 0.375-inch diameter ball in a 0.390-inch diameter socket minimizes the relative motion between the surfaces in the contact zone. It does, however, increase the unit load in the contact zone and during hydrodynamic operation would allow some of the film pressure to bleed off through the hydrostatic orifice and the pivot joint. This necessitates a check valve between the pivot and the shoe face.

The nonconforming pivoted-pad journal bearing (designed and fabricated by Mechanical Technology, Inc.) is shown in figure 5. The chrome-oxide-coated pad is supported by a removable tool-steel nonconforming pivot and seat. Hydrostatic (externally-pressurized) lift-off is provided each pad during start-up and shutdown. Hydrostatic lift-off is obtained via a single hydrostatic orifice and a flow-control valve located within each pad. The pivot rod of one pivot of each bearing is flexibly supported radially with respect to the bearing carrier on a resilient mount having a nominal spring rate of 2000 lb/in.

This bearing has been tested cold in a BRU simulator and has demonstrated adequate load capacity and dynamic stability. The accumulated test time is only 25 hours; therefore, no evaluation of pivot wear can be made.

CRUCIFORM PIVOT - The cruciform pivoted-pad bearings were designed and fabricated by Mechanical Technology, Inc. to eliminate the metal-to-metal sliding contact in the pivot and, thus, eliminate the potential pivot-wear problem. The cruciform bearing segment shown in figure 6 is composed of three parts: chrome-oxide-coated pad, the cruciform flexure and the bearing support by which the mount is attached to the BRU bearing carrier. The cruciform flexure consists of two orthogonal flexure beams with low stiffness in the pitch, roll and yaw directions of the individual tilting pad and high stiffness in the radial direction. Each end of the beam is attached to a transverse member by which it is held in a fixed relationship to the adjacent member. The transverse member of one beam fits into the recess between the lugs on the bearing pad and is attached to the pad by electron-beam welding. Similarly, the other transverse member is attached between the lugs of the bearing support forming the cruciform-supported tilting-pad segment. The operating stresses in the flexures are low enough that the fatigue life of the flexures should not limit the operating life of the unit.

Single-pad hydrostatic tests that were performed showed no significant difference in the performance between this bearing and nonconforming pivoted-pad bearing. No hydrodynamic tests have been performed on this bearing at this time.

RIBBON-FOIL JOURNAL BEARING - A ribbon-type of foil journal bearing has been developed by the Ampex Corporation under contract with NASA. This concept has been tested extensively in a bearing test fixture and is presently being installed in a BRU for testing. Figure 7 shows a schematic of the bearing and shaft in cross-section. A metal foil approximately 0.002 in. thick and 1.5 in. wide is threaded through the positioning pins as shown. At assembly the foil is preloaded in tension and secured by the clamping block. The foil bearing has several desirable features. It is free of dynamic instabilities inherent in fixed geometry bearings and will accommodate distortion resulting from thermal gradients. Its performance is relatively insenitive to misalignment and the pliable foil should be highly forgiving of ingested particles and high-speed rubs.

Testing to date has verified the predicted performance of this bearing and has demonstrated its capability to start and stop without external pressurization.

SPIRAL-GROOVE THRUST BEARING - The spiral-groove thrust bearing and gimbal shown in figure 5 were designed as a backup to the Rayleigh-step bearing. The objective was to increase the load-carrying capacity or operating film thickness.

This thrust bearing consists of two flat plates bolted together at the periphery and separated by a spacer that is 0.004 in. thicker than the thrust runner. The surface of each stator plate is chrome-oxide coated and contains both the spiral grooves for hydrodynamic bearing operation and a number of orifices for hydrostatic bearing operation. The bearing assembly is flexibly supported by four spokes from an outer member which locates and attaches the thrust-bearing assembly to the frame.

This bearing has been tested in conjunction with the nonconforming pivoted pads. Performance evaluation was not possible because a gimbal instability prevented operation of the thrust bearing in the hydrodynamic mode. Excessive gimbal motions developed when making the transition from the hydrostatic to the hydrodynamic mode. This gimbal is presently being modified to provide coulomb damping. Testing will be continued.

LEAF-TYPE OF FOIL JOURNAL AND THRUST BEARING - A foil journal bearing and a foil thrust bearing, using over-lapping leaf-type foils, have been developed by the AiResearch Company. These bearings have been assembled and tested in a BRU simulator. Testing has been done with the unit in a vertical position and repeated starts have been accomplished without external pressurization. Repeated shock loads in excess of 100 g have been applied to the housing in a direction normal to the shaft with the unit running at design speed. No adverse effect was noted in bearing performance.

A BRU is being retrofitted with this bearing system and will be tested under design thermal conditions.

DISCUSSION OF RESULTS

Presentation of the bearing test results and a comparison of the merits of the bearings systems considered for BRU application can best be accomplished by comparing each bearing to a list of those bearing characteristics desired for this application. Such a comparison is made in table I.

Eight desired bearing characteristics are listed in column headings in the table:

1. Load capacity
2. Dynamic stability
3. Thermal integrity - tolerance of both operating temperature and thermal transients

4 & 5. Ability to withstand rubs and ability to ingest particles - These characteristics greatly increase tolerance of abuse and reliability.

6. Dry-start capability - Eliminates the need for external pressurization for starting and stopping which, in turn, eliminates a complex gas management system and associated electronic controls.
7. 50 000-hour life - This is the most difficult characteristic to verify; endurance testing cannot be accelerated and extrapolations are questionable.
8. Resistance to shock & vibration - Definite requirements cannot be specified without a definition of the application and mission. The objective at this time, therefore, is to explore the tolerance limits of the various bearing designs.

The bearing systems under consideration are listed vertically and can be evaluated on the basis of their ability to satisfy the desired requirements. The shaded block indicates that the bearing has demonstrated the ability to satisfy that requirement defined in the column heading. The cross hatched block indicates that, based on design characteristics and the present state-of-the-art, the bearing can probably satisfy the requirement but this has not been verified by test.

All bearings have demonstrated adequate load capacity and dynamic stability except the spiral-groove thrust bearing and its gimbal. This bearing should have more load capacity than the Rayleigh-step bearing because it is a larger bearing. The cruciform and the nonconforming pivoted journal bearings demonstrate the same thermal integrity as the nonconforming pivoted journal bearing since they have the same basic shoe design. The ability of the journal bearing to withstand rubs and ingest particles is enhanced by the low spring rate of the flex mount. The flex-mounted shoe moves out and opens the clearance circle, allowing an ingested particle to pass through the clearance space. This same feature damps out the violent shaft motions that result from a high-speed rub. All the pad bearings have this same mounting system and, therefore, should exhibit the same capability in this area. The foil bearing should have an even greater tolerance to particles and rubs.

The foil-type bearings are the only bearings of those investigated for this application that are presently capable of dry starting. The tilting-pad journals were not designed with this as an objective and will, therefore, have to be modified to eliminate the clamping preload before dry starts can be accomplished. The Rayleigh-step and spiral-groove thrust bearings would also have to be modified to reduce the starting torque required to dry start.

Vibration tests of the prototype bearing system demonstrated that under certain conditions there was separation between the ball and socket of the pivot. This could result in severe wear in the pivot joint. The cruciform-supported mounted pad would eliminate this problem. The flex beam used with the tilting pads must be modified to prevent excessive deflection under extreme shock or vibration loads. The limited shock loads sofar applied to the BRU simulator with leaf-type foils indicate that they will offer the greatest resistance to shock and vibration.

Endurance testing of the engine and prototype bearings is continuing. The spiral-groove thrust bearing will be modified and tested cold with the cruciform journals in a BRU simulator. The ribbon foil journal bearings will be cold tested with the prototype thrust bearing and a BRU shaft assembly. A BRU is being retrofitted with leaf-type foils and will be tested in a hot closed loop.

CONCLUDING REMARKS

The fully-conforming pivoted-pad journal and the Rayleigh-step thrust bearings have demonstrated life capability in excess of 10 000 hours and there is no apparent indication that they cannot achieve 50 000 hours. Modifications are required to improve their resistance to shock and vibration and to provide dry-start capability.

The cruciform-mounted bearing pivots on flexure beams with low resulting flexure stress should eliminate the potential problem of pivot life. It should perform in all respects as well as the fully-conforming pivoted-pad bearing and should offer increased pivot life. This, however, remains to be verified.

The spiral-groove thrust bearing and gimbal is being modified to correct the observed instability. If the performance is not affected by thermal distortion, the increased operating film thickness will improve the resistance to shock and vibration relative to the original bearing system.

The ribbon-foil journal bearing, having no wear points, will have greater life than the ball-and-socket pivoted-pads. It also has the advantage of dry-start capability. This type of foil, however, cannot be adapted to the thrust bearing. The ability of this bearing to limit shaft excursions under shock loads is yet to be evaluated.

The leaf-type foil thrust and journal bearings have demonstrated adequate load capacity, dynamic stability, the ability to accept shock loads in excess of 100 g, and the capability of operating the BRU without jacking gas. This system offers an additional advantage in that the assembly of the unit would be greatly simplified. The thrust bearing does not require a gimbal assembly and the complex beam-mounting assembly is eliminated.

REFERENCES

1. J. L. Klann and W. T. Wintucky, "Status of the 2-to-15 kWe Brayton Power System and Potential Gains from Component Improvements," NASA TM X-67835, 1971.

2. J. H. Dunn, "Post-Test Inspection of Three Brayton Rotating Units," NASA TM X-67841, 1971.

3. J. E. Davis, "Design and Fabrication of the Brayton Rotating Unit," NASA CR-1870, March 1972.

TABLE 1

	1	2	3	4	5	6	7	8
	Adequate load capacity	Dynamic stability	Thermal integrity	Ability to withstand rubs	Ability to ingest particles	Dry start capability	50 000 hr life	Resistance to shock and vibration
Fully conforming pivoted pad journal						Requires modification of beam	Tested to 10 500 hr	Requires improve-ment
Rayleigh step thrust					Particles in cavity were not ingested	Will result in high starting torque	Tested to 10 500 hr	
Nonconforming pivoted pad journal						Same as original	?	Same as original
Cruci-form journal						Same as original	Should be better than original	Should be better than original
Spiral groove thrust		Requires modifi-cation			Same as original	Will result in high starting torque		
Ribbon foil journal								?
Leaf foil journal and thrust								

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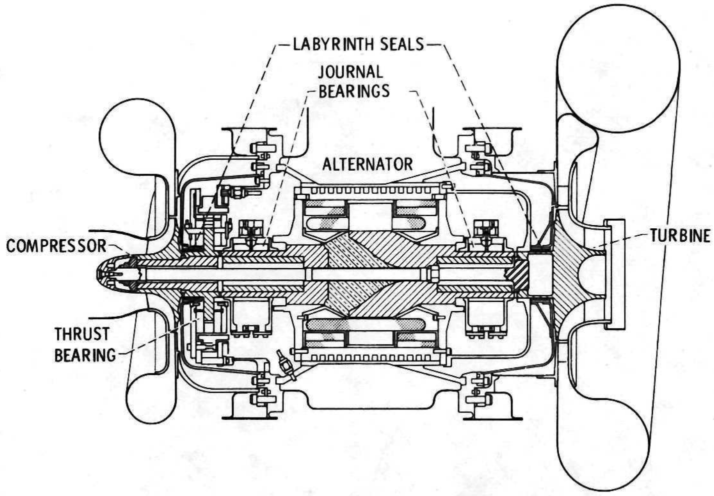

Figure 1. - Brayton rotating unit cross section.

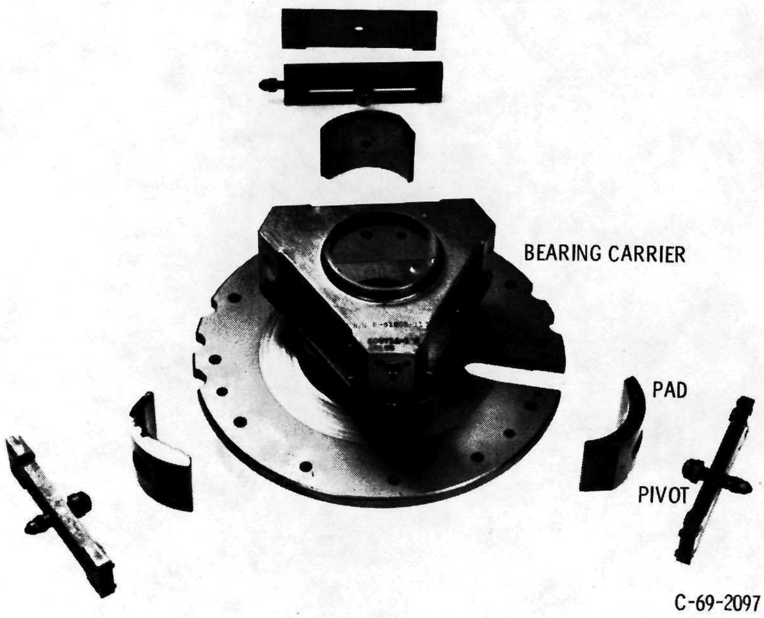

Figure 2. - Journal bearing assembly.

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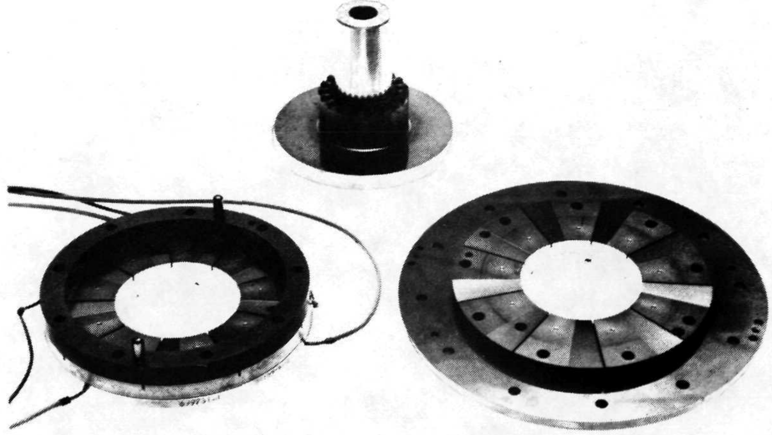

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Figure 3. - Thrust bearing stators and runner.

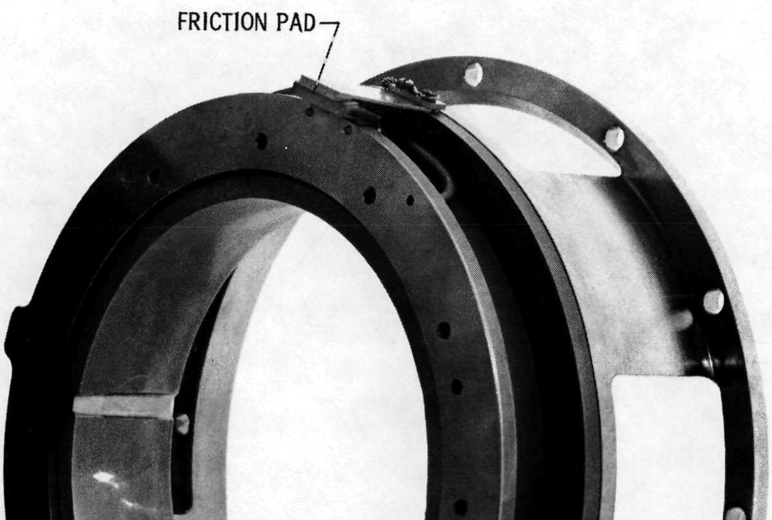

Figure 4. - Flexure pivoted gimbal assembly.

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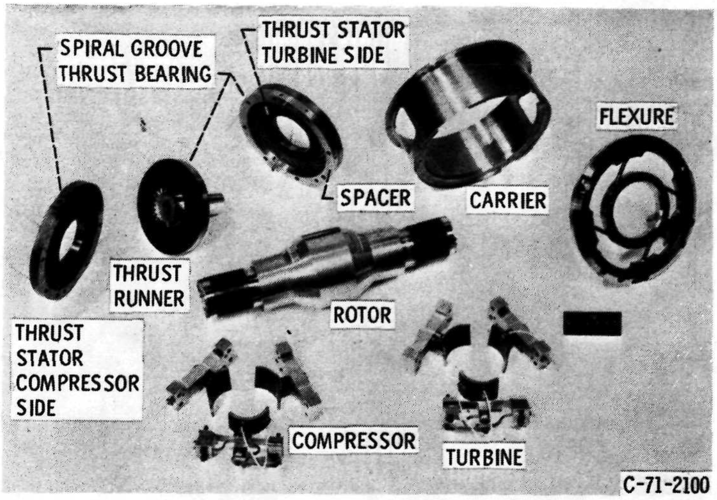

Figure 5. - Non-conforming tilting pad journal bearings.

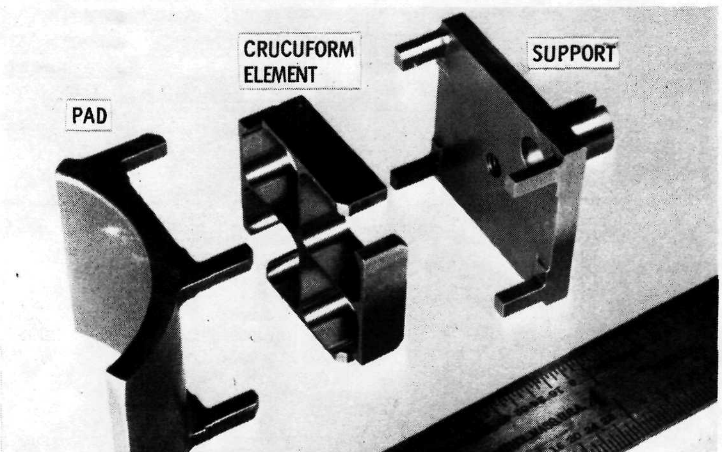

Figure 6. - Cruciform journal bearing.

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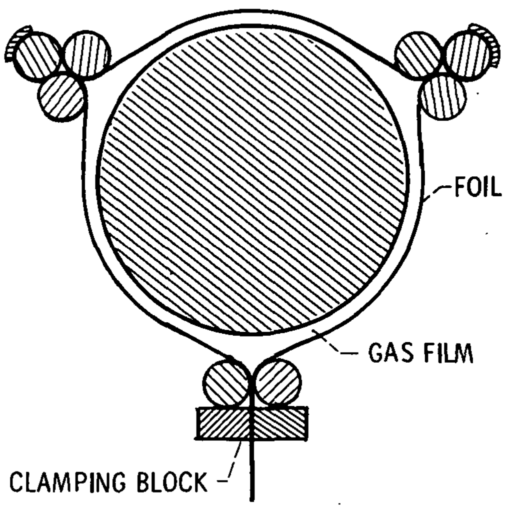

Figure 7. - Continuous Ribbon-Foil Journal Bearing.