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Tribological Limitations in Gas Turbine Engines: A Workshop to Identify the Challenges and Set Future Directions

Chris DellaCorte
Glenn Research Center, Cleveland, Ohio

Oscar Pinkus
Mohawk Innovative Technology, Inc., Albany, New York

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Chris DellaCorte
Glenn Research Center, Cleveland, Ohio

Oscar Pinkus
Mohawk Innovative Technology, Inc., Albany, New York

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TRIBOLOGICAL LIMITATIONS IN GAS TURBINE ENGINES: A WORKSHOP TO IDENTIFY THE CHALLENGES AND SET FUTURE DIRECTIONS

Chris DellaCorte
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Oscar Pinkus
Mohawk Innovative Technology, Inc.
Albany, New York 12205

SUMMARY

A Workshop cosponsored by NASA (Glenn Research Center), ASME (Tribology Division) and industry (Industrial Tribology Institute and Mohawk Innovative Technology) was convened to consider the tribological limitations that inhibit progress in present-day and future turbomachinery, particularly gas turbine engines. Parallel to the determination of such constraints the Workshop was to consider and evaluate a range of new technologies in the field of tribology that may eliminate or alleviate the present deficiencies. This gathering bears a close relation to the IHPTET program launched by the Government in 1988 to meet the challenges of advanced turbomachinery over the next decade and a half.

The Workshop was co-chaired by Dr. Hooshang Heshmat (Mohawk) and Dr. Christopher DellaCorte (NASA) who are both officers of ASME's Research Committee on Tribology (RCT). Represented at the Workshop were both small and large gas turbine manufacturers; the three U.S. armed services and NASA; and a number of participants from research group and Universities. The 3-day meetings were attended by some 40 people and consisted of the following schedule. Presentations were delivered by participants from industry, Government agencies and research organizations. Five subgroups were then formed focused on the following specialized areas: rolling element bearings together with the required materials, lubricants and seals; magnetic bearings plus back-up systems; compliant foil bearings including required materials and coatings; modeling of bearing performance and integration into the overall system; and advanced monitoring and predictive tools to serve the present and new technologies.

The five panels evaluated the range of available innovations against the existing tribological needs and prepared a list of development programs aimed at advancing the design of high performance turbomachinery. At the plenary meeting these lists were scrutinized and discussed in order to assign to them some hierarchical order of importance. In the final session a priority list was arrived at consisting of some 20 programs deemed most important for the future of advanced turbomachinery.

LIST OF ABBREVIATIONS

AB	Auxiliary (back-up) bearings
ACM	Air cycle machines
AGT	Aircraft gas turbines
APU	Auxiliary power unit
CFD	Computational fluid dynamics
CFB	Compliant foil bearings
DN	Diameter × speed (mm × rpm)
DoD	Department of Defense
EHD	Elastohydrodynamic process
FAA	Federal Aviation Administration
IHPTET	Integrated high performance turbine engine technology
ISG	Integral starter generator

ITG	Industrial turbogenerator
MB	Magnetic bearings
MEM	Micro electronic mechanism
REB	Rolling element bearing
RF	Radio frequency
SBIR	Small business innovative research
SFC	Specific fuel consumption
UAV	Uninhabited air vehicles

1.0 PREFACE

Gas turbines constitute the main prime movers in nearly all airborne vehicles ranging from commercial transports to military aircraft, ballistic missiles and the most advanced space vehicles. In addition they are the main components of turbocompressors, turbogenerators and a wide assortment of auxiliary machinery. Many land based conveyances such as the Army's AFV's and civilian automobiles are, likewise, converting from internal combustion engines to gas turbines. Consonant with the general technological advancement of these systems, gas turbines are required to operate at ever higher speeds, loads, and temperatures, as well as in such new environments as near-vacuum atmospheres and cryogenic fluids. Particularly demanding is their dynamic performance under the prevailing extreme speeds and g-forces. An essential ingredient in realizing these advanced models is the satisfactory functioning of their tribological elements involving the entire gamut of component design, lubricants, coatings, and materials. In addition, the taxing technical specifications are often coupled with requirements for lower costs and higher power densities in order to remain technologically ahead in the U.S. defense posture as well as commercially competitive in the world market.

It has been apparent for some time that tribological bottlenecks constitute one of the major impediments to the realization of many advanced gas turbine designs. Certainly when projections are made for the next several decades the presently used bearings, limited both as to their DN range and life span, or the presently available lubricants and material, are inadequate for the tasks assigned to the new military and space systems. The demands placed on the tribological components cannot be resolved by a mere advance in existing practices; entirely new bearing designs, high temperature lubricants, and tribomaterials will have to be conceptualized, developed and tested.

It was the task of the present Workshop to identify the areas and nature of tribological limitations as far as their application to gas turbines is concerned, and lay out a matrix of specific development programs to meet present and future needs in this field. The framework of the Workshop was all-encompassing in that it canvassed the views and projections of participants from industry, government, universities and companies involved in the development of lubricants, materials, and other tribological components. The 3-day Workshop, adhering to no predetermined agenda, provided a forum for open discussion and critique, culminating in the formulation of some two dozen priority programs deemed necessary to make the next generation of advanced gas turbines a viable proposition.

2.0 OBJECTIVES AND PROCEDURES

While no delimitation as to subject and scope was imposed on the Workshop, in general its objectives, as spelled out in the Letter of Invitation (see appendix), were as follows:

2.1. Discuss in an open forum from several viewpoints—those of industry, users and researchers—the degree to which the development of advanced gas turbines is hampered by tribological constraints.

2.2. Identify specific tribological areas which impose limitations on the successful development of high-speed, compact gas turbines.

2.3. Evaluate the extent and nature of the restrictive tribological technologies mentioned under 2.2.

2.4. Establish a hierarchy among the identified areas in terms of their relevance to gas turbine development and the feasibility of their successful resolution by research, testing and funding.

2.5. Formulate a matrix of priorities of tribological programs—new bearing and seal systems, synthetic and solid lubricants, advanced tribomaterials, etc.—which the Workshop deems of highest importance to the development of modern gas turbines.

2.6. Disseminate the conclusions of the Workshop among industrial, educational and professional institutions.

In the opening remarks of the Workshop's two co-chairmen the above objectives were supplemented by the following suggestions:

- The Workshop was to be less in the nature of a Conference or Symposium but rather a free and open exchange of views with no restriction on the range of subjects or issues discussed
- From the Government representatives it is hoped to obtain projections of future needs and trends in the area of aircraft gas turbines
- It was recommended that the procedural format of the Workshop consist first of general presentations and discussion; followed by having the participants divided into subgroups centered around a specific interest or technology in order to formulate a list of topics of particular importance to the field; and concluding with a formulation of a final list of priorities
- The drafted Report on the Workshop proceedings and conclusions would be disseminated among the participants for their scrutiny and recommendations; following which the final Workshop Report would be issued, possibly under the ASME imprint

A list of participants together with their affiliations is given in the appendix.

3.0 THE IHPTET PROGRAM

As a brief introduction to the motivation and efforts of the present Workshop the program known as IHPTET - Integrated High Performance Turbine Engine Technology-represents a cogent subject. This is a three-phase,15 year program launched in 1988 jointly by the DoD and industry which consisted of three phases aimed at the following objectives:

- Enhance critical U.S. defense technology
- Provide for a dual-military and commercial-utilization of this technology
- Involve industry and Academia in the effort
- Use a phased strategy via a graded Component Improvement Program for fielded engines

Guiding the program is a Steering Committee of Government and industrial managers which includes the Army, Navy, NASA, DARPA and six major domestic engine manufacturers. Its overall organization is shown in figure 3.1. Each engine Company has an Advanced Turbine Plan with a highly detailed roadmap and identified critical areas. The program concentrates specifically on high temperature, high speed capability; on durability and reliability of engines; on reducing the weight and cost of mechanical components; and what it considers most essential technical innovation.

Beyond the present IHPTET which ends in the year 2003, further planning is being extended to year 2015 and beyond. For this period the concentration is to be on advanced materials. The temperature limits and strength of organic and ceramic matrix composites are being stressed as well as those of superalloys and intermetallic technologies. One of the aims is a 50 percent increase in (power thrust/weight) ratio and a 20 to 30 percent boost in SFC via higher component efficiency and higher compression ratios in the engine. And lastly a significant reduction in overall production and maintenance costs by the utilization of advanced engine modeling and simulation tools. Some of these projections are shown in figure 3.2.

Of particular interest to the Workshop are the tribological goals and concerns specified in the IHPTET Program. In the overall area of tribology these include the following technologies:

- High temperature liquid lubricants such as polyphenylethers and perfluoroalkylethers
- Hybrid ceramic-steel bearing materials
- Advanced alternative lubrication systems
- Coatings
- Vapor phase lubrication
- Magnetic bearings alone or in combination with auxiliary bearings; these to include an appropriate control system and a rotor-centering paradigm

Specific tribological advances that are under development include the following items:

- Cageless thrust REB's with silicon nitride rolling elements. This design has been tested for 10 hrs at 47,000 rpm using mist fuel as the sole lubricant and coolant.
- Circumferential Film-riding Seal. At the hot section this seal was evaluated as likely to reduce leakage by 60 percent and yield an SFC saving of 2 percent.
- Air driven oil mist producing a 20 ml/hr vapor phase lubricant to a REB with a carbon-to-carbon cage. It underwent a 12 hr test at 850 °F temperature running at 50,000 rpm.
- An on-line oil conditioning monitor system capable of detecting wear debris in the oil as well as its level of degradation and contamination. It essentially eliminates the need for conducting oil analyses.

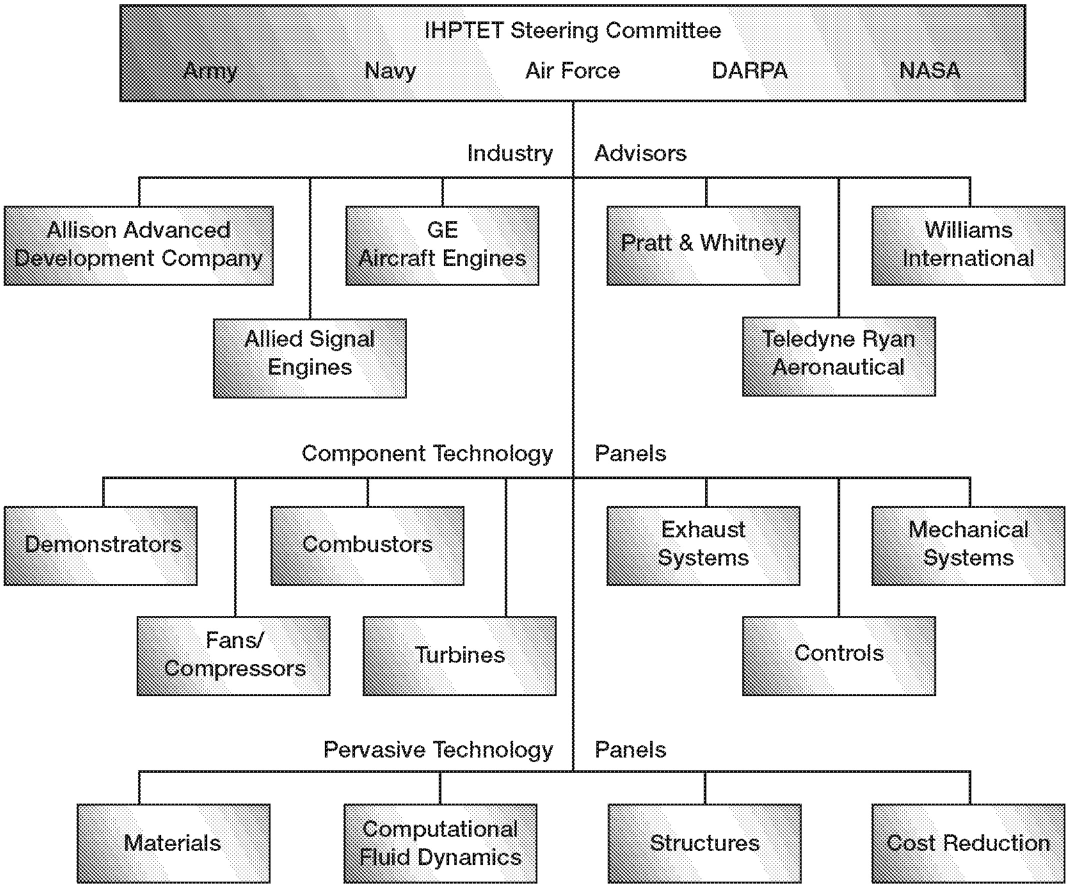


Figure 3.1.—Government-industry steering committee for the IHPTET program.

Turbine Engine technology Goals*		
	Phase III (2003)	Strategic Vision (2009-2015)
Thrust/Weight	2X	2.5-30.X
Specific Fuel Consumption	–10 to 15%	–20 to 30%
Development Cost	-	–50%
Production Cost	–35%	–50%
Maintenance Cost	–35%	–50%

*Compared to YF119/120 Engines

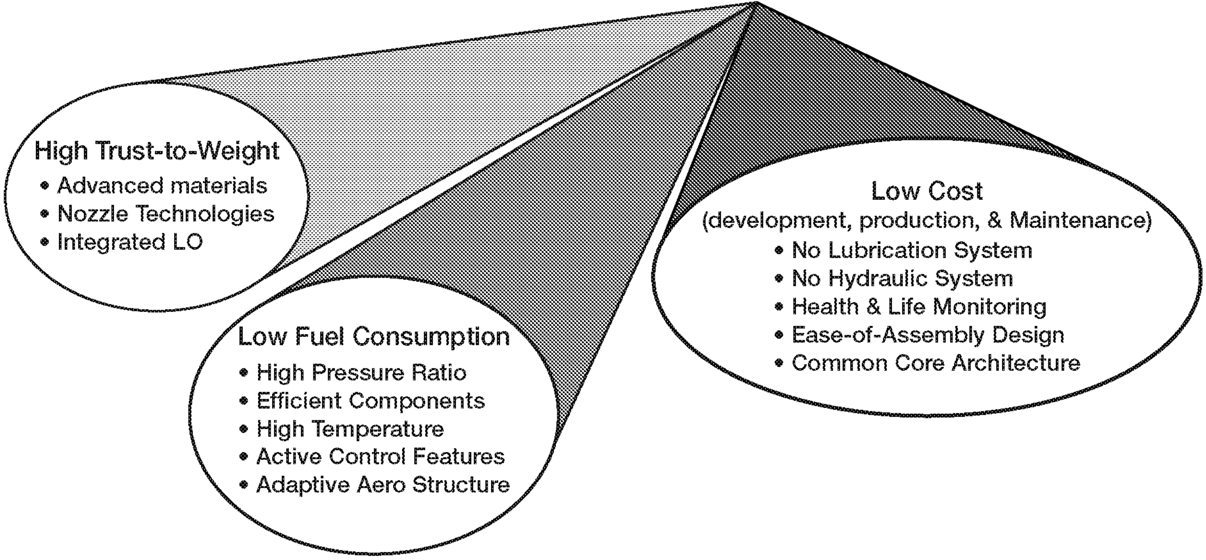


Figure 3.2.—New technologies and projected goals for gas turbines under the IHPTET program.

4.0 PARTICIPANTS' PRESENTATIONS

The presentations by the Workshop participants will be arranged in order of deliveries by representatives from industry, several Government agencies and research organizations. At the end of each delivery the substance of the ensuing discussion will be incorporated. The write-ups do not follow the actual sequence of talks; this can be read from the Program notes in the appendix. They will be presented by topics; thus the presentations from industry will start with small and proceed to medium and large size gas turbines.

4.1 Industry

4.1.1 Williams International.—The Company's products include a range of small advanced gas turbines which are either expendable systems such as cruise and tactical missiles or uninhabited air vehicles; as well as equipment on small commercial aircraft. In the category of expendable engines the lubrication system constitutes a bulky component-some 30 to 40 percent of the engine's total weight, and operational problems encountered on these engines. Whereas the actual use of, for example, cruise missiles may last only hours-they require storage which last years and yet must be able to function whenever needed. The storage requirement initially set at 3 years, has now been extended beyond 10 years, the engine to start up within 6 sec. From the tribological standpoint these operational requirements present the following problems:

- The bulkiness of the lubrication system cuts into space available for fuel
- Corrosion problems on the rolling element bearing and the 52100 and M 50 steel due to oil film breakdown with time
- Breakdown of the elastomeric components in the seals and gearbox
- Deterioration of damper performance due to long-time exposure to the oil and fuel aboard
- Contamination of the oil
- Some of these problems are itemized in table 4.1

Due to these difficulties, development has proceeded toward using the engine fuel as a lubricant and coolant. The path of the fluid in a gas turbine at high Mach number is shown in figure 4.1. The bearings used are a hybrid ceramic some with and some without cages. This, in a way, is one version of an oil free system. The use of fuel in place of oil is also being applied to the IHPTET supersonic missile program. The use of fuel seems to give promising results for the above cases, primarily because of the limited operational life cycle required. Even so there are still problems with its use, viz.

- With the use of JP10, the fuel presently used, the bearing operates in the boundary lubrication regime instead of the EHD mode. For long-term operation this may not be adequate.
- As a result of the above, REB raceways from a cruise missile showed, upon inspection, wear of 0.2 μm (5 μin.) surface roughness with deep and sharp peaks and valleys. Some of the implications of the generated surface roughness are illustrated in figures 4.2 and 4.3.

In general, disposable engines raise the complex issue of making the system good enough for its brief life cycle and yet not to over-design it so as to increase its complexity and cost.

Another family of sometime expendable but more often reusable engines are the practice target decoys. These use the W J 24-8 turbojet which has a 275 lb thrust. Its function is to fly for several hours followed by a splash into saltwater (the ocean) during which it goes from a temperature of 2,000 °F to that of cold seawater where it may remain for one or more days. When it is retrieved its decontamination consists of flushing the engine with cold water and introducing a spray of rustlick after which it goes into storage. The system may be reused 25 times with long storage periods in between. It is mist lubricated which requires the installation of a mist generator and associated plumbing. Here, too, efforts are under way to introduce fuel lubrication.

Another system is a missile capable of eliminating Scud mobile launchers (used in the Iraqi war). This involves a cruising speed of Mach 5 with a minimum baggage of hardware and fuel. The coolest part of the engine is about 1,800 °F and the overriding issue is the thermal problem-where and how to dissipate the heat. There seems to be no alternative here to bearings that can tolerate this high temperature environment. This leads to foil bearings as one possible solution, although high thrust loads present substantial problems.

As mentioned, the Company is also in the general aviation business, particularly in small commercial jets which use exclusively oil lubricated REB's. These are very small engines running at speeds in the range of 60,000 rpm which a suffer tribological problems due principally oil contamination. Bearing wear and seal leakage are next on the list of potential problems. In dealing with commercial aviation fuel lubrication and foil bearings are not being considered as possible solutions for the near term.

A wish list by this manufacturer would consist of the following items:

- Rules and tools for designing bearings operating under boundary lubrication conditions
- Modeling of tribological systems designed for long storage periods and brief operational cycles
- Corrosion resistant materials and coatings
- Data on fuels as lubricants
- Applicability of foil bearings to the company's particular engine requirements
- Turbine blades; fir tree problems in blade roots; abradable materials for blade tips

In the discussions after the talk the following points were brought up:

- Tricresyl phosphates are added to the fuel used but this is damaging to any nickel parts present in the engine
- Anything that may ameliorate the corrosion problem will hurt the mechanical properties of the material
- UAVs fly at altitudes up to of 65,000 to 100,000 ft. Even compared to commercial jets (30,000 ft) the use of gas bearings would yield a low load capacity which for compressible fluids is proportional to the ambient pressure
- Since fuel lubrication is a two-phase process, data on tribological properties of fuels alone would not be enough. A two-phase characterization of fuels as lubricants would require a special study program
- A seemingly mundane problem is the difficulty of locating suppliers for nonstandard rolling element bearings; when found, the time to have an order filled is long.

4.1.2 Capstone Turbine Corporation.—This Company developed the first commercially available oil-free gas turbine running exclusively on air lubricated foil bearings. These are all equipped with special proprietary coatings for multiple start-stop cycles. A 30 kW unit running at 96,000 rpm uses a double-faced thrust bearing and 3 journal foil with one located in the hot section. This bearing operates at temperatures over 1,000 °F. Fielded systems have accumulated over 300,000 hr and over 100,000 start/stop cycles of service. Capstone has also demonstrated 14,000 start/stop cycles on a single engine. The rotor weighs 5 to 6 lb including the permanent magnet portion of the starter/generator. Capstone has also successfully demonstrated internally a 12 lb rotor in a microturbine at 96,000 rpm. These systems are mostly for on-site power generation. Several hundred stationary systems have been produced to date. One HEV bus installation so far has accumulated some 30,000 miles running service without unscheduled maintenance. A point worth noting is that the Capstone Turbine Corporation has designed and is developing its own foil bearings for their machines. Capstone is considering a number of future product improvements, including ceramics to raise the operating temperature and overall efficiency of their microturbine systems.

4.1.3 Sunstrand.—The gas turbines produced by this Company are mostly for Auxiliary Power Units to provide air conditioning and shaft power when the aircraft is on the ground. They also provide starting and emergency power for the main engines. They are either in the 100 hp range with a shaft diameter under 3 in. or 500 hp with a shaft diameter of 7 to 8 in. Most of these are used on commercial aircraft. These are almost expendable units in the sense that if anything goes wrong they are not fixed but simply replaced. Consequently the main concern here is reliability—of the order of 6,000 hrs or 6 years service life without replacement or overhaul. Thus, a listing of important concerns for this outfit would include:

- Reliability of unit as a whole
- Minimum number of components
- Low cost even at the expense of performance
- Great concern with reducing weight and size

One consequence of these priorities is that even should foil bearings be a candidate there would be no room for heavy support housings these bearings may require.

4.1.4 Allied Signal (now Honeywell).—This Company embraces also the divisions of Torrance, Garrett and Lycombing. It is the largest manufacturer of small to medium gas turbines with a range from 100 to 12,000 hp units. In the use of REB's they found the oil lubricants to be a bigger problem than that of materials. While they are a good medium as a coolant their problem is temperature limitation with a tolerance of local temperatures up to 400 to 450 °F. While the bulk temperature is only a little over 300 °F, the spot temperatures are much higher. The next problem with oil is that it requires a bulky support system such as scavenging, sealing, buffering, etc. In addition to adding weight cost and maintenance chores, the support system interrupts the flow path penalizing engine performance. In civilian aircraft there is also the problem of an oil seepage into the bleed air system. The DN's employed are high, of the order of 3.5 to 4.5 million; 4.5 million is considered the maximum possible from an engine design standpoint. The minimum thrust is set by avoidance of slip in the bearing whereas the maximum thrust is set by fatigue requirements. At a DN of 4.5 million the two points meet and with time there will be a need to go to higher DN's. Also the attempt to keep the DN's low leads to small shaft diameters which in the case of an overhung rotor produces super-critical operation and attendant stability problems. Also with REB's the knee for a thrust reversal requires a duplex bearing which does not have the same speed capacity as the single REB.

Air foil bearings are used extensively by Torrance on its Air Cycle machines. These units, 23,000 in number, have now accumulated 300,000 million hr of service. Garrett likewise uses foil bearings among them on a commercially available 75 kW industrial turbo generator. The machine operates at 65,000 rpm with an overhung rotor which runs above the first bending critical. In the area of APU's they have a gear-less, oil-less demonstrator producing 120 kW, supported exclusively by foil bearings. A central problem with foil, bearings is their clearance. Thermal considerations call for large clearances whereas rotor stability needs tight clearances. In flying machines the thermal problem is aggravated because, due to variations in altitude, they have a range of pressures and temperatures to deal with. Another critical item is that of coatings which in the Company's view constitutes the lubricant. These coatings have to be adequate for both cold and hot start-ups which may range from –65 to 1,200 °F. With higher performance engines which means fewer stages and higher compression ratios, the air available for cooling and supplying the bearing is getting hotter. Air to air heat exchangers are then required. But should the foil bearings be capable of tolerating these higher temperatures then such heat exchangers could be dispensed with resulting in lower engine weight and cost. Thus in sum foil bearings with appropriate coatings by tolerating higher temperatures could yield higher performance engines. This is not to say the REB's are going to disappear. Particularly for the IHPTET program they will still be in service—but they will have to have oils or other lubricants capable of tolerating the severe thermal environment Along with all this there will also be a need for an advanced health monitoring system.

In the discussion that followed the talk, the following additional points emerged:

- Contamination of foil bearings. Water and dust were deliberately introduced without affecting the performance of the foil bearings. It was added from the floor that while water and sand may prove harmless, a soft debris such as a plastic or thermoplastic may produce different results.
- Foil Bearing Design. The foil bearings used by Garrett are of the overlapping leaf type, that is bending-dominated. A question arose whether tension dominated foil bearings—the predecessor of latter day foil bearing designs—are being used. It was explained that tension foil bearings are good at most up to speeds of 30,000 rpm after which they start vibrating like "guitar wires."
- Foil Bearing Clearance. In elaborating on foil bearing clearance, in addition to the thermal and stability problems there is also a third aspect. This relates to the blades' tip clearances which in the IHPTET program are becoming exceedingly small and particularly so during transients. The bearings must limit any radial excursion so as not to damage the blade tips. This issue would be particularly severe with the proposed use of magnetic bearings which do have large clearances.
- Coatings. A distinction was made by the speaker between hot and cold coatings—the latter claimed to have a lower load capacity. The reason for this, in Torrance's case, was that the cold coating used Teflon which tends to freeze in a process called "cold flow." This does not occur with hot coatings. The Teflon has now been replaced by another material which raised the cold temperature tolerance from 400 to 600 °F. Hot coatings still require considerable development work.

4.1.5 Pratt & Whitney.—This manufacturer of large and the largest gas turbines serves both civilian and military needs. In the commercial field one objective is lengthening of overhaul time—several years of operation without such a need. Along with this there is the drive to reduce weight and cost. Both objectives call for better bearings and seals. The desirability of improving the present carbon seals was singled out as one such area AEA needing improvement possibly in the form of rotating noncontacting seals. Oil coking as a consequence of high temperatures was, as with other speakers, a concern. Another problem with oil lubrication is that, due to the churning of the oil in the REB's and frothing in the oil tanks, there is a need for an oil-air separator to assure pure oil delivery at the inlet to the pumps. The possibility of using vapor lubrication is being considered except that this would reduce the oils function as a coolant. The burden of an adequate monitoring system would have to be not only to indicate the presence of debris due to wear or contamination but also such things as an interpretation of the cause of vibration, if any, or any other anomalies in the engine.

There are no major difficulties with the present day engines but this is due to the designs staying within known envelopes. The speeds on the Company's products are in the range of 15,000 to 17,000 rpm. For the future however, this capability would have to be raised. The goal is to go from the present limit of 3 million DN to 5 or 6 million. And this would pertain not to an increase in shaft diameter but to speed only. This makes the matter of proper materials even more urgent. In this area one objective is to obtain lighter materials in order to reduce the high centrifugal forces in the engine. Ceramics are one class of materials being considered. But whatever material is selected its corrosion resistance characteristics would have to be maintained.

A sum-up of several viewgraphs presented by the speaker is presented in combined form in table 4.2.

In the subsequent discussion two additional items of interest emerged, viz.

- Lubricant. The lubricant used in most engines is MIL 23699. In the past manufacturers used lubricants developed at government facilities for military aircraft. Some time back the Government decided that this should be industry's function. But the oil companies persisted in producing oils to existing specifications only and hesitated to embark on the development of new products. Consequently, as with nonstandard REB's mentioned earlier, there are difficulties in procuring oils made to new specifications.
- Monitoring. In the area of oil contamination, there is in addition to particulates, also chemical contamination. This is often due to the additives in the oil, frequently carried over from automotive practices. If a monitoring system is to be installed it ought to be able to reveal something about chemical contamination, too. This clearly is a complex task and although some beginnings have been made in this direction the consensus was that it would take another 6 to 7 years before such a system is developed.

4.1.6 G.E.—Like Pratt & Whitney this manufacturer, too, is involved with large gas turbines and its top concern is, likewise, with reliability. Even though the Company is interested in the subject of oil-free engines its present and next generation engines still remain geared to the use of REB's. Designers, as the speaker put it, are "risk-averse" and tend to pick "off-the-shelf" technologies. In the discussion period the issue arose as to the time cycle required for a new technology to be considered, designed, tested and applied to a prototype. This went under the heading "maturation." No definite time period—years or decades—could be arrived at what the brackets for such a cycle might be.

Table 4.2 presents in summary form the various needs and goals that emerged from the presentations by the representatives of the six industrial concerns at the Workshop. These items are to be part of the prioritization process scheduled for the latter part of the proceedings.

4.2 Government Agencies

All three branches of the Armed Services as well as NASA participated in the Workshop and gave presentations on tribological needs in the application and development of gas turbine engines.

4.2.1 U.S. Navy.—The Navy's orientation with regard to its tribological problems has much to do with its operating environment. For ships and particularly aircraft there are strong effects of the proximity of the sea on the integrity and safety of their machines. The ever present saltwater, the effects of saline air sprays and excessive humidity lead to a high rate of corrosion and wear of the machine parts and contamination of lubricants. This is aggravated by the prevailing space congestion where the effects of debris and perennial washdowns by plain water add to the difficulties of proper maintenance. The problems of replenishment and supply are, likewise, severe because of the need to transport them over great distances both overland and across the seas. Being dispersed and isolated literally over all the oceans of the globe, both ships and aircraft must be self contained, carrying on board the spare parts, tools and facilities required in order to remain operational and meet any ensuing emergencies.

The naval air fleet, naturally, also shares a number of concerns with land-based aircraft. Thus in addition to the high speed high performance bearings in their turbines, attention must be given to the bearings on the air frames and control surfaces; to the demands of high impact loadings on landing; and to centrifugal and inertia forces. The Navy is also involved in what is called "autonomous air vehicles." These crew-less systems—unlike cruise missiles which are launched and discarded—are meant to fly and report back on a continuous basis on their mission without risking human life. Such systems naturally would have to be able to operate without logistical support, minimum maintenance or assistance from the outside.

From this perspective the Navy's two foremost requirements are system reliability and its corollary—minimum maintenance needs. Since, as alluded to, Naval supplies and spare parts have to be carted over great distances, involving expense and loss of time, affordability and long life of its tribological systems enter the list of priorities. The Navy is also constrained to make a distinction between evolutionary and innovative approaches to resolving outstanding tribological problems. Thus helicopters which do not provide the pilot with such features as an ejection seat, dictate rather conservative practices, with the main efforts directed toward advancing existing systems rather than resorting to new technologies.

A categorization of the Navy's needs arising from present tribological limitations would encompass the following items:

- Corrosion-resistant Bearings and Lubricants. An advancement in these areas would span almost the entire gamut of existing problems from simple reliability concerns to the viability of the projected "autonomous air vehicles." Some success in these fields has been achieved with 23699 corrosion-inhibiting oils and the use of Pyrowear 675 materials in both bearings and gears.
- Cost Reduction. The navy had adapted the practice of refurbishing REB's by dismantling them, cleaning the rings and stripping the cages for replating, thus effectively obtaining a new REB.
- More Effective Seals. This would entail low wear, noncontacting seals including co-rotating and counter-rotating applications. Longer life and better CFP performance would be required.
- Oil-free Bearings. Under the innovative part of the Navy's program this would encompass magnetic and compliant foil bearings.
- Advances in REB Technology. One desirable step in this area would be to improve the M50 and M50L materials with a hardened and fracture-resistant variety. But more important would be a new corrosion-resistant alloy. Cromidor 30 shows some promise as it performed exceptionally well in the space shuttle; problems, however, arise when an attempt is made to upgrade it to large size REB's. For high speeds new carbonizing chromium steels proved to be an advancement. The previously mentioned case-carburized steels such as Pyrowear 675 as well as CSS42 are possible candidates. In applications where high inertia forces are present silicone nitride materials would have to be considered.

Some of these needs, as they have been presented on viewgraphs at the Workshop, are reproduced in figure 4.4 and table 4.3.

In the subsequent discussion the issue of on-line monitoring was raised and discussed at some length. As part of its cost reduction program the Navy often times dispenses with the use or support of programs dealing with "predictive maintenance." This, it was pointed out, amounts to a "penny wise but pound foolish" attitude. The Navy speaker explained that there are several aspects to this issue. One form of monitoring consists of crews going to the aircraft to check on the performance of the engine, using primarily vibration diagnostics. In these cases there is no cockpit monitoring. Another way of reducing on-board equipment is exemplified by debris management. Using finer filtration the debris in the lubricant has been reduced from 35 μm-sized contaminants to 10 and in some cases to just 3 μm. While savings are achieved such economies at times neglect overall engine monitoring. A related problem is that even when on-board monitoring is employed the data is often not utilized. Thus in one tracking program it was determined that 70 percent of all reported bearing failures were due to corrosion. As a result the Navy has introduced fleet-wide a corrosion-inhibited oil. The data from this changeover are still waiting to be statistically analyzed whether the inhibitor is effective.

4.2.2 U.S. Air Force.—This presentation started with a overview of the origins of tribological limitations in gas turbine engines. These were classified as deriving from three sources. In order to raise the performance of the turbines one can resort to the following design steps:

(a) Raise the pressure ratios across the compressor. Higher pressure ratios mean higher thrust loads on the bearings. Today fighter planes carry thrust loads approaching the capability of the bearings. Also, at these high loads, the time left to realize and react to any bearing difficulties is decreased with all that this implies for the pilot and the aircraft.
(b) Utilize higher air flow rates. To achieve higher air flows one must increase shaft speed. But in order not to go supercritical the shaft must be made stiff which calls for an increase in shaft diameter. The combination of higher speeds and larger shaft diameter leads to high DN values. In addition, with such designs there is also more heat generation adding to the problems associated with item C below; already at DN values of 2 million heat generation becomes a problem.
(c) Increase combustion gas temperature. Higher combustion temperatures, naturally, raise the temperatures in the entire system including the bearings seals and lubricants. In addition to raising bearing surface temperatures, the viscosity of the lubricant drops. Using an excessive amount of cooling air to reduce bearing temperatures constitutes a parasitic energy loss and a drag on turbine efficiency.

The above considerations were presented in the slides grouped together in table 4.4.

To cope with some of these problems one needs new steels which have a higher fracture toughness, improved fatigue life and are more resistant to wear. While there are some new steels which have improved characteristics in one respect, there is none that combines them all. When, for example, fatigue life of a steel is improved this usually happens at the expense of its wear resistance. One new material introduced in tribological applications is ceramics which can be employed in the rolling elements of high-temperature REB's.

With regard to the temperature problem it is clear that, at least in aircraft, liquid lubricants will continue to be employed. The current lubricants are the familiar 7808 and the 23699 specs. Their viscosity is low, in the 3 to 4 cSt range, to facilitate cold starts. Work on appropriate substitutes has now been going on for 30 years without much success. Polyphenylethers and perfluoroalkylethers do have good lubricating properties but fail in the previously mentioned important aspect—good pumpability at low temperatures. Perfluoros was tried briefly in actual flight but caused corrosion problems. Esters can be used down to 25 to 30 °F but no lower. One may, of course, accept this as an inherent temperature limit of the lubricant and instead concentrate on lowering the temperature—either by reducing the temperature spikes or improving the heat transfer out of the bearing and the gearbox. This is indeed an area to which insufficient attention has been devoted to. The fashionable approach to this problem is to use computer modeling done usually as part of the entire engine represented as a virtual system.

The speaker then extended his list of tribological limitations to the very innovations meant to alleviate such problems. In talking about problems with the new bearings he defined "limitation" as a deliberate concentration on their shortcomings. The first on the list were magnetic bearings whose main problem he cited as being load capacity. When they are sized to carry the entire load, the bearing structure plus the required control system, they weigh more than a conventional lubrication package—and in an aircraft no one would think of introducing anything that weighs more than what is being replaced. Moreover magnetic bearings need a back-up bearing in case the electronics fail-and these back-up bearing still need development work.

The issue of back-up bearings led to the general subject of compliant foil bearings. While these bearings have been employed extensively in aircraft, in air cycle and auxiliary equipment, the point was that they have not yet proven themselves in larger size machines. They also need improvement as far as their load capacity and dynamic characteristics. Most of all they need a valid demonstration in larger size engines than has been the case heretofore.

Vapor lubrication was successfully employed in a system with the following characteristics; DN of 2 million, 300 psi contact stress, 1,000 °F temperatures and a life of some 10 hrs. But vapor lubrication seems to be applicable for short cycles only. The reason for it is that vapor lubrication produces a chemical reaction between lubricant and steel. In the process the lubricant consumes iron from the bearing substrate. Although the wear rates are not high the friction soon rises and the process can be maintained for brief durations only; the above 10 hrs at 2 million DN seems to be the limit.

The above cited limitations as presented on viewgraphs during the Workshop are shown in tables 4.5 and 4.6. In general one can say that there is no single approach which is totally suitable for all conditions of operation of a gas turbine. Some specific remedy—application cases are given in table 4.7.

The comments following the presentation dealt primarily with the future prospects of magnetic bearings in aircraft. Questions were raised on the functions of the electronic control system and its relation to the overall electric system; the role of the backup bearing as a reliable component in case of primary bearing malfunction; the extent to which it can share the load, thereby reducing the size and weight of the primary bearing; and its integration with the overall engine envelope as the large size and clearance of a magnetic bearing may require a realignment of rotor position. Even more serious were the doubts of what was termed the ‘infrastructure’ problems relating to magnetic bearing technology. This alluded to the commitment and viability of bearing manufacturers who would not possibly wait for the successful development of these new system before deciding to withdraw from the field, as has happened to a number of U.S. companies.

4.2.3 NASA/U.S. Army.—The NASA and Army presentations were delivered jointly by the two speakers as some of the programs they pursued overlapped the two agencies. However, the bulk of the material stemmed from NASA’s extensive work in the area. The opening subject concerned “ tribology maturation” as this often affected the decision whether to support or reject innovative projects. Figure 4.5 illustrates this concept in the case of computer technology. In part (a) of the illustration it is seen that initially the realization of a new technology brings tangible results but with time it becomes more difficult to extract any new payoffs from the same technology. (It was pointed out from the floor that its shape is rather an S curve as initially progress is slow and only later does its slope rise the way it is on the figure.) A “wall” seems to be arising putting a stop to any further efforts to obtain more progress from what was originally a promising innovative approach. What must be resorted to is a fresh breakthrough that can provide a new cycle of growth, the way the older idea had originally worked. Thus in part (b) of figure 4.5 we see that the previously conceived computer tapes have by 1968 reached their limit of information storage capacity. Then came the hard disk which raised the storage density from kilo- to megabytes. At present this technology, too, has aged and no significant boost in its capability can be achieved so that a quantum leap is being contemplated in the form of optical or even biological storage systems which would raise the storage capacity to the level of gigabytes.

A similar dynamic seems to be operating in the field of gas turbines. Today these engines can be considered a mature technology and progress in their performance has pretty much leveled off. To get off this plateau new approaches are called for. For example, the bulk temperature with which engine designers are comfortable today is in the vicinity of 300 °F; 25 years ago it was 275 °F, a tiny progress. What is needed is not to press against the present 300 °F ceiling but a new start to enable bearings and lubricants to operate at much higher temperature levels.

Another preliminary observation concerned the criteria by which worthiness of innovations are judged. The most common one is that of cost reduction. But this should by no means be the sole or even the primary consideration. Other important criteria include ecological, noise and pollution concerns and the ability of an innovation to reduce stress levels or excessive weight which often place limitations of engine advancement. In evaluating a new technology one must keep in mind the two-sided implications of such a step. One is not only the relief it may bring to the tribological problem but to the engine as a whole; and on the other side to realize that a changeover in the lubrication system may have a negative effect on the system as a whole. Furthermore one must remember that tribological processes involve a wide gamut of components. In modern machinery these include:

- Bearings—involving oil, air, or process fluid lubrication
- Lubricants—liquids, gases, solid or synthetics, plus additives
- Seals—brush, face, and noncontacting or hydrodynamic designs
- Gears—involving materials and complex elastohydrodynamic processes
- Splines—dependent on materials and internal friction phenomena
- Dampers—run on a liquid, gas, or in combination with structural elements
- Bushings—for frame and control surfaces

Each of these families has its own wall to overcome and a different potential for significant improvement.

(a) Tribological Limitations.—As seen by NASA the tribological constraints include first of all the familiar problem of limiting DN values. These should be raised to at least 3 million. Though previous speakers claimed an ability to run REB's close to that value , this has not been NASA’s experience. Using silicon nitride hybrid REB's a maximum DN of 2.4 million was achieved with some difficulty. A 1984 national advisory committee on engineering, as related specifically to aircraft propulsion systems, projected that by the year 2,000 the country would need a DN capability of 3.5 million; at that time the DN stood at 2 to 2.5 million. In the elapsed 25 years no great gains had been achieved in this area.

As shown in table 4.8 the other areas that need substantial progress span the following technologies:

- Contacting Seals which have limited life when run at high speeds
- Lubricants incapable of enduring the ever rising engine temperatures
- Gear teeth which need better materials and a better understanding of their elastohydrodynamic behavior. The one improvement in this area has been in carburizing and hardening gear teeth without sacrificing fracture toughness
- Dampers, particularly at high temperature. These would be particularly vulnerable should oil-free engines become a reality. It will take great ingenuity to impart to foil or magnetic bearings the levels of damping that liquids have
- Bushings and splines which are vulnerable to high temperature
- Here, too, one must be aware of the interrelation between any possible improvements. Eliminating one wall may unintendedly knock down another wall; as an example, should magnetic bearings be introduced one may consider using them as a starter for the generator and eliminate thereby the accessory gearbox. On the other hand eliminating one barrier may erect a new one.

(b) Innovative Systems.—At present the main tribological innovations are compliant foil bearings, magnetic bearings, and solid lubricants. When first considered there were troubling questions about these novel systems. The foil bearing is run on air with a viscosity three orders of magnitude below that of oil. How was it to start under load? How about damping which is such an important feature in rotor dynamics? Some answers have been found to these problems. As far as starting under load the solution lies in coatings. Both NASA and other groups have developed extremely successful high temperature coatings which are discussed below. With regard to damping new finite element modeling codes are being worked out to properly integrate the foil bearing into the system’s structure to take account of the dynamic requirements of the rotor. And in some cases what seems an exorbitant demand actually turns out to be beneficial and, ironically, running bearings at high temperatures is one. When flying at Mach Number of 2 or 3, there is at present no outside sink to dump the generated heat. This is because at these speeds the kinetic energy of the airstream produces stagnation temperatures of the order of 600 to 700 °F. Given that the bearing is run at about 400 °F no outside cooling is possible. But if it is run at, say, 1,000 °F the outside air could be used as a sink for cooling the bearing compartment.

One of the major issues to be considered is: what are the prospects for foil and magnetic bearings, both upcoming candidates, vis-a-vis REB's which are an established but aging bearing system. Following are some pertinent data on the status of these new technologies.

1. Foil Bearings

- Start-Stop Characteristics. It was mentioned above that start up under load seemed to be a stumbling block in the employment of foil bearings. Very significant progress has lately been achieved in this area. NASA has developed a plasma sprayed composite, specifically designed for foil bearings. This coating, designated PS304, consists of the following:

Binder—60% NiCr
Hardener—20% Cr_2O_3
High Temp. Lub.—10% BaF_2/CaF_2
Low Temp. Lub.—10% Ag

Foil bearings coated with this PS304 have undergone tests at temperatures ranging from 75 to 1,200 °F and endured 100,000 start/stop cycles with no damage, no vaporization and no emissions from the bearing surface. What this 100,000 number means in service one can take the case of a 737 jet. This aircraft flying 5 flights a day, 300 days of the year would after 60 years accumulate only 90,000 start-stop cycles.

- There is no speed limit in the operation of foil bearings. Using in most cases ambient air they require no lubrication accessories providing complete release from all the consequences of an oil system.
- By adjusting the matrix of the spring foil substructure they can provide a variable stiffness field tailored to the specific requirements of the machine.
- They can endure very high temperatures and by their ability to deflect and conform they can tolerate shaft excursion caused either by shock or centrifugal and thermal expansions of the rotor.

2. Foil Bearings and Rolling Element Bearings

The ranking of foil bearings vis-a-vis rolling element bearings is graphically represented in figure 4.6. A limiting feature of foil bearings is their low load capacity at low speeds. At present there also seem to be questions about their suitability for large size engines. Thus in large low-speed turbomachinery REB's have the upper hand. However, the foil bearing's load capacity rises with speed and it remains resistant to the accompanying high temperatures, whereas REB's, subject to fatigue and temperature limitations, decline in their load capacity with a rise in speed. It must, however, be remembered that insertion of a foil bearings is not a matter of simple substitution but requires modification in engine design.

3. Magnetic Bearings and Foil Bearings

As shown in figure 4.7 magnetic bearings' load capacity, being supported by electromagnetic forces only, is independent of speed. Its load capacity is the same at standstill as at any speed which is both a good thing and a limitation. At higher speeds magnetic bearings are susceptible to shock overloads and need an elaborate electronic control system to compensate for any rotor excursions from its equilibrium position. However, the same electronic control system can be utilized to impart any desired stiffness and damping. A major concern is the contingency of malfunction of the control system or even a total loss of electric power. For these reasons they need a back-up bearing which would support the rotor in the event of failure of the primary magnetic bearing. Such a back-up bearing can also be made to share the load during routine operation. Naturally, foil bearings are a prime candidate for such a back up system. These various ramifications are portrayed in figure 4.7.

(c) Benefits.—The above approaches are clearly audacious—but this is NASA's role. With recent global communication and information networks in operation, technology transfer and assimilation by other countries has become easy and it is the function of governmental agencies to see to it that despite such rapid interchange of technical know-how the U.S. remains in the forefront not only in its defense establishment but also in aviation and other commercial enterprises. NASA is interested not only in large engines but also in small gas turbines for space application and civil aviation which is becoming a widespread industry. Using some conservative estimates NASA and the Army came up with some quantitative projections for the possible savings when using an oil-free systems.

- In 747-size engines the reduction in direct operating costs would amount to some 5 percent. This is a significant economic gain since the profit margin of a typical airline is somewhere between 2.5 and 3 percent.
- For regional type jets like the 50-passenger Embracer 145, the saving would amount to 8 percent. This gain would come from lower acquisition costs (no need for an oil system) and lower maintenance. It is reported that 30 to 50 percent of unscheduled maintenance is due to problems with the oil system.
- With regard to the hardware that could be dispensed with, table 4.9 provides a sample list There are some 50 items here and the list is by no means exhaustive.

(d) Army Special Interests.—The Amy's interest in gas turbines is in the field of land based machines—tanks, armored vehicles and specialized equipment. These of course are subject to the ingestion of debris and have noise and emission problems to contend with. They do, however, share in common with aircraft space restrictions. One advantage of foil bearings not listed previously is their ability to tolerate the presence of contaminants originating either from wear of machine parts or ingested from the outside. Special tests were conducted by the Army on how far a foil bearing's tolerance of debris can go. The tests were conducted on a turbocharger bearing one inch in diameter. The debris was sand introduced either at the inlet or directly into the bearing clearance using a sandblaster. The amounts of sand injected were manyfold what is typical in actual service. The bearings continued to run without any sign of distress, not to speak of seizure, with the debris mostly disgorged at the sides of the bearing. An additional important benefit for Army vehicles is, given the restricted space under the armor, the turbocharger can be installed at any orientation without worrying about drainage. Aside from Army vehicles the Diesel trucking industry is interested in this new technology, given the potential for reducing the emission levels in the absence of oil.

A specific oil-free turbocharger, now being tested at MiTi, is shown in figure 4.8. It has two journal foil bearings and a double acting foil thrust bearing, all using NASA's PS304 coating. This is a project involving NASA, the Army, MiTi and Caterpillar Engine Co. The turbocharger was run for the first time last March at 95,000 rpm with an inlet temperature of 1,200 °F covering a wide range of operating parameters—a major milestone. With this success the Army plans using foil bearings in a small gas turbine program aiming at the year 2003. The steps in this extension will follow the ones used previously, viz

a. conduct an overall conceptual study
b. determine as to where the foil bearings are to be located
c. investigate the dynamics of the system with the foil bearings in place

It is visualized that the first application for this engine would be in small commercial jets since they are at the present in the process of converting their old turboprops to jet engines.

(e) Oil-free Turbomachinery.—Overall NASA is looking forward to the advent of oil-free turbomachinery. It is an ambitious program but, as was pointed out, the technology of gas turbines is approaching maturity and a quantum leap in the supporting tribological technologies is mandatory. Figure 4.9 shows a schematic of the motivations behind this enterprise and the hoped for benefits from its realization. Figure 4.10 gives NASA's road map for the next decade in pursuing the across the board goal of oil-free gas turbine engines and its accessories.

Parallel to the compilation for industry, table 4.10 provides a summary of the more prominent tribological limitations cited by the participants from the several governmental agencies.

There was questioning from the floor regarding the implications of figure 4.6. One objection concerned the portrayal of REB's as suffering a reduced load capacity with an increase in speed. From the discusser's knowledge speed does not generally reduce load carrying capacity in rolling element bearings. It may affect the fatigue life of the bearing by raising the number of cycles but not load capacity. Countering this argument it was pointed out that with higher speed there is an increase in heat generation and bearing temperatures and that at high speeds the centrifugal forces raise the stress levels in the rings and cages all this representing a brake on the loading that a REB can tolerate at increased speed. These secondary effects did not allay the discusser's original contention that load and speed are not related in the manner portrayed on figure 4.6. More generally it was argued that the merits of rolling element bearings have been understated in comparison with those of foil bearings.

4.3 Research Groups.—Three research companies reported on their activities as related to some of the innovations discussed above as well as on developments that could assist indirectly in the utilization of these new systems. In the discussions of these presentations faculty members from a number on Universities added their views, particularly with regard to the use of advanced modeling and computer coding.

4.3.1 PKG, Inc.: This Company has long been active in the field of rolling element bearing analysis, including extensive computer modeling of the dynamics of REB's. Much of this work was, of course, based on the use of petroleum and synthetic oils. The Company's recent concentration is on what the speaker called "contact mechanics," that is lubrication modes different from liquids and on their dynamic modeling. Some of the characteristics of such interactions are shown on the viewgraph of table 4.11. Contact mechanics involves the following new modes of lubrication as applied to foil bearings, powder lubricated devices, cams, gears and other types of concentrated contacts. A large place in all this is occupied by the analysis of ball and roller bearings.

- coatings
- dry lubricants
- powder lubrication
- vapor lubrication

A new aspect in the modeling of concentrated contacts is that of thermal phenomena. As compared to liquid lubricants, the use of these new media produces high rates of heat generation and the two basic parameters of friction and wear become functions of temperature. As a consequence the evaluation of component life which is dependent on the levels of friction and wear now becomes enmeshed with the problems of heat generation at the interface and the rate of heat transfer. The modeling of a system in which the tribological, thermal and mechanical elements enter into the equations becomes complicated. Moreover, whereas in the past most frictional and wear data were obtained from experiments and used as inputs, when thermal effects are present this approach can not be easily used. To keep the model within reasonable analytical limits one may still use friction data as a function of sliding or of both sliding and rolling in the case of traction coefficients. One can then borrow some of the existing thermal solutions for liquid lubricants and add the appropriate heat transfer expressions. In this manner one obtains some sort of a thermal model for concentrated contacts and a prognosis for the life of the component. One such successful model was generated for an MoS_2 powder lubricant based on tribological properties obtained experimentally at MiTi. Figure 4.11 shows how the model solution compares with what was obtained experimentally.

It is even more complicated when wear enters the picture because wear depends also on thermally activated phenomena, much of them chemical in nature. To make such accounting possible the model for wear is a so-called multiprocess mode in which one can introduce both temperature and thermal activation effects. The presence of several terms in the model permits the introduction of heat generation from several sources. A model correlation of wear as a function temperature is portrayed in figure 4.12.

This leads to the subject of modeling and computer coding as applied to contact mechanics. Generalized flow charts of modeling concentrated contacts for computer solutions are shown in figures 4.13 and 4.14. Not less problematic is the question of the practical use of these tools. One difficulty is simply that of interpreting the obtained solutions. To alleviate this problem animation was introduced in addition to the customary charts and graphs. It is then possible to visualize the physical displacements and motions of the bearing, including visualization of the thermal effects. This problem is further aggravated when in place of a single solution one attempts to optimize a design and the user is faced with deciding what to select from the multiple options presented. This difficulty is the most common complaint one hears from potential users. What, it seems, is needed in this area is Integration, a program which would take the disparate codes of inputs, computation and outputs and put them in a single file. One advance in this area was to introduce interactive type tools which provide continuous user interaction in the process of executing a program. The results can then be read and interpreted and new inputs inserted with a menu that provides for different options.

One general observation made was that many of these programs, having been funded by government agencies, are in the public domain and could be of use to industry as a whole. Yet this fact is largely unknown. It would be a service if some public organization, perhaps the ASME, provided information and facilitated access to these programs, on the web site or by some other means. Likewise the previously mentioned problem of integration of computer programs should be undertaken by some agency and, likewise, placed in the public domain.

4.3.2 Mechanical Solutions, Inc.: Along with the emergence of new technologies arises the need of advanced or new monitoring tools. There are several trends in this field that need to be brought to attention of the technical community.

- Array of technologies. Instead of using one instrument to monitor a single quantity as a criterion of the health of the machine, there is today a need to have a series or overlay of sensors recording in parallel various aspects of engine performance. Some of the advanced measurements would include vibration based spectra, thermography and electric current analysis along with better means of oil analysis. Likewise, accelerometers will have to be mounted in larger numbers to respond adequately to a greater range of engine operation anomalies.
- Wireless Monitors. One of the most important aspects of the new sensors is that they be wireless. This is something that the industry is most insistent on. Engines being as complex as they are, the crews, whether at a ground panel and certainly on an aircraft wing, do not want to contend with additional wiring. If not wireless, the new monitors would have to perform double duty with existing sensors. Some RF tagging or a device based on light beams would have to replace wiring.
- Trending. This approach is to replace a single or instantaneous measurement with monitoring over time. This goes hand-in-hand with multilevel signal processing. Thus instead of looking at a signal at a given instant or at a single vibrational frequency an on-going spectrum of measurements would be recorded. When, for example, vibration is measured the aim is to see how the frequencies are modulated in time which would give

a better picture of the ongoing process and potential difficulties. This approach would have to consider either a model-based or knowledge-based approach such as a neural net system.

- Integral Detectors. An example that pertains to oil monitoring is to put special additives into the oil which would signal to a panel any untoward processes taking place in the lubrication system and particularly in the bearing itself. These additives would be more sensitive than the oil itself not merely to the presence of debris but to such things as acid build-up, oxidation, excessive temperatures, and so on. The history of the lubricant's viscosity could likewise be monitored on a continuing basis from which much could be deduced about the thermal picture or changes in bearing performance.
- "Active Interrogation" Technique. This was compared to the old practice of the locomotive attendant who from time to time went out to tap the wheel to see whether there was a crack in the rim. Another example is a combined accelerometer and impulse device, able to independently excite the engine to determine changes in component stiffness, damping, and connection integrity.
- On-line Profilometers. Such an instrument by measuring the surface of the balls and races and sending back information via miniaturized lasers would provide statistically correlated changes in bearing profile, which could be used in the prognosis for a given bearing.

With these possible advances in monitoring technology one has to proceed so as not to overburden the attendant and certainly not the pilot with a plethora of instrumentation which he could neither quickly read nor interpret. This important point is discussed in detail below by the subgroup on monitoring.

4.3.3 Tour of Mohawk Innovative Technology, Inc. (MiTi): During the evening of the second day the participants toured the Albany plant of MiTi. The visitors were shown the experimental facilities and devices being investigated and, where feasible, were given a demonstration of their operation. Described below is a sampling of what the visitors saw which was directly related to the subjects discussed at the Workshop.

(a) Hybrid Magnetic-Foil Bearing. In a recent series of tests MiTi successfully operated an oil-free hybrid magnetic-foil bearing under a U.S. Army SBIR Phase II program. The bearing was an L×D = 75×100 mm size, designed to a carry a load 1,500 lbs, and running at 30,000 rpm—equivalent to a DN of 3 million. Once successful operation of the system was demonstrated, a series of magnetic bearing failures were simulated followed by a continuous operation of the back-up foil bearing alone. Evidence that both components of the system were participating in load sharing can be seen from figure 4.15. At the inception of motion the MB supported almost the entire load; as speed increases and hydrodynamic forces were generated in the AB the magnetic bearing carried only 20 percent of the load. To demonstrate its reliability as a back-up, the foil bearing was made to carry the entire load for 1 hr at 25,000 rpm producing a maximum rise of the cooling air of only 60 °F.

To determine the ability of the foil bearing to function under transient conditions sudden failures of the magnetic bearing were simulated. These were run at 15,000 to 20,000 rpm when the load capacity of the foil bearing was not at its highest The rotor response to these transitional stages and the ability of the system to recover and continue operation once the magnetic bearing is restored to operation is convincingly portrayed in figure 4.16.

(b) Zero-Clearance AB. As part of the program to develop reliable back-up systems for magnetic bearings MiTi has conceived and patented a novel configuration, named Zero-Clearance-Auxiliary-Bearing (ZCAB) aimed at solving the usual problems associated with conventional large clearance REBs. The ZCAB consists of an array of rollers positioned circumferentially around the shaft as shown in figure 4.17. Under routine operation there is clearance between the rollers and shaft. When due to an MB failure the shaft drops, the rollers eliminate the clearance by moving radially inward to engage the shaft. Once engaged the ZCAB performs as a regular rolling element bearing. Damping and compliance are provided by a proper ZCAB's mount. When needed the ZCAB can also function in a load sharing capacity. A version of this bearing for thrust loads has also been developed.

The ZCAB bearing has been tested in conjunction with a magnetic bearing on a test rig capable of speeds up to 11,000 rpm. A number of rotor drops were performed and the responses of the ZCAB recorded. Figure 4.18 shows the quick recovery and ability of the ZCAB to recenter the shaft. During operation, the orbit of the ZCAB, as shown in figure 4.19, is minimal and the ability of the ZCAB to either engage or disengage during operation without inducing instabilities is portrayed in figure 4.20. No backward whirl typical, of REBs has been encountered on any of the tests.

A prototype of this design has been recently supplied by MiTi to a major gas turbine manufacturer. This ZCAB is designed to operate at 18,000 rpm with radial and axial loads of 1,000 lbs each on a 140-mm diameter shaft. Prior to shipment demonstration tests were run which included the activation of the ZCAB under a variety of speeds, rotor drops and coast-downs. It performed flawlessly throughout. Figure 4.21 presents a typical plot of shaft position during a simulated magnetic bearing failure at 18,000 rpm, the ZCAB operation during the interval and start of its coast-down.

(c) Oil-free Turbocharger. This is the turbocharger the Army speaker referred to during his presentation (sec. 4.2D). It is a 150 hp machine running up to 95,000 rpm and turbine inlet temperatures as high as 1,200 °F. It runs exclusively on foil bearings, their location in the machine shown in figure 4.22. Vibration measurements conducted at Schwitzer produced figure 4.23 showing peak amplitudes of 1.25 mils at the outermost portion of the compressor at the maximum speed of 95,000 rpm. A similar application is scheduled for a 600 hp heavy duty diesel engine at Caterpillar.

(d) Additional displays. In addition to these demonstrations visitors observed the operation of a foil bearing supported shaft system operating below, at, and above its bending critical speed and a group photograph was taken.

TABLE 4.1.—SELECTED VIEWGRAPHS PRESENTED BY WILLIAMS INTERNATIONAL AT THE WORKSHOP

For High Mach Missile Engines Bearing operating environments are especially severe – High inlet recovery temperature – No adequate heat sink or cooling source – Bearing operate well above boiling point of JP–10 fuel At high Mach numbers, bearing thrust loads climb dramatically – Ball and race Hertzian stresses increase several times over subsonic conditions Fuel lube system successfully tested at simulated high Mach conditions – Rig testing demonstrated 10 hours cyclic life – Hybrid ceramic cageless bearings – Operated with boiling JP–10 as sole coolant and lubricant – Design methods do not predict life or performance adequately	Storage Life Cruise missile engines require long term inert storage – 10 year current capability – Being extended in future to 20 years – Stored installed in vehicle, fueled and ready to shoot Bearings, gears, and lube system components are primary concerns for long term storage – 52100 and M50 corrosion – Elastomeric gaskets, seals, and dampers – Oil system contamination and leakage – Recertification costs Strong driver to remove oil lube system on all future missile engines
General Aviation and UAV Propulsion Focus for future GA and UAV engines is on non-contacting systems – Driven by cost, weight, and maintenance requirements – Foil air journal and thrust bearings – Hydrodynamic thrust bearings – Shaft-mounted ISG, no gears Design DN limits of conventional bearings limit growth of current engine designs – Small engines run at HP shaft speeds > 60,000 rpm – Relatively large HP shaft journal diameter required on 2-spool engines 30,000 hour cyclic life required	Small Engines in Business Aviation Mainstay of WI current business A large fraction of all unscheduled maintenance is related to – Oil system contamination – Bearing wear and damage – Seal leakage – Gear wear and fretting For long-life commercial engines, fuel-lube and foil bearings are not near term options – Need bearing, seal, and gear materials and designs for improved life with conventional oil-lube systems – Need methods to reduce contamination problems

TABLE 4.2.—INDUSTRY'S TRIBOLOGICAL LIMITATIONS IN GAS TURBINES

Manufacturer (Engine Size)	Bulk Of Lub. System	Materials	Oil As a Lub.	REB Inadequacy	Thermal Problems	Brg. and Lub. Suppliers	Reliability and Maintenance	Cost and Weight	DN Limitations
Williams Intern. (Small)	√	√	√	√	√	√		√	
Capstone Turb. (Small)		√							
Sunstrand (Small)	√						√	√	
Allied Signals (Small & Med.)	√			√	√				√
Pratt & Whitney (Large)		√			√	√	√		
G.E. (Large)							√		

4.3.—TWO VIEWGRAPHS PRESENTED BY THE U.S. NAVY

(a) Technology Approach

Near Term “Evolutionary”
Corrosion inhibited lubricants
Corrosion resistant bearings and gears
Longer life/higher load capacity components
Improved seals
Far Term “Revolutionary”
Requirements from new system capabilities
Alternative configurations made possible by expanding SOA

(b) High Speed Bearings and Seals

Challenges
Increase bearing and seal speeds while maintaining reliability
Off-set centrifugal loads with lighter materials or higher capacity
Advancements
Improved quality cleaner steels
Improved life modeling with contamination
Possible Direction
Fracture tough ring materials
Advanced materials for corrosion resistance

TABLE 4.4.—IMPACT OF HIGHER GAS TURBINE ENGINE PERFORMANCE ON THE ENGINE’S TRIBOLOGY

Increased Engine Performance = Increased Tribological Demands
Higher pressure ratios = Higher bearing thrust loads = Shorter life and increased propensity for catastrophic bearing failure Higher air flow = Higher shaft speeds = Larger shafts required to avoid supercritical bending modes = Higher bearing DN (shaft size × speed) and Seal velocity = Catastrophic bearing fracture and increased heat generation Higher gas path temperature = Higher bearing, component, and lubricant temperature = Increased coking (increased maintenance, potential for loss of lubrication = catastrophic failure), increased cooling air (parasitic loss), reduced viscosity (reduced bearing life)
Today’s SOA production engines are pushing the limits of conventional rolling element bearing/liquid lube technology
We either need improved bearing steels and lubricants, or we need novel approaches which remove load, speed, and temperature limitations

TABLE 4.5.—LIMITATIONS IN TODAY'S BEARING STEELS AND LUBRICANTS

Limitations of Bearing Steels
Currently there is a strong requirement for a steel with improved fracture toughness, wear resistance, improved fatigue life, and corrosion resistance While there have been several promising candidates, (M50 NiL, Pyrowear 675, and Cronidur 30) a single steel combining all of the required properties is still not available for production engines However, a steel with sufficient load, speed, and temperature capability appears doable
Limitations of Liquid Lubricants
Current polyol-ester liquid lubricants (Mil-L-7808K/23699) are limited to 400 °F. Potential to develop new chemical classes for production engines is doubtful Thermal management through modeling and design represents a new approach which allows conventional lubricants to be used in more advanced engine cycles.

TABLE 4.6.—LIMITATIONS IN THE PROPOSED ADVANCED TRIBOLOGICAL SYSTEMS

Limitations of Magnetic Bearings
Magnetic bearings offer the ability to remove speed and liquid lube temperature barriers, with additional performance benefits from active rotor control. However, load carrying of the bearings is a major issue. Systems where magnetic bearings have been sized to take the entire load for a fighter engine are excessively heavy. Systems where auxiliary bearings are used to share the load suffer from limitations of the auxiliary bearings. Life, lubrication, and load carrying ability are substantial issues for developing reliable auxiliary bearings.
Limitations of Foil Bearings
Air foil bearings remove temperature and speed barriers. Have been used in small production propulsion systems (air cycle machines) for years. However, have not made the transition to larger engines primarily due to load carrying capacity and rotor dynamics. Need to see a successful demonstration in an engine with a 20 lb rotor.
Limitations of Vapor Lubricated Bearings
Vapor lubricated rolling element bearings with carbon-carbon composite cages can operate at high speed, high temperature, and high load. The primary obstacle is life. The bearings last for about 10 hours at conditions for a high mach gas turbine.

TABLE 4.7.—CONCLUDING VIEWGRAPH BY THE U.S. AIR FORCE PRESENTATION

[There is not a single approach which is totally suitable for all conditions of future engines.]

Possible Approaches	
Fighter engines	Due to the extreme load conditions and reliability requirements of man-rated fighter engines, liquid lubes will be used for decades. However, new technologies such as modeling and simulation for improved heat transfer, small composite oil tanks with an ISG to eliminate the gear box, and improved steels can remove tribology barriers and significantly improve engine performance.
UCAV engines	In the near term, corrosion resistant steels and corrosion inhibiting lubricants offer substantial benefits. In the long term, foil bearings for engines of 5,000 lbs of thrust and below, magnetic bearing for 5,000 – 15,000 lbs thrust class, and liquid lube system for greater than 15,000 lbs of thrust represent viable approaches.
High mach interceptor/transport	High temperature magnetic bearings with active rotor control represents an attractive solution.
High mach missile engine	High temperature vapor lubrication represents an attractive solution.

TABLE 4.8.—TRIBOLOGICAL LIMITATIONS IN SPECIFIC GAS TURBINE COMPONENTS

Gas Turbine Engines	
Tribological Component Limitations	
Bearings	High DN (≈3 MDN), speed and size
Lubricants	Temperature (≈400 °F)
Seals	Leakage, surface velocity, temperature, life
Gears	Tooth loading and surface velocity
Splines	Wear and friction
Dampers	Temperature (≈400 °F)
Bushings	Polymer based (≈600 °F)
Each component has its own “wall” to overcome	

TABLE 4.10.—TRIBOLOGICAL LIMITATIONS CITED BY GOVERNMENT AGENCIES

	Materials	Contamination	Bulk of Lub. System	Maintenance	Reliability	Seals	Shortage of Manufacturers	Thermal Management	High temp. Lubs.	Cost
Navy	√	√	√	√	√	√	√	√		√
Air Force	√		√				√	√	√	
NASA/Army	√	√	√			√			√	√

TABLE 4.11.—CHARACTERISTICS OF A CONCENTRATED CONTACT

Problem identification
Concentrated contact behavior fundamental of many components –Rolling bearings –Gears –Cam and cam followers
In extreme operating environment –Conventional liquid lubricants cannot be used –Solid lubricants in the form of coatings, transfer films or powder a possibility –Vapor lubrication another possibility –Contact friction is generally high –Greater heat generation –Friction is generally temperature dependent –Increased wear –Wear process is also temperature dependent –Component life is dependent on tribological characteristics
What is needed? –Contact model to integrate mechanical and thermal environment for prediction of friction and wear –Incorporation of the contact model in component models, such as those presently available for rolling bearings and gears

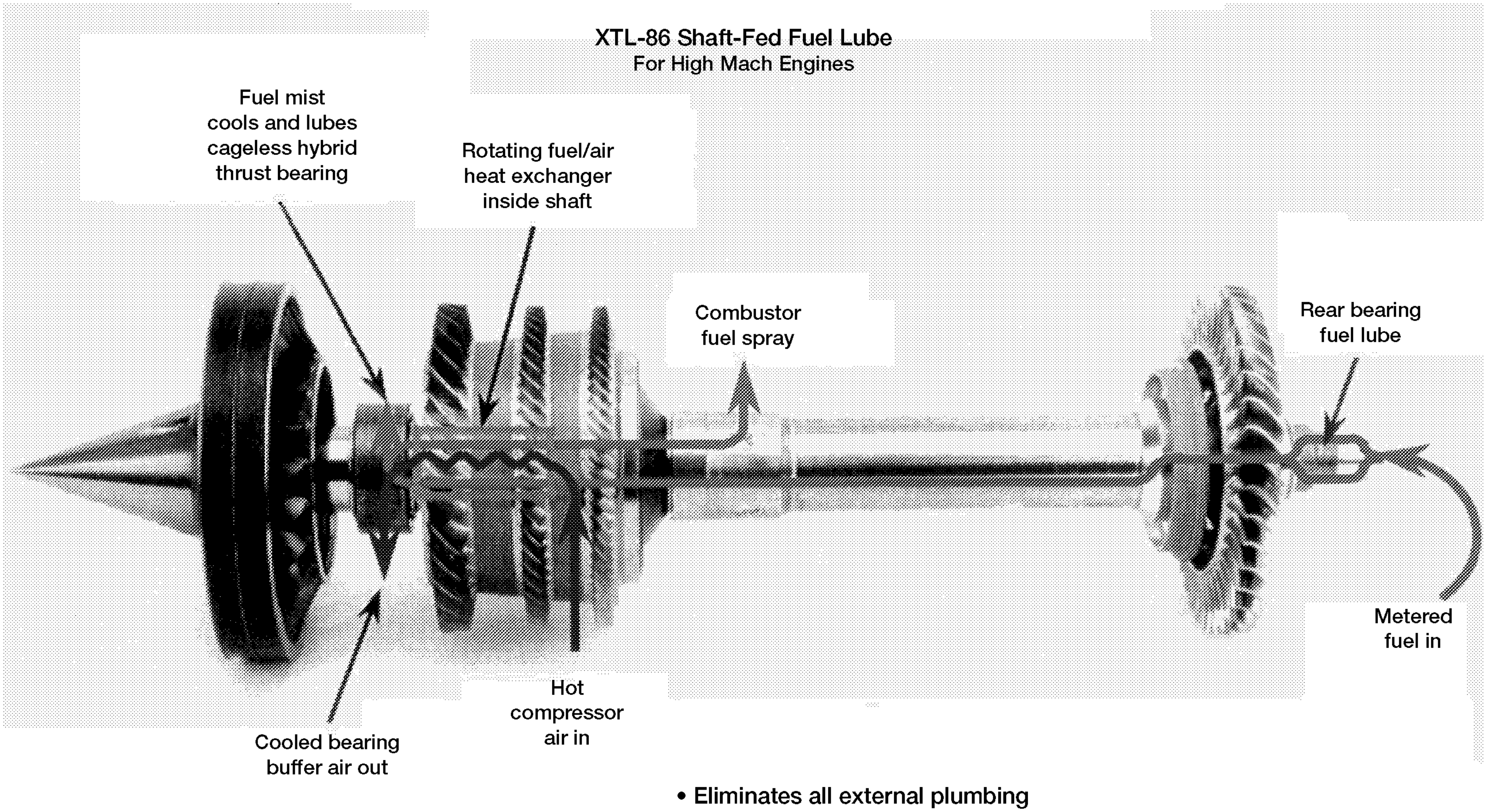
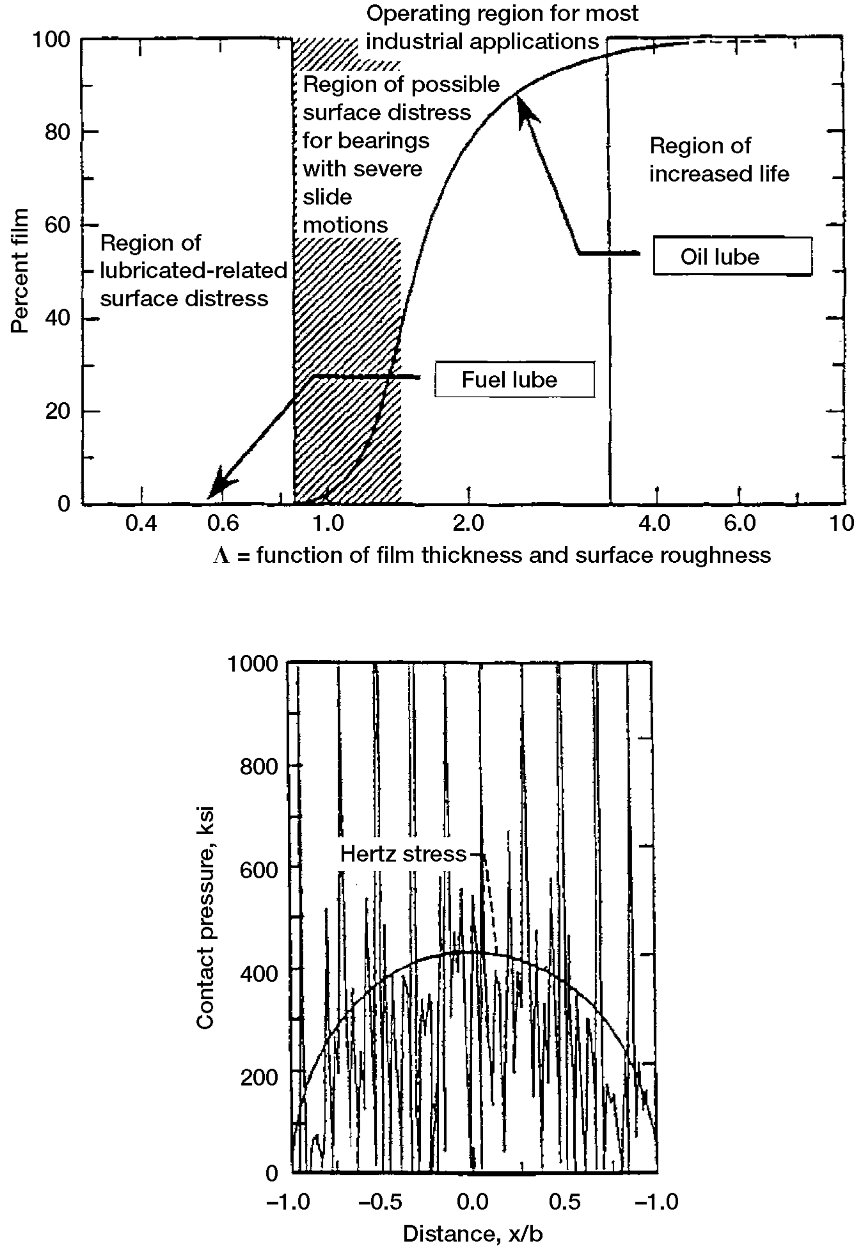


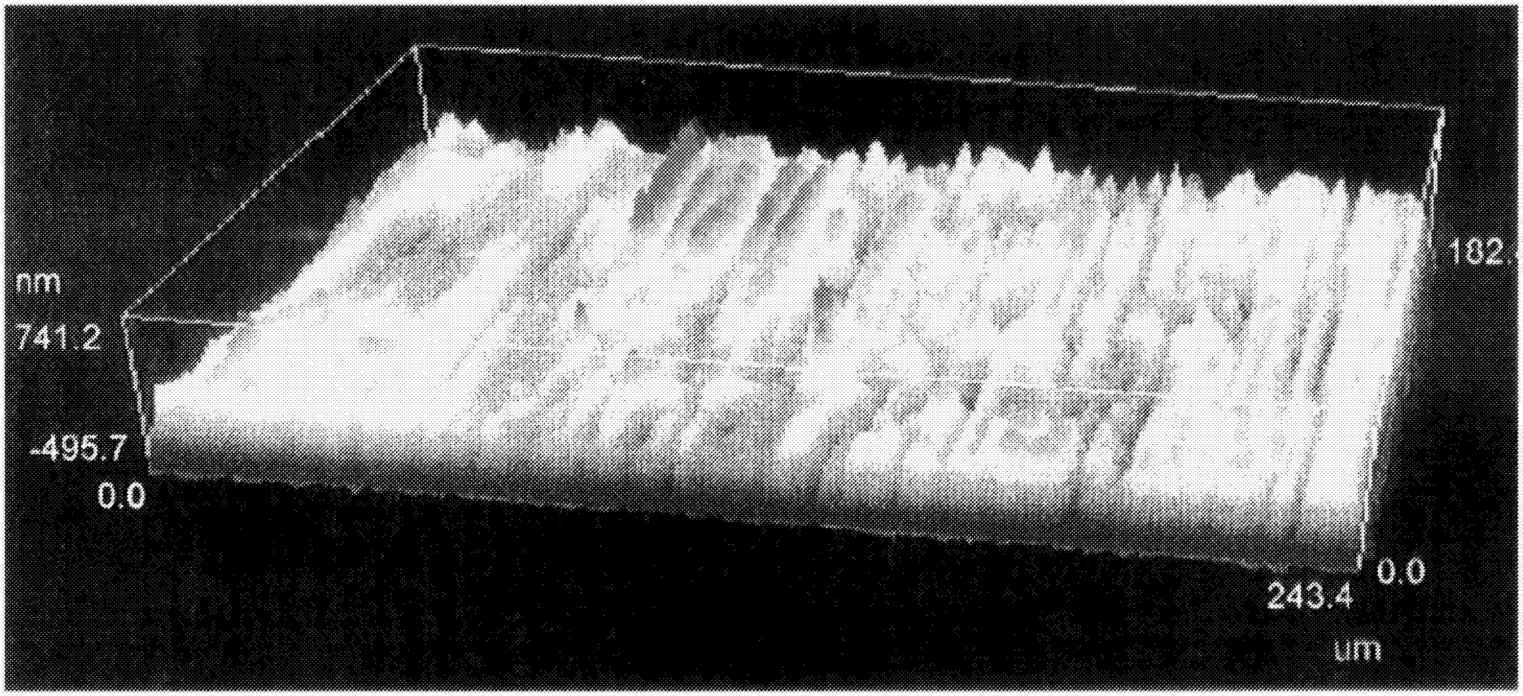
Figure 4.1.—Fuel lubricated XTL-86 rotor for high MACH numbers.



Local contact stress with fuel lubrication

Figure 4.2.—Effect of generated surface roughness in a REB using fuel as a lubricant.

3D surface texture of raceway
Timken Bearing



Average roughness: 4.7 μin.
Valley-to-peak: 48.7 μin.

Measurement technique: optical phase-shifting and vertical scanning interferometry

Figure 4.3.—Three-dimensional surface roughness on the raceway of a Timken REB

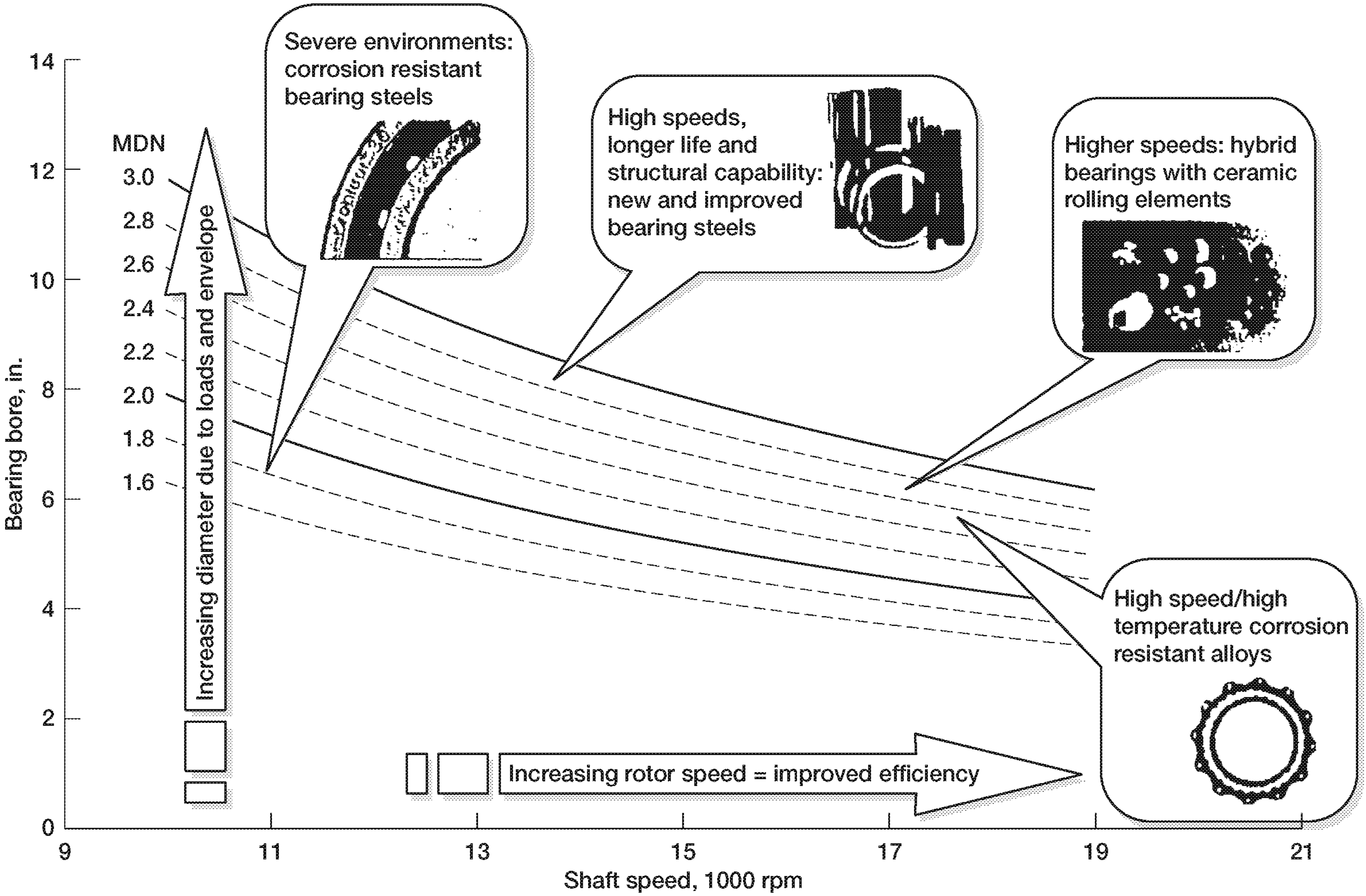
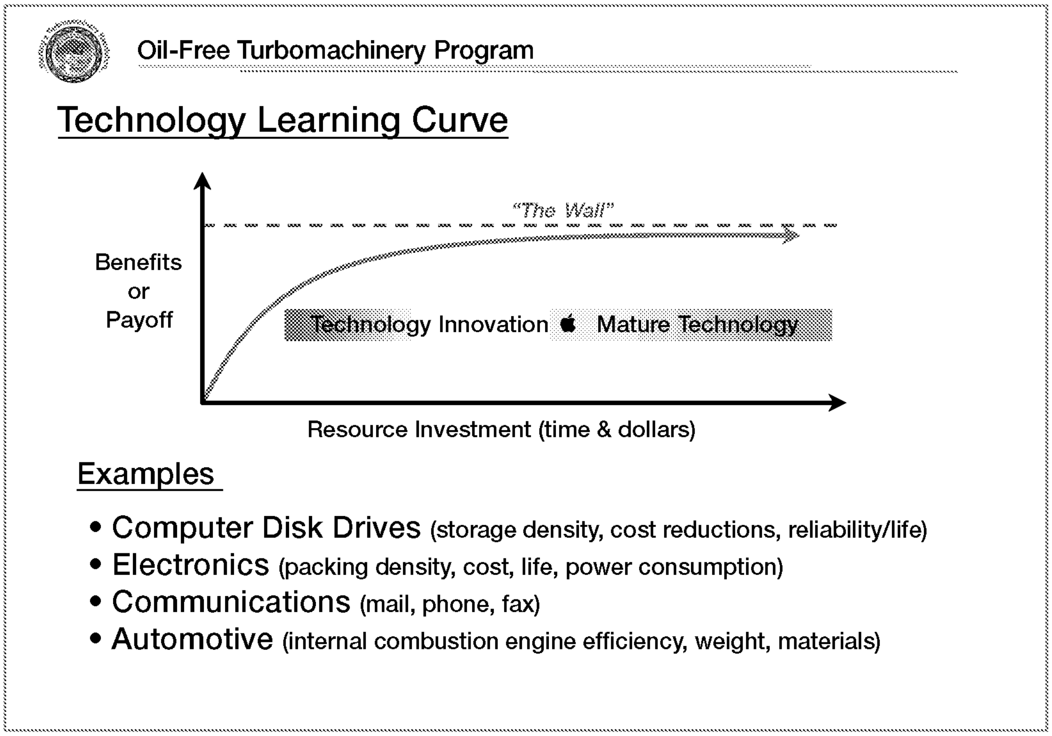


Figure 4.4.—Tribological requirements as a function of increased DN values.

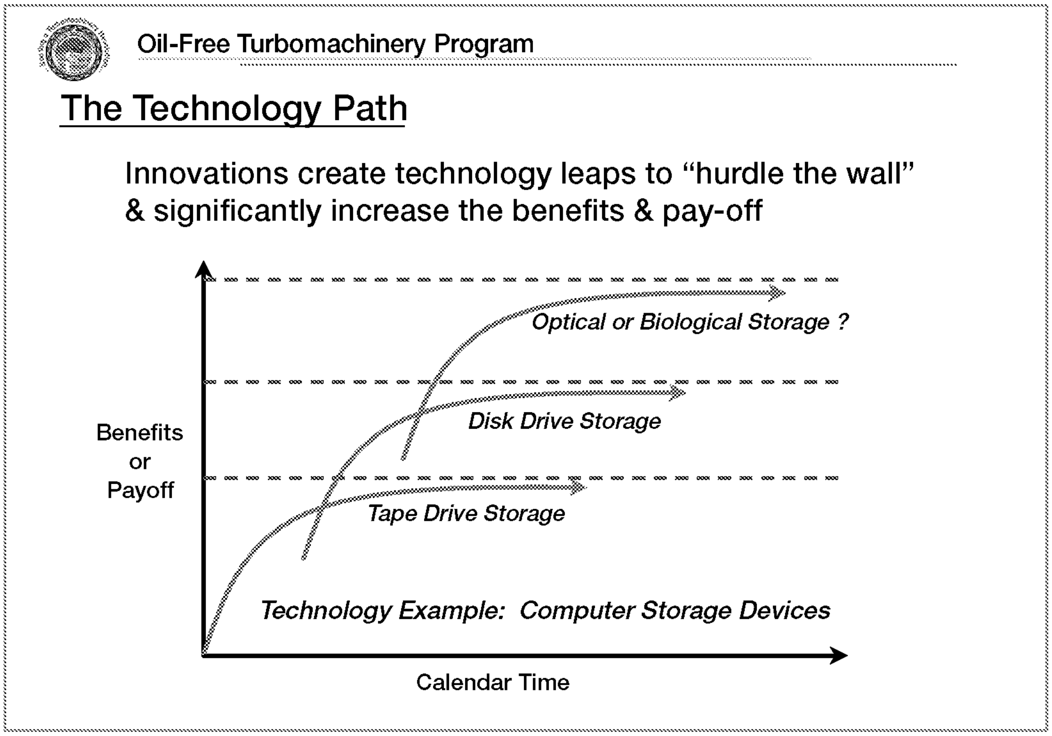


Oil-Free Turbomachinery Program

Technology Learning Curve

Examples

- **Computer Disk Drives** (storage density, cost reductions, reliability/life)
- **Electronics** (packing density, cost, life, power consumption)
- **Communications** (mail, phone, fax)
- **Automotive** (internal combustion engine efficiency, weight, materials)

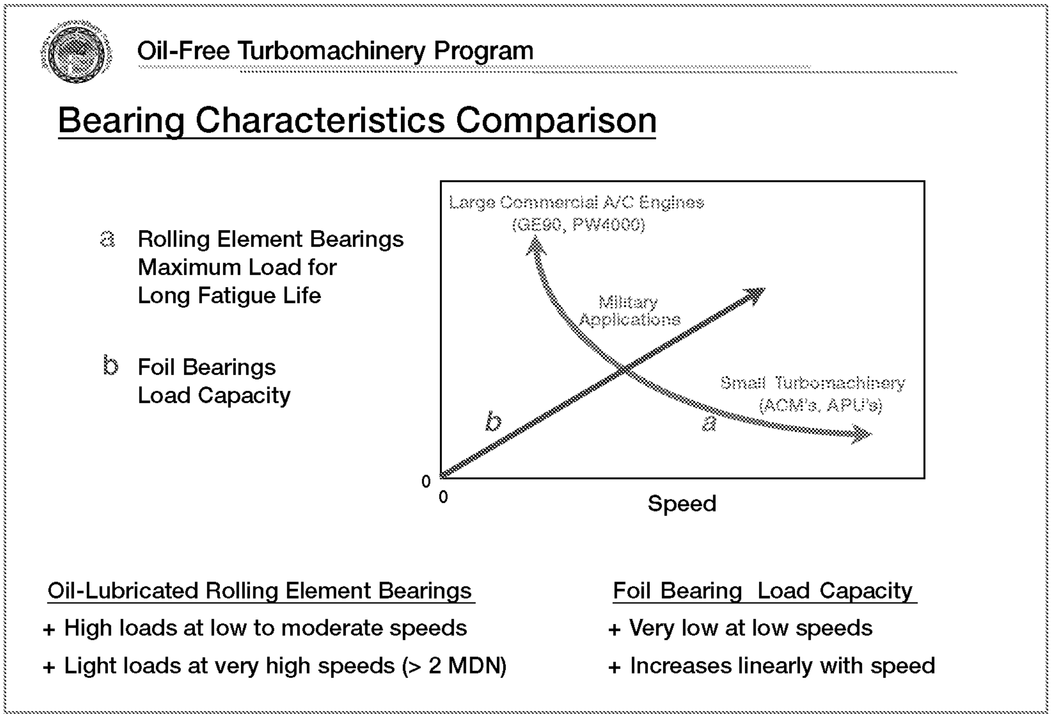


Oil-Free Turbomachinery Program

The Technology Path

Innovations create technology leaps to "hurdle the wall" & significantly increase the benefits & pay-off

Figure 4.5.—An example of technology maturation and renewal.



Oil-Free Turbomachinery Program

Bearing Characteristics Comparison

a Rolling Element Bearings
Maximum Load for
Long Fatigue Life

b Foil Bearings
Load Capacity

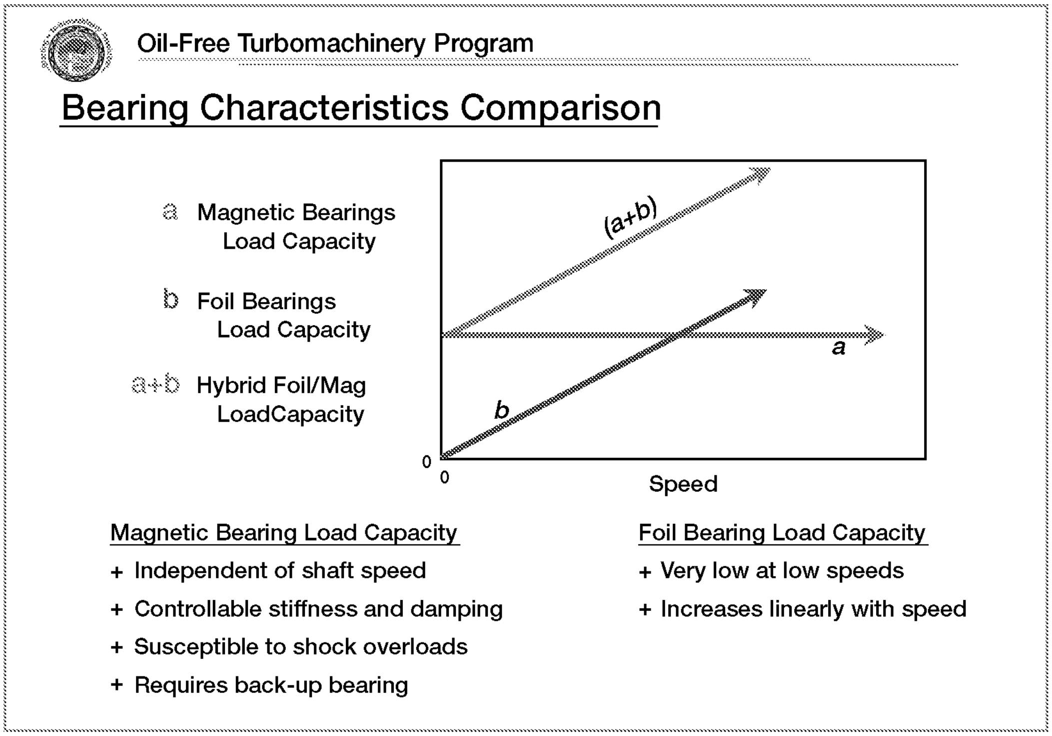
Oil-Lubricated Rolling Element Bearings

+ High loads at low to moderate speeds
+ Light loads at very high speeds (> 2 MDN)

Foil Bearing Load Capacity

+ Very low at low speeds
+ Increases linearly with speed

Figure 4.6.—Comparison of foil and rolling element bearing performance.



Oil-Free Turbomachinery Program

Bearing Characteristics Comparison

a Magnetic Bearings
Load Capacity

b Foil Bearings
Load Capacity

a+b Hybrid Foil/Mag
LoadCapacity

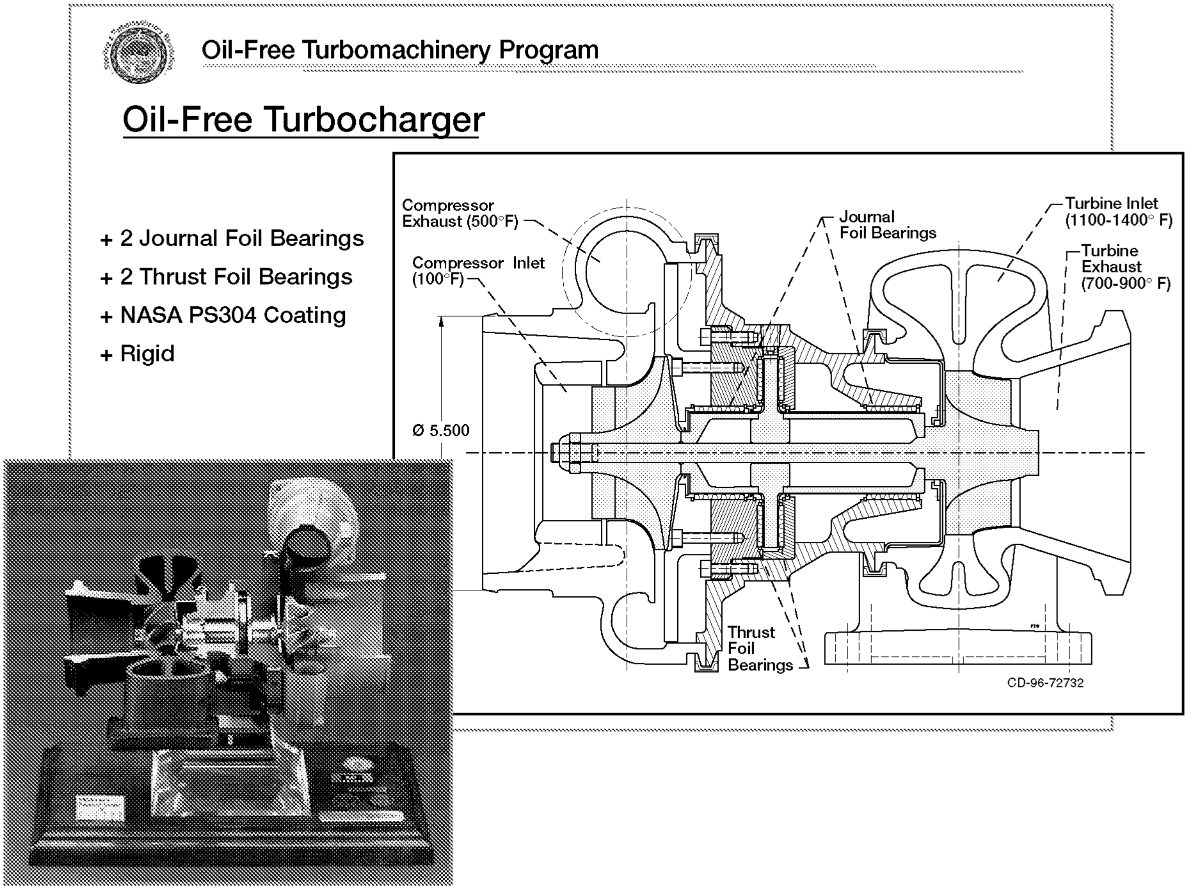
Magnetic Bearing Load Capacity

+ Independent of shaft speed
+ Controllable stiffness and damping
+ Susceptible to shock overloads
+ Requires back-up bearing

Foil Bearing Load Capacity

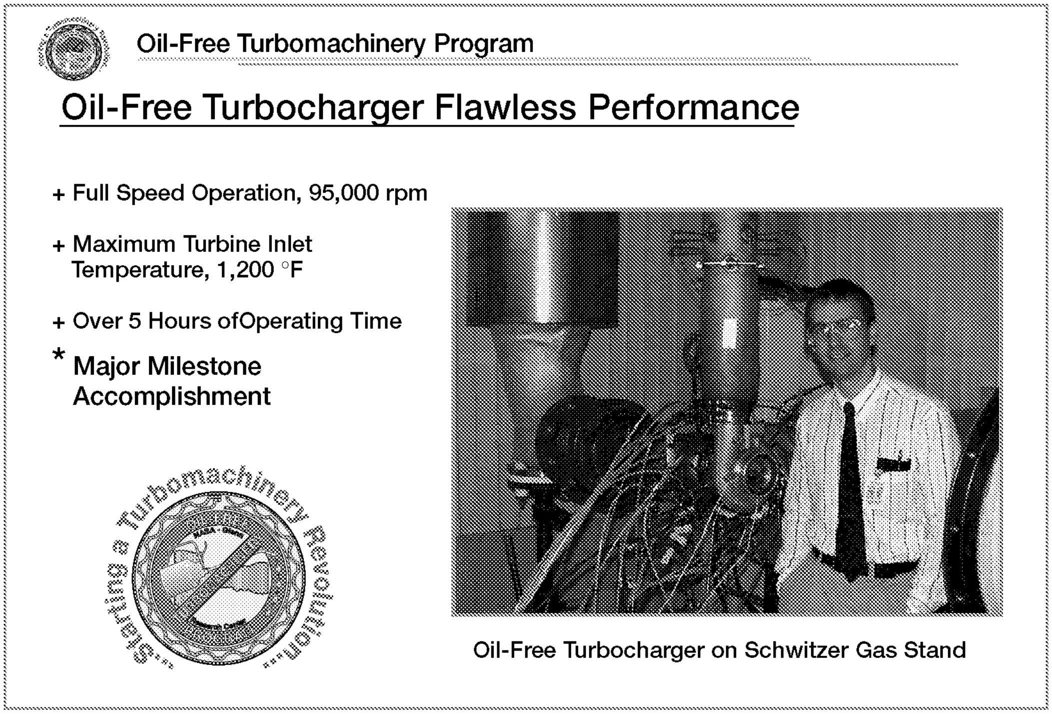
+ Very low at low speeds
+ Increases linearly with speed

Figure 4.7.—Comparison of foil and magnetic bearing performance.


Oil-Free Turbomachinery Program

Oil-Free Turbocharger

- + 2 Journal Foil Bearings
- + 2 Thrust Foil Bearings
- + NASA PS304 Coating
- + Rigid

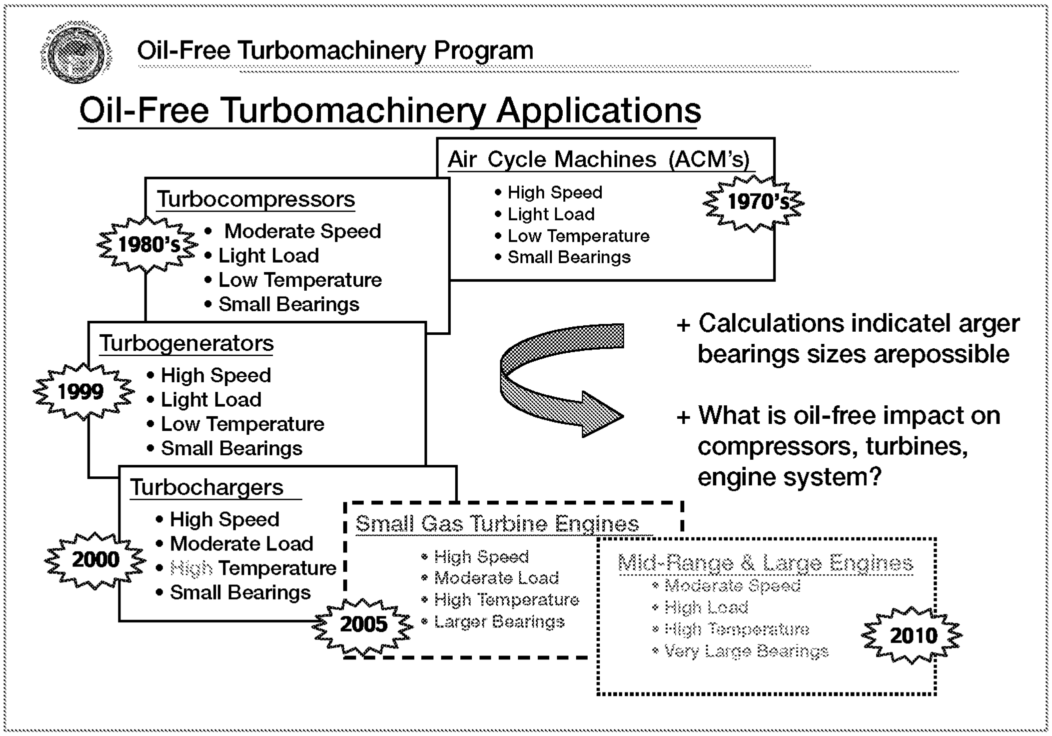

Oil-Free Turbomachinery Program

Oil-Free Turbocharger Flawless Performance

- + Full Speed Operation, 95,000 rpm
- + Maximum Turbine Inlet Temperature, 1,200 °F
- + Over 5 Hours ofOperating Time
- * Major Milestone Accomplishment

Oil-Free Turbocharger on Schwitzer Gas Stand

Figure 4.8.—Turbocharger equipped with foil bearings on test stand.



Oil-Free Turbomachinery Program

Oil-Free Turbomachinery Applications

Air Cycle Machines (ACM's)
- High Speed
- Light Load
- Low Temperature
- Small Bearings

1970's

Turbocompressors
- Moderate Speed
- Light Load
- Low Temperature
- Small Bearings

1980's

Turbogenerators
- High Speed
- Light Load
- Low Temperature
- Small Bearings

1999

Turbochargers
- High Speed
- Moderate Load
- High Temperature
- Small Bearings

2000

Small Gas Turbine Engines
- High Speed
- Moderate Load
- High Temperature
- Larger Bearings

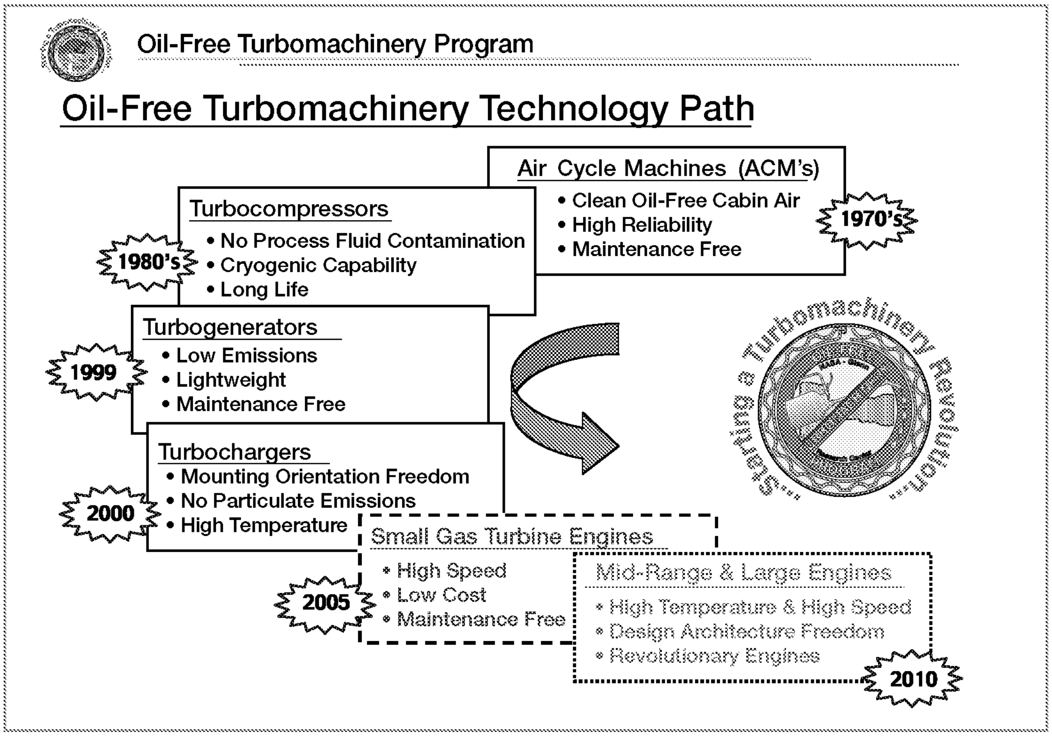
2005

Mid-Range & Large Engines
- Moderate Speed
- High Load
- High Temperature
- Very Large Bearings

2010

+ Calculations indicatel arger bearings sizes arepossible

+ What is oil-free impact on compressors, turbines, engine system?



Oil-Free Turbomachinery Program

Oil-Free Turbomachinery Technology Path

Air Cycle Machines (ACM's)
- Clean Oil-Free Cabin Air
- High Reliability
- Maintenance Free

1970's

Turbocompressors
- No Process Fluid Contamination
- Cryogenic Capability
- Long Life

1980's

Turbogenerators
- Low Emissions
- Lightweight
- Maintenance Free

1999

Turbochargers
- Mounting Orientation Freedom
- No Particulate Emissions
- High Temperature

2000

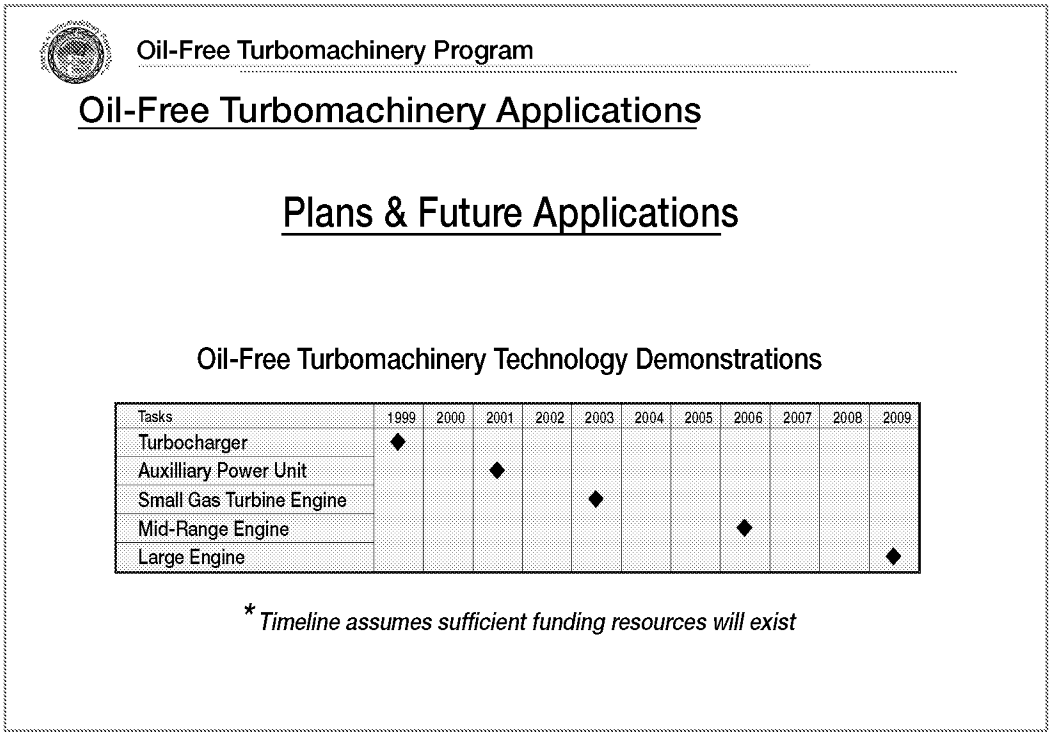
Small Gas Turbine Engines
- High Speed
- Low Cost
- Maintenance Free

2005

Mid-Range & Large Engines
- High Temperature & High Speed
- Design Architecture Freedom
- Revolutionary Engines

2010

Figure 4.9.—Projected applications and benefits for oil-free turbomachinery.



Oil-Free Turbomachinery Program

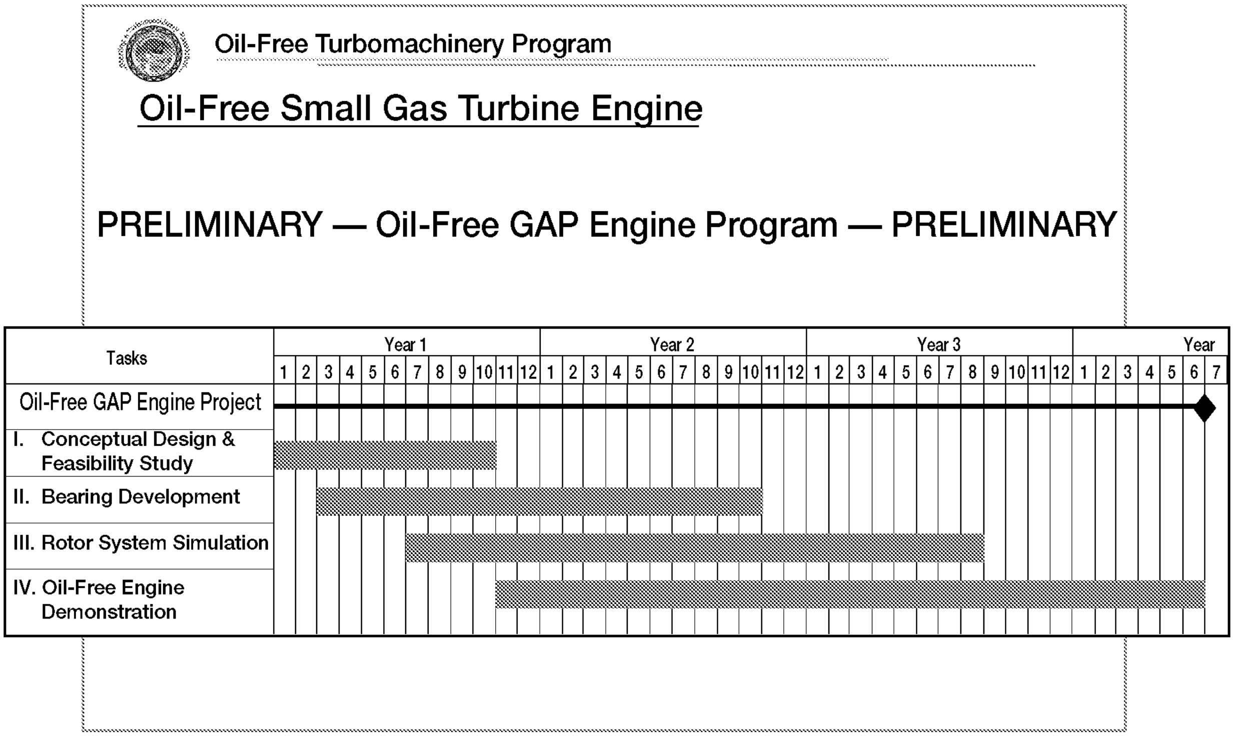
Oil-Free Turbomachinery Applications

Plans & Future Applications

Oil-Free Turbomachinery Technology Demonstrations

Tasks	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Turbocharger	◆										
Auxilliary Power Unit			◆								
Small Gas Turbine Engine					◆						
Mid-Range Engine								◆			
Large Engine											◆

** Timeline assumes sufficient funding resources will exist*



Oil-Free Turbomachinery Program

Oil-Free Small Gas Turbine Engine

PRELIMINARY — Oil-Free GAP Engine Program — PRELIMINARY

Tasks	Year 1												Year 2												Year 3												Year						
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7
Oil-Free GAP Engine Project	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	━	◆	
I. Conceptual Design & Feasibility Study	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																																	
II. Bearing Development			▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																					
III. Rotor System Simulation							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨											
IV. Oil-Free Engine Demonstration											▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	

Figure 4.10.—NASA road map for oil-free turbomachinery program.

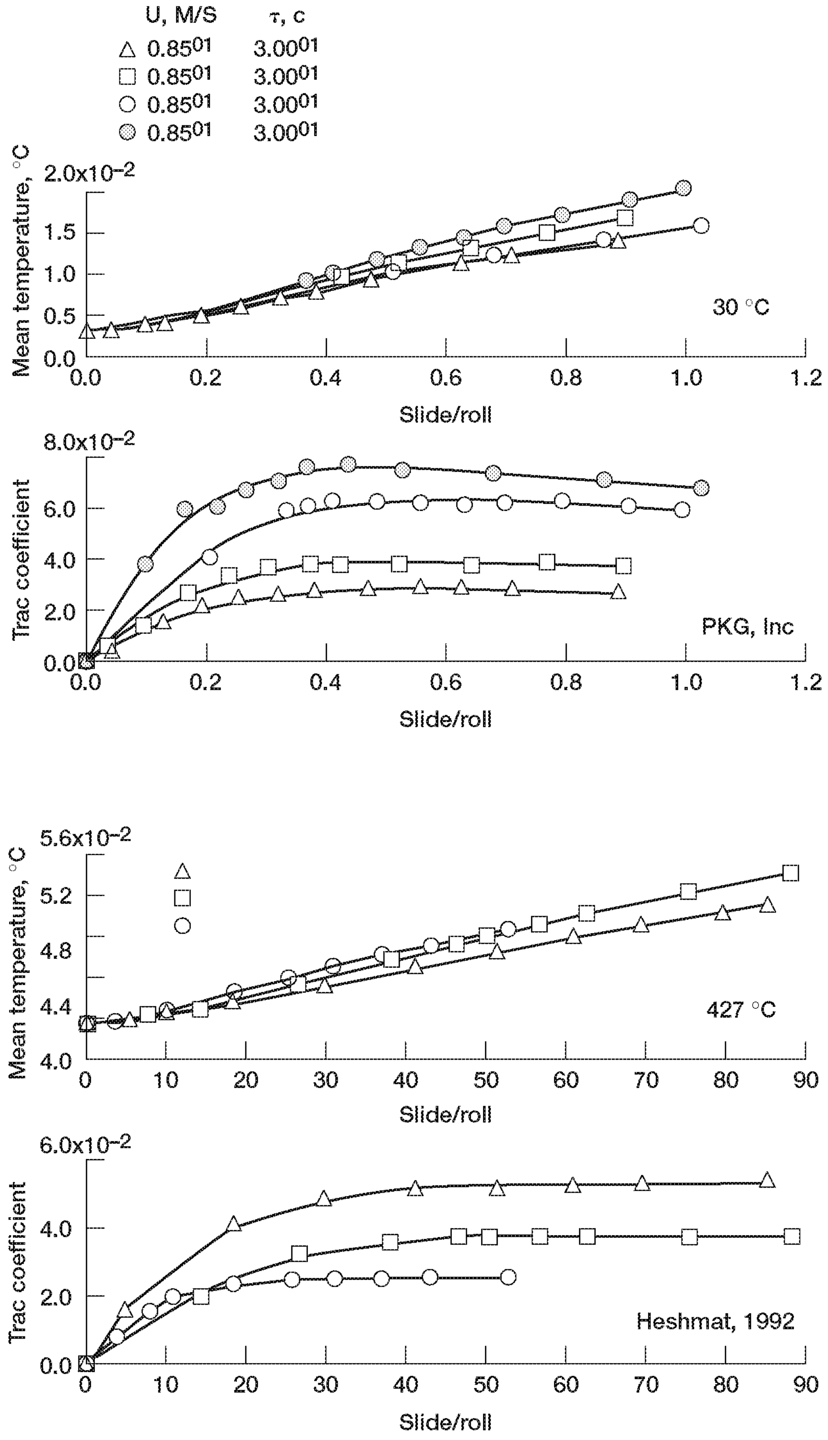


Figure 4.11.—Friction model correlation with experiments at two temperatures.

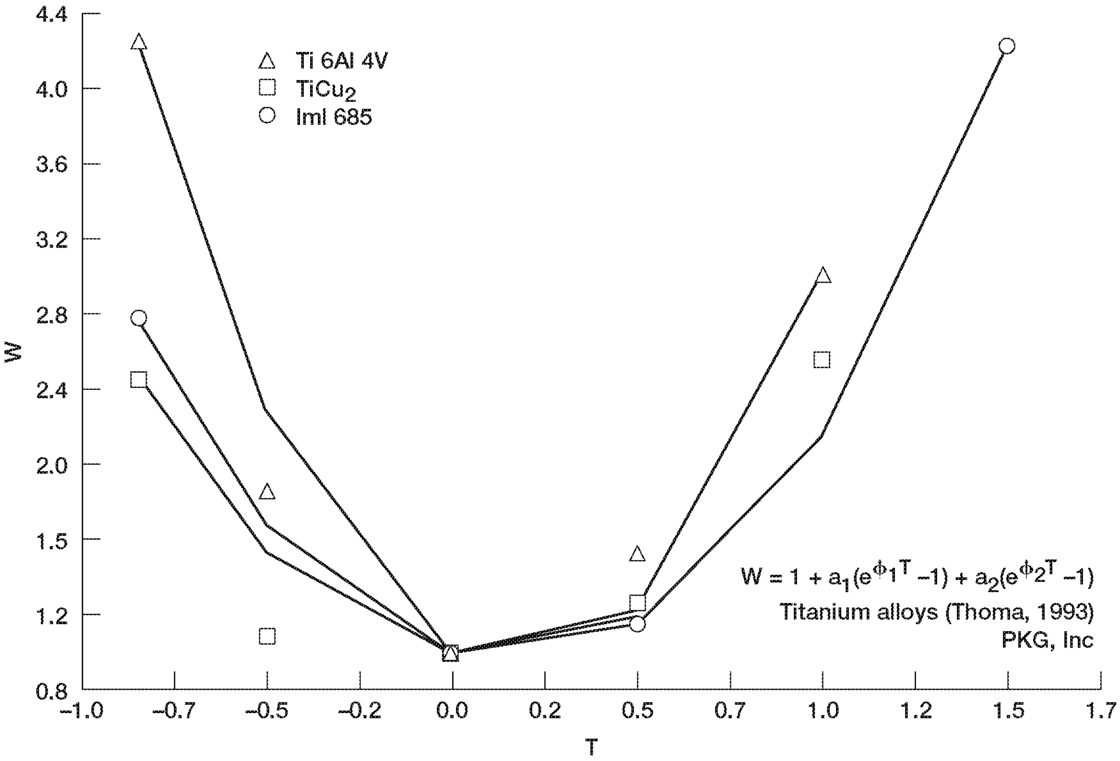


Figure 4.12.—Wear model correlation with experiment data.

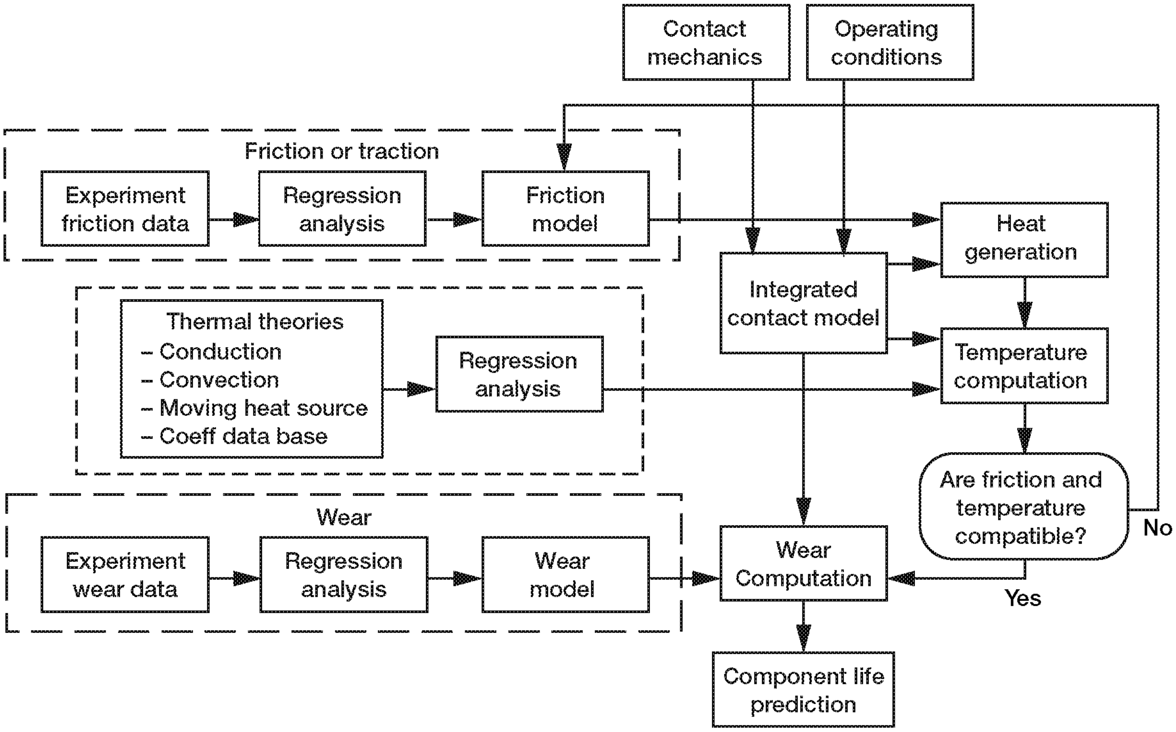


Figure 4.13.—Generalized flow chart for modeling of concentrated contacts.

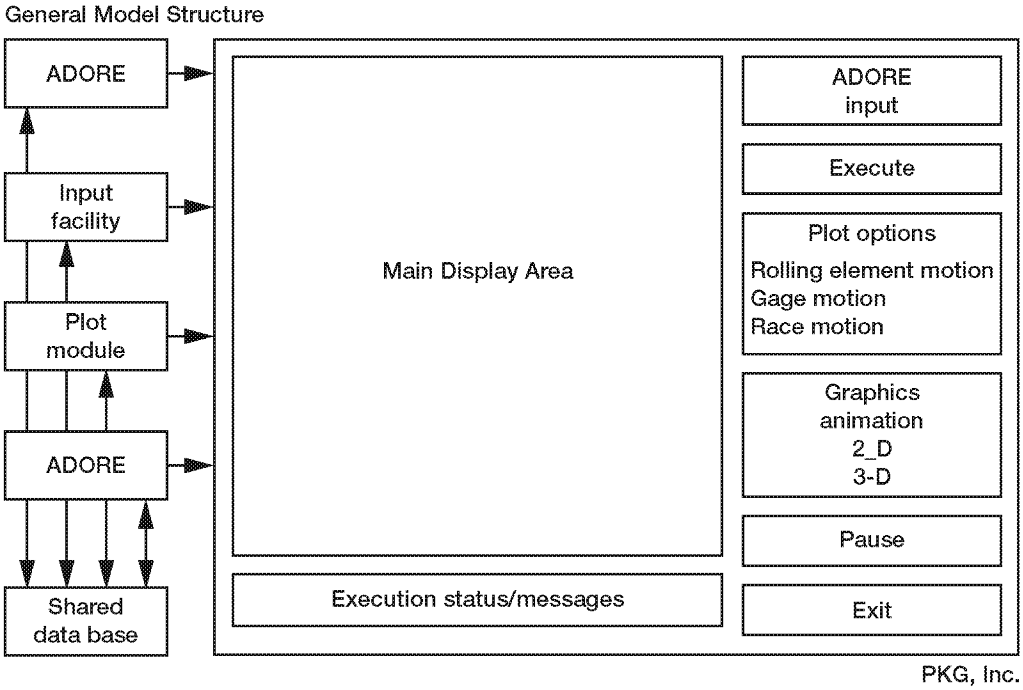


Figure 4.14.—Schematic of the interactive graphics model.

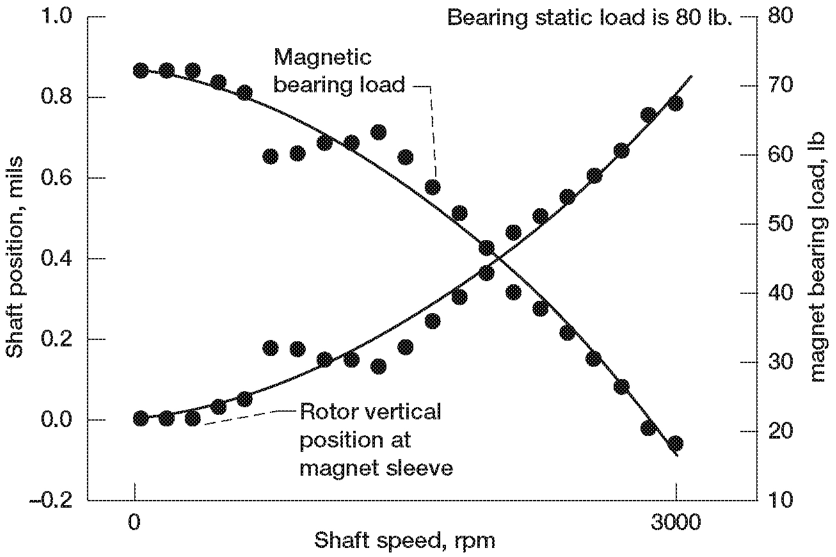


Figure 4.15.—Load sharing by the two component bearings in a hybrid magnetic-foil bearing system.

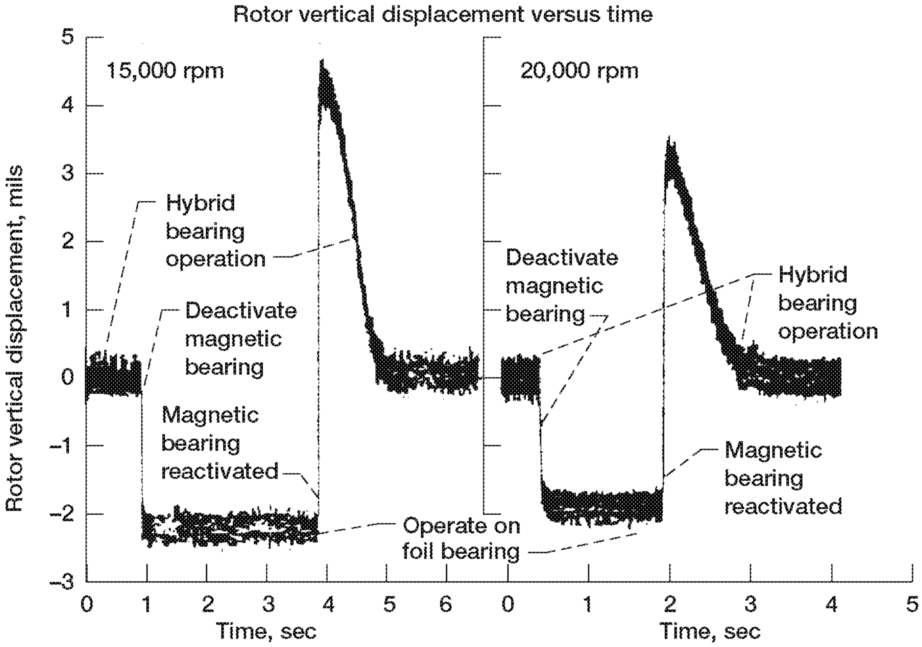
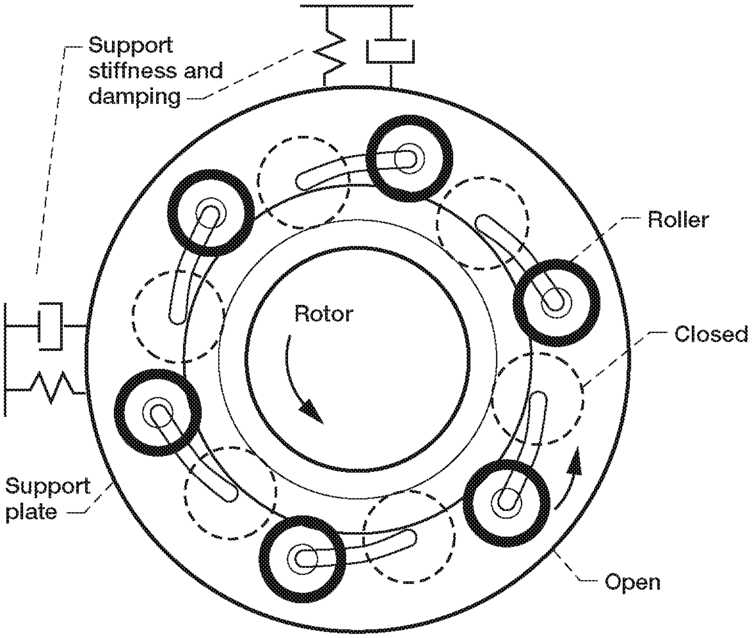
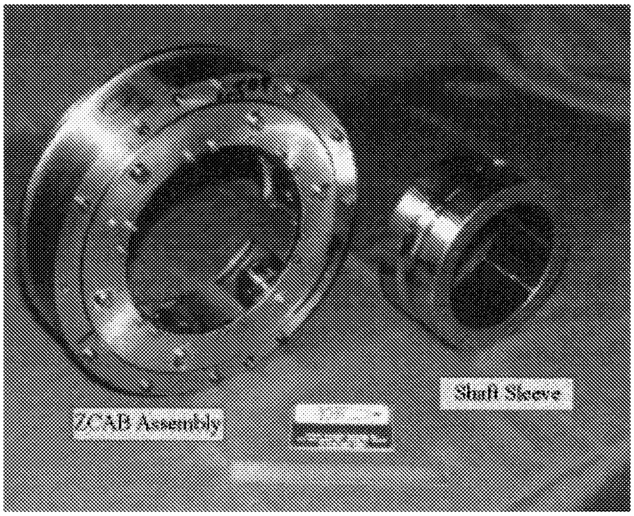


Figure 4.16.—Rotor and backup foil bearing response during a simulated magnetic bearing failure and recovery.



(a) Sketch of the ZCAB concept.



(b) Photograph of a ZCAB.

Figure 4.17.—New design of a Zero Clearance Auxiliary Bearing (ZCAB).

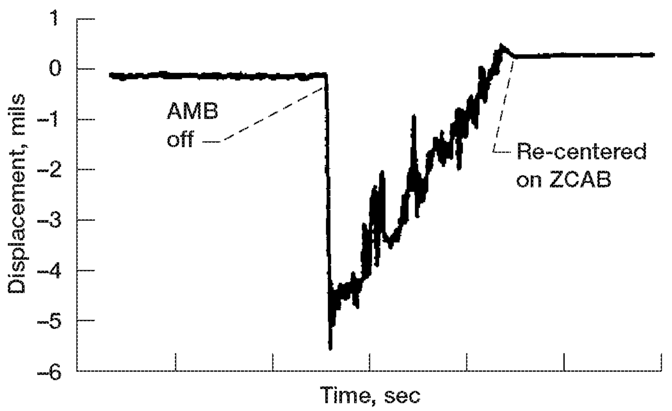


Figure 4.18.—Rotor response during activation of the ZCAB.

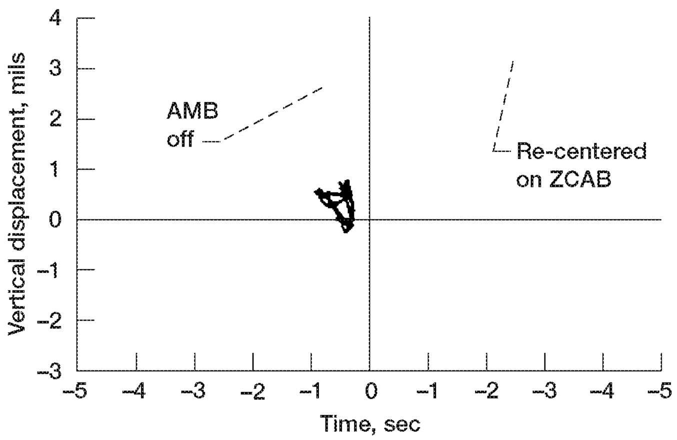


Figure 4.19.—Typical rotor orbit while running on the ZCAB.

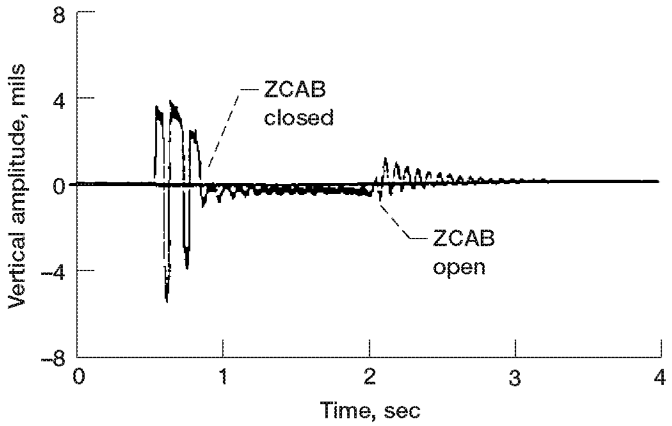


Figure 4.20.—Hybrid magnetic—ZCAB bearing response to shock.

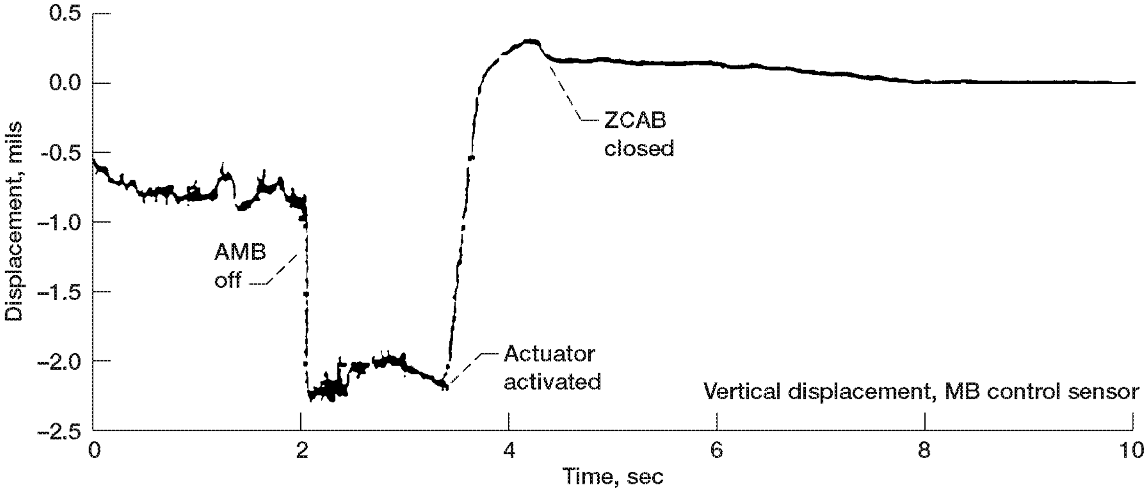


Figure 4.21.—Rotor and ZCAB response to a failure of the magnetic bearing in the hybrid system at 18,000 rpm.

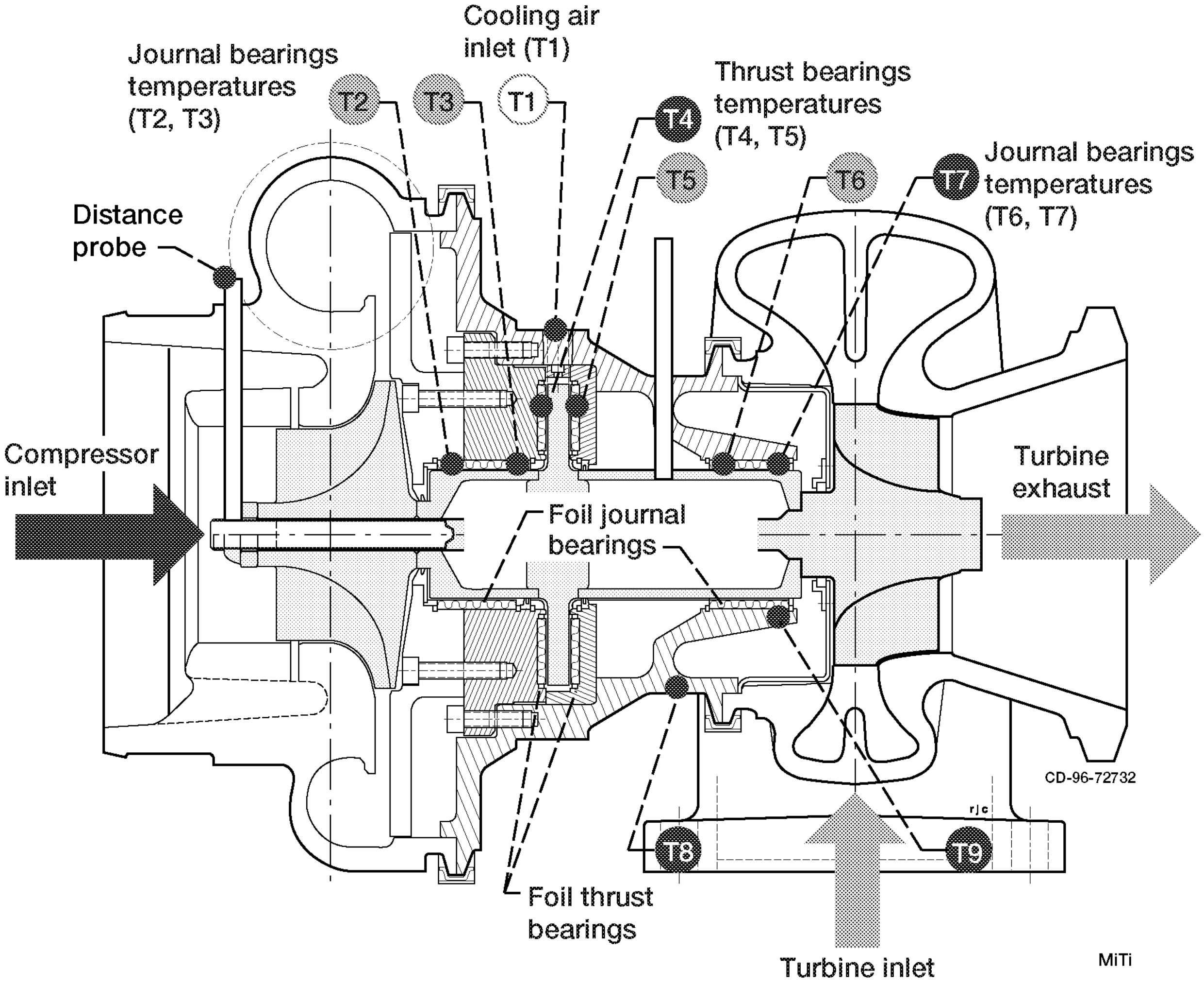


Figure 4.22.—Oil-free turbocharger showing location of journal and thrust foil bearings and thermocouples.

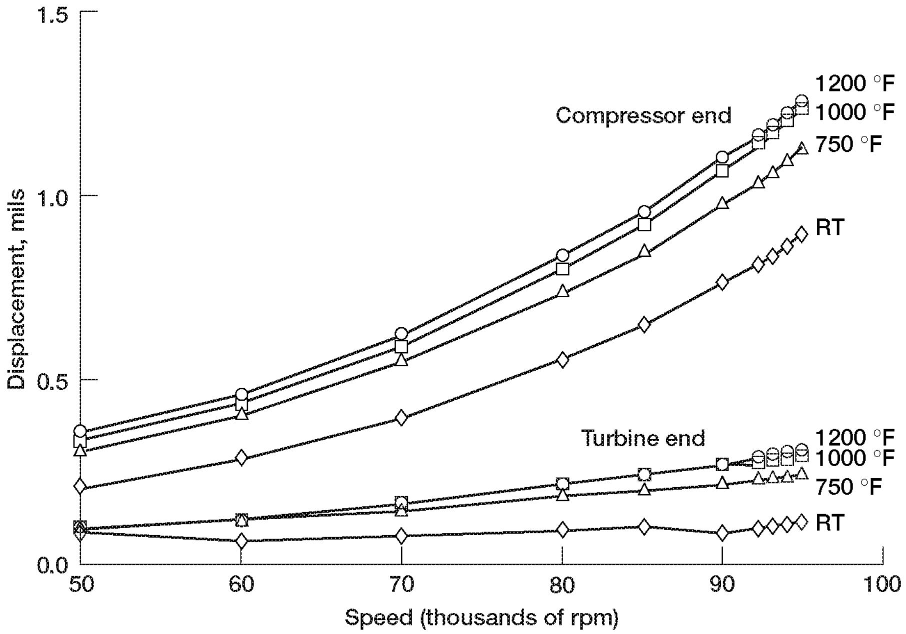


Figure 4.23.—Turbocharger rotor displacements as function of speed at various turbine inlet temperatures.

5.0 SUBGROUP PANELS

Following the presentations the plenum was divided into subgroups each focused on a specific technical area. These panels were to continue the discussions engendered by the presentations and to come up with a list of tribological programs related to their specific areas. It was somewhat uncertain how to accomplish this task. The subjects overlapped and some of the participants were interested in more than one topic. Eventually, one group was formed dealing with the subjects of REBs, seals, materials and lubricants since the last two could not be separated from the problems attending rolling element bearings. Though unintended, forming this large group essentially separated issues connected with established tribological components leaving the other subgroups to deal with innovative systems. In the end, five panels were formed centered around the following technological areas:

A. REBs/Seals plus Materials and Lubricants
B. Magnetic Bearings plus Back-ups
C. Compliant Foil Bearings
D. Modeling
E. Monitoring

Following the panels' work sessions the compiled lists were presented on posters before the full Workshop for discussion and comments.

5.1 REB's/Seals: Panel (A)

The priority programs selected by the subgroups were as follows:

Lubricants:
- improved stability at high temperatures
- boundary lubrication additives for satisfactory interaction with stainless steel
- thermal management over a spectrum of heat related problems
- vapor spray and de-oiler problems
- contamination, involving filtration and internal wear debris

Materials
- adequate materials for REB races
- fatigue failures in ceramic balls
- corrosion and wear resistance

Bearings
- shoulder wear on races
- surface topography

Seals
- advanced designs for high temperature and high speed
- advanced materials for the above condition as well as abradable materials for the tip clearances of compressor blades

The poster prepared by this panel is shown in retyped form in table 5.1 including additions and deletions entered in the course of the general discussion. This list was written without assigning to it any hierarchy of importance. However, during the discussion what emerged as the foremost item on the list was wear on the REBs occurring on the race of the inner land cage; in this process the cage itself does not wear but the race does with the wear extending over the entire periphery of the bearing. This issue was commented upon at some length by various speakers, their main points being as follows:

- There is no clear understanding of its mechanism. There are suppositions that it is aluminum oxide that starts the process; that high speeds are the cause; perhaps unbalance, misalignment or friction induced instabilities.
- The problem is linked to the use of M50NIL or small carbide structured materials in general. Other materials that have a microstructure similar to M50NIL seem to suffer similar wear. An M50 steel which has a different

microstructure is not susceptible to it. In fact, this problem arises with nearly all new materials. Identical bearings using conventional alloys run well.

- The wearing of the race shoulder is not the result of prolonged operation; if it is to happen at all it occurs in a matter of hours and often causes wear as deep as an eighth of an inch.
- The discussion was somewhat hampered by the fact that much of what pertains to the new alloys involves proprietary information.

The next item of importance was assigned to thermal stability of the lubricants used. Depending on the mode of operation the present levels of acceptable temperature range from 200 to 400 °F. A desirable goal would be 750 °F; this in face of the fact that over the last 20 years an advance of only 50 °F was achieved. In the opinion of one speaker the best that can be expected with the presently available lubricants is a rise of 100 °F. Even though the materials, too, must be able to tolerate such elevated temperature, still the lubricant is the limiting factor in running hotter engines. In materials it is fracture toughness and hardness at these temperatures that must be attended to but these are easier to deal with than the lubricants. In addition there are few oil companies willing to attend to new formulations since these need extensive research and the returns are meager; the smaller companies merely build on existing compositions by introducing solid additives. It was the view of this panel that with better lubricants there should be no problem in running REBs at DN values of 3 million and higher.

The next item deemed a priority was that of contamination of the lubricant. The biggest cause of bearing rejection is corrosion and next to it are scratches resulting from contamination. Moreover it was found that contamination has a very deleterious effect on bearing fatigue. Thermal management, too, was considered important but it was the opinion of many that this is not an exclusively or even mostly a tribological problem but one of design; how to manage the heat transfer from the engine components, how to distribute and lead it away from sensitive locations including the bearings, for example, thermal management has a lot to do with fuel flow aboard the aircraft. Seals were relegated to the last place primarily because a great deal of work is being conducted throughout the country on improving existing and developing new designs. Here, too, not much could be discussed in detail because of proprietary interests of the companies involved in these projects.

5.2 Magnetic Bearings Plus Backups: Subgroup (B)

The use of magnetic bearings (MB) was linked to two sets of criteria. One was the size of the engine. APUs which are considered small to medium size, from medium to large were driven by weight and cost while the large propulsion engines in addition to weight were concerned with performance. The second set of criteria related to what was expected of the auxiliary bearing (AB) and what would be the acceptable consequences in case of magnetic bearing failure. There were four permutations on this theme:

(a) Total failure of the magnetic bearing with the auxiliary bearing permitting merely a shut-down of the engine to save it from damage
(b) Lack of electric power at start-up or shutdown (low rpm) when the AB would perform both of these functions until sufficient electric power is generated
(c) Load sharing when the MB is exposed to excessive loads due to a maneuver or gyroscopic loading
(d) Emergency assist by the AB or what the speaker called “limp home” capability. This would require the AB to last until the aircraft can land—a time interval from 5 to 30 min.

An important aspect of MB's emerged to be electromagnetics, including the MB’s hardware and possibly seals. The issues raised by the MB subgroup is portrayed in the poster given in table 5.2 and of these electromagnetics occupied most of the discussion. It touched on the following concerns:

- The viability of winding insulation when current is cut at very high frequencies. The wire is then flooded and it is possible to abrade the insulation off the wire. This in turn may induce turn-to-turn “shorts” in the circuit. There is uneven coaxial expansion between the wire and insulation leading to wear.

- To reduce losses in the MB the laminates are thin and are provided with interlaminar insulation. These materials are subject to flutter under electromagnetic loading and it is possible to rub off the interlaminar insulation and create an inner circuit loop.
- In medium to large engines there is a problem with the soundness of the electrical connections at the prevailing high temperatures. There are no good production facilities for high temperature insulation or ceramic coated wires.
- Conventional insulation meant to have a long life—hundreds of thousands of hours—must be kept below 200 °C; for a life of 10,000 hrs one can go up to 250 °C.
- Electromagnetic materials at high temperatures present a serious life problem. Mechanical strength of the magnetic materials, creep, and loss of magnetic properties at high temperatures are all central problems here. The best kind of magnetic material, Hyperco 47S or 50, has been tested in an atmosphere of 483 °C (900 °F) but has not been used under running conditions.

There was some objection from the floor that the above concerns are not tribological issues—but problems in electric controls and materials. It was, however, agreed that introducing a magnetic bearing into a system is a tribological function and just like materials in REBs which have always been a tribologist's concern so here, too, it remains within the purview of this Workshop.

A fresh angle on the problem of magnetic materials at high temperatures was introduced by mentioning the potential of superconducting materials. There are some proposals for using such materials on the generators of gas turbines. They could make the MB's not only functional but also competitive with other systems. Also permanent magnets were broached. Samarium cobalt is a stable material at higher temperatures and neodybium iron is capable of a higher flux density. But these, it was pointed out, being constructed of rare earths are very dense, almost as iron, and would add appreciably to the total weight. In general most interested parties prefer electromagnetics. Magnetic materials are a weighty enough subject to have been dealt with in a couple of Workshops. One such Workshop, cited in reference 3, contains listings and tables of properties of a number of magnetic materials.

The next subject of discussion was the auxiliary bearing. Among the candidates were the following designs:

(a) Open-clearance REB. This would be a conventional large-clearance REB unengaged during routine operation meant to handle the rotor dropping onto it when the MB defaults. The problem arising here is rotor whirl induced by this process.
(b) Zero-clearance REB. This is a soft-mount, lightly loaded REB which rotates during routine operation. When the MB fails, the load is transferred to the rotating REB.
(c) Hybrid Foil Bearing.
(d) Powder-lubricated Hydrodynamic Bearing.
(e) Bushing that would accommodate the dropped shaft by simple sliding.

The view was expressed that none of the above would be an across-the-board panacea and the use of a particular system would depend on the application. Thus in some cases there is need for an AB that would prevent any damage to the engine. Another case is of the FAA where everything remains under control even though the engine may be damaged in the process. This was related to the level of redundancy or fault tolerance within the magnetic bearing system. An issue seemingly ignored is the need for the AB to damp out the vibrations of the dropped rotor; certainly this would be a serious issue if the system ran at supercritical speed. As an example, an engine with a radial load of several thousand lbs dropping on a 150 mm REB from a speed of 3 million DN, the energy due to the sudden REB acceleration would be sufficient to melt ten such REBs.

The discussion then reverted to the sort of scenario one visualizes in the case of the MB failure. When dealing with APUs all that is needed is a safe shutdown. From the military viewpoint it is the ability to limp home, that is the AB should be able to take over operation for a certain time period. And still from the military viewpoint, if the aircraft has to engage in combat which may last only a few seconds only but, due to maneuvering it has high transient g's, there must be load sharing by the AB. In emergency situations when the MB suffers total failure the AB must be able to carry the entire load.

5.3 Compliant Foil Bearings: Subgroup (C)

Table 5.3 gives the poster list compiled by the panel on foil bearings. Neither at the panel meeting nor in the general plenum discussions was it possible to arrive at consensus to establish a hierarchy of preference to the technological areas jotted down by this subgroup. Part of the reason for this was that different groups had different priorities and a number of participants felt that only a parallel effort in the various areas would be of help when it comes to actual engine design. A number of issues were then debated and qualified with regard to the employment of foil bearings.

1. Range of Operation of Compliant Foil Bearings (CFB). There was a strong emphasis that rather than assign upper bounds on the capabilities of foil bearings it would be more useful to specify their range of operation. By specifying the maximum and minimum temperatures, for example, it would give an idea as to their suitability for cryogenic applications as well as in hot turbomachinery. Since these bearings are mostly lubricated by air and their load capacity is a function of the ambient pressure, it would be useful to know the altitudes at which these bearings are still expected to function. While their static capacity has been determined by tests it would be good to know what kind of overloads they can endure.
2. Vibration. Much still remains to be determined about a CFB's ability to endure sustained vibrations. A particular case is the capacity of the thin foils to tolerate shock loads and vibration when they are at rest or transported-similar to the brinelling problem with rolling element bearings.
3. Load capacity. While this term is more or less clear with rigid surfaces this is not the case with CFBs. Even before qualitative figures can be given this term needs first of all a definition—and this is as yet lacking. A primary difficulty with arriving at a valid definition is that the film varies both along and normal to the velocity vector; furthermore, if the hydrodynamic film is thin then taking into account the surface roughness of the two mating surfaces the film also varies normally to the planar film distribution.
4. Variety of Designs. The attempt to offer general performance data is in large part frustrated by the proliferation of a variety of designs. To start with there are two generic families of foil bearings, either tension-dominated or bending-dominated and, lately, also combinations of both. Even within the bending-dominated family various manufacturers use different substrates-overlapping leafs, spiral geometries, bump foils, and others.
5. Design Tools. There was mention of the fact that no manual or catalog exists to guide the engine designer in calculate bearing performance-similar to what is available in the field of REBs. The points raised in items 3 and 4 above are the reason. In the meantime the following approach was suggested by those with experience in the field. If the load capacity of a CSB is known at a single point-load carried at a given speed-this can be linearly extrapolated to the origin of the plot. Such a plot would be valid for a given design only. Having a family of such load-speed plots the designer may pick whatever is most appropriate to his application. The moral of all this is that there is still a great deal of experimental and theoretical work to be done in this field.
6. Dynamic Characteristics. The last remark holds even more when the question of foil bearing dynamics is raised. Bearing stiffness is made up of the hydrodynamic stiffness of the gas film and the structural stiffness of the substrate and the immediate dilemma is how to combine the two. Damping is an even more serious problem, given that the viscosity of air at room temperature is 300 times lower than of a typical oil. While these implications are serious enough for bearings an even more critical question is how air or process fluid dampers would perform in oil-free turbomachinery.
7. Surface Finish and Coatings. In this area it is important to consider what happens to the coating when exposed to a large number of starts and stops and the possible fretting of the bump foils when exposed to prolonged or continuous vibration. The foil materials must be able to withstand temperatures above 1,200 °F as well as a cryogenic environment, the cryogens having poor lubricity and low viscosity.
8. Thermal Management. This can be broken up into a system and bearing thermal problem:

   - System. Normally the heat is syphoned from the hot parts of the engine to the bearing cavities using the lubricating oil. No air would be capable of the job that the oil has conventionally been doing. Introducing foil bearings brings with it the task of thermal management in the whole system.

- The foil bearing sitting in a hot environment would itself be needing cooling. Usually side leakage of an oil accomplishes much of that-up to 80 percent. As tests at MiTi have shown, air is capable of only 10 percent of heat removal.

9. Modeling and Performance Prediction. Modeling of CFBs is difficult because, starting with the compressible Reynolds Equations itself, the relationships are not linear. Then there is the need for a simultaneous treatment of the hydrodynamic and elasticity equations. Whatever good modeling codes exist are proprietary with the manufacturers of these bearings.
10. Design Integration. This has to do with the effect that insertion of foil bearings has on the overall engine design. Care must be taken of the adequacy of blade tip clearance; there is the question of starting the engine without oil for the gearbox; and problems with the accessories and engine assembly.
11. Thrust Balancing. Foil thrust bearings are technologically less developed than journal bearings. In conventional designs, in addition to accommodating overloads, the thrust load is used to prevent ball skidding during transient speeds. The latter would not be required with foil bearings. The design, therefore, must look toward a system of zero net thrust load. The thrust foil bearing can just merely idle on a thick film and, since power loss is inversely proportional to film thickness squared, this will eliminate the power loss associated with a loaded thrust bearing.
12. Seals. One lesson from foil bearings applicable to air seals is that it is very difficult to push through a flow of air in the axial direction—a desirable feature in air seals.
13. Life. With all the laboratory and analytical data available for foil bearings it would still be desirable to ascertain how they would perform over time in actual service—what their life expectancy would be.
14. Instrumentation and Health Monitoring. This is very much in its infancy. Given the fine structure of a foil bearing it would be both desirable and difficult to enter the tight spacing between the foils to measure temperatures and pressures. Knowing the pressure profile over the top foil and the film thickness distribution would go a long way toward defining and quantifying load capacity—all uncertain at the present time.
15. Scalability. This issue arose at the first mention of foil bearings. It was granted that these bearing are very adaptable to small engines. But for larger engines there was scepticism as to its adaptability. At present they can carry something like 2,000 lbs on a 15-cm (6 in.) diameter bearing. Much remains to be done to offer convincing evidence of their applicability to propulsion engines.

The extensive discussion on the above aspects of foil bearings reconfirmed the initial feeling that should foil bearings be contemplated beyond the present range of applications, all the above mentioned implications would have to be pursued simultaneously. The argument was that should the effort be concentrated in only a few areas even if these were successfully resolved, the total engine system may still not perform satisfactorily and one would be thrown back to the beginnings of the effort.

5.4 Modeling: Subgroup (D)

In a sense the selection of modeling programs is a function of the prioritization in the other technologies. Whatever the choices, they will have to deal with the mechanical and thermal aspects of the subject and, internally, with computational problems. Given the present state of computer capability the latter should not prove to be a major impediment. Table 5.4 lists the kinds of modeling desired and, as in the other lists, the items here are not placed in any order of importance.

1. Dynamic Characteristics of Foil Bearings. This involves the mathematical coupling of the hydrodynamic and structural elements of the bearing. It may be similar to the dynamic modeling of REBs where, likewise, there are the elastic and lubricant film equations to contend with.
2. Computational Aspects. Here perhaps an important aspect may be whether a given model is made system dependent or independent. In the past most tribological codes were independent and applicable to a range of problems and systems. It would have to be seen to what extent this is possible in the present case.

3. Traction Modeling. This is the subject referred to under 4.3 as concentrated contacts and includes vapor phase, solid and powder lubrication. Some of these subjects are in need extensive work both analytical and experimental before adequate models can be constructed. For the vapor phase the problem is particularly complex as it is not quite clear what the inputs should be and what kind of a film is generated. Does the film consist of a vapor which is a compressible fluid or does it consist of solid particles, forming a discontinuous film. Mathematically this would be a most difficult problem to formulate. On the other hand the Air Force reported an experiment on vapor phase lubrication which did produce a continuous film, 200 nm thick. Being independent of speed it is surmised that its mechanism is not hydrodynamic, more likely a powder-like effect due to the ongoing wear.

4. Wear Modeling. This is partly related to the modeling concentrated contacts. There are recent results showing that hard surfaces can wear more severely than soft ones. The race wear at the cage contact mentioned under 4.2 may be a case in point. If it is due to particles embedded in the softer surface this may be an instance of what is called "third-body" interaction—the basis of powder lubrication.

5. Stress Modeling in Coatings. This would require obtaining the shear and normal stresses both on the surface of the coating and at the interface where it is bonded to the substrate.

6. Micro- and Macro Models. This refers to the iteration between separate systems for which there exist different models—such as the interaction between the bearing surface and the lubricant film whether liquid, solid or powder; between two gearing sets; or between a rotor dynamics model with a model for bearing dynamics.

7. Thermal Management. As partly alluded to previously when the talk was for friction and wear to be related to the prevailing temperature, this modeling task, too, would be an elaborate undertaking. Extensive mechanical, thermal and tribological data would have to be on hand to proceed with thermal modeling. Additionally, it was questioned how such data would be selected as not all of them are reliable nor consistent.

In a follow-up discussion it was posited that perhaps the problems facing a Workshop like the present should be subdivided into two categories, at least in certain cases. One would be where the physics of a process are sought and this would be the purview of academic research and doctoral theses. When engineering solutions are sought one may sidestep the principles involved but with the help of experiments resolve the problem as a system even if the reasons for the eventual success are not fully clear.

5.5 Monitoring: Subgroup (E)

The list prepared by the Monitoring panel is shown in table 5.5. As seen, it follows closely the presentation given by the speaker at the plenary session. Some of the supplementary comments by the speaker, panel, and audience follow:

- It was suggested to put MEMS directly into filters to get a continuous reading of the accumulating debris. If not in the filter they could be placed in a bypass line and where they could record the level and kind of debris. It was pointed out that the flow pattern in a filter is a fairly disorderly affair and it may be difficult to read the accumulating debris. For this reason a bypass loop may be a better choice.
- Any system of on-line accelerometers supplying continuous information must be installed and interpreted in a manner that would guarantee it would not produce false alarms. It is most important for both military and commercial aircraft not to shut down an engine unnecessarily.
- Knowledge-based systems and neural nets need further investigation. These use computer software that recommends action based on comparing recently read to stored information and "decision trees" based on cause-and-effect problems seeded beforehand into test-bed turbines. In tribological or fatigue-based diagnostics, for example, such systems would use data from vibration sensors and thermistors to try to detect incipient bearing failures, rubs, cracks, etc. Neural nets attempt to mimic human reasoning by using nets of node points. The net strands' information is weighted against expected outcomes. When enough nodes feed enough current through the net strands to a given outcome the rise in potential passes a threshold value predicting a likely positive or negative event.

- Fuzzy Systems. These are AI systems that deal with probabilities and likelihoods rather than facts. They make predictions or recommendations to the user based on what probably is the right choice. From the Air Force came the message that they are putting together an “ultra-intelligent” diagnostic/prognostic engine program. The intent is to free the attendant from making “fuzzy” decisions.
- With regard to wireless instrumentation there were suggestions of using RF-tag transmission, pulse-width modulated electromagnetic signals or lasers. Also one can install a data recorder and analyze the readouts after landing to detect potential problems and evaluate life expectancy of the components. A seemingly trivial but human characteristic is that even were the information available it would still be difficult to get people to make use of it.
- The ideal would be to have an automated system which would not have the capability to shut down the engine but would provide a warning such as a flag on the instrumentation panel that potentially something is wrong.

TABLE 5.1.—POSTER LIST PREPARED BY THE REB/SEAL: SUB-GROUP (A)

LUBRICANTS
Improved chemistry for thermal stability Interaction with materials Vapor phase life and thermal management Liquid lube thermal management Efficiency of de-oiler
MATERIALS
Fracture toughness, hybrid fatigue, corrosion resistance, wear resistance, and surface damage resistance—all in one material Cage composites Coatings
CONTAMINATION
Cleanliness Filtration Internal wear Fatigue life Shoulder wear. Need to define mechanism (contamination ? speed ? load ?). Effect of change of material. Effect of microstructure.
SURFACE TOPOGRAPHY
Correlation to life prediction Effect of ultra-fine surface finish
SEALS
Face seals Advanced configurations Material selection for high temperature and speed Non-contacting designs Large excursion capability Abradable seals Active clearance control capability
THERMAL MANAGEMENT
Lubricant delivery Heat exchanger Churning Sump pressure

TABLE 5.2.—POSTER LIST PREPARED BY SUB-GROUP ON MAGNETIC BEARINGS: SUB-GROUP (B)

ENGINE SIZE CATEGORIES AND CONCERNS
APU Small and medium sizes; the concerns are cost, reliability and weight Propulsion Medium and large sizes; the concerns are performance and weight
BACK-UP BEARINGS
Safe shutdown (one time) Spool-down and start-up (Power ?) Transient assist; load assist; recovery (analog versus digital) Limp-home –5 to 30 min.
HIGHLY INTEGRATED DESIGN PROCESS
TRIBOLOGICAL REQUIREMENTS
Auxiliary bearing Electromagnetic materials and assembly Seals
AUXILIARY BEARINGS
Damping Open clearance REB's Soft mount light load continuous REB Zero clearance engagement Hybrid foil Powder hydrodynamic Bushings—sliding
CONTROLLER AND POWER ELECTRONICS
Winding insulation/manufacturing Laminates insulation/manufacturing Electrical connections Diagnostic life cycle management and health Active/passive auxiliary bearing lubricant deliver
SEALS
Sliding wear Excursions
EXAMPLE ISSUES
Open clearance REB; high sliding speed; ball acceleration and skidding; cage sliding/inertia Lubricant (how and when to deliver) Passive (safety/shutdown); dry film; sacrificial cage; stick Active or fail-safe (Smart ?); powder; vapor phase; fuel

TABLE 5.3.—POSTER LIST PREPARED BY THE FOIL BEARING: SUB-GROUP (C)

OPERATING ENVELOPE RESTRICTIONS
High and low speeds; temperature range; routine and over loads; altitude variation Vibration and shock in operation; vibration and shock during transport
BEARING LOAD CAPACITY
ROTORDYNAMIC STABILITY CONCERNS
Damping and stiffness
MATERIALS AND COATINGS
High temperature capacity Surface finish
THERMAL MANAGEMENT
System level Bearing heat and temperature levels Power loss
MANUFACTURING COST (SUBSEQUENTLY DELETED)
MODELING AND PERFORMANCE PREDICTION
Testing Hydrodynamics and elasticity characterization
DESIGN INTERACTION
Misalignment and blade tip clearance Thrust balancing and accessory implications Assembly issues—seals
PERFORMANCE OVER TIME/LIFE
Environmental durability Contamination
INSTRUMENTATION AND HEALTH MONITORING
Vibration Wear measurement Orbit monitoring Temperatures

TABLE 5.4.—POSTER LIST PREPARED BY PANEL ON MODELING: SUB-GROUP (D)

DYNAMIC CHARACTERIZATION OF FOIL BEARINGS
Structural Coupling with hydrodynamic
THERMAL MANAGEMENT OF FOIL BEARING SYSTEM
INTEGRATION OF TRIBOLOGICAL COMPONENT MODEL (CODES) WITH OTHER MODELS
COMPUTING PLATFORM CONSIDERATIONS
System dependent System independent
TRACTION MODEL FOR SOLID, VAPOR, AND POWDER LUBRICATION
Empirical approach
GREASE PACKED BEARINGS
THERMAL MANAGEMENT OF ROLLING ELEMENT BEARINGS
SQUEEZE FILM DAMPER MODELING
WEAR MODELING
Two-body and three-body Temperature/environment
FATIGUE LIFE AND OIL CONTAMINATION
CORROSION AND STRESS CORROSION CRACKING
STRESS MODELING OF COATINGS
MICRO AND MACRO MODELS
Interaction between the two
TEMPERATURE DEPENDENT MATERIAL PROPERTIES
GAS LUBRICATION WITH ROUGH SURFACES
TECHNOLOGY TRANSFER AND EDUCATION
Software distribution Public domain software
IMPACT/INTEGRATION WITH OTHER AREAS
Diagnostics Foil bearings, etc. Input/output formats Control/Smart components

TABLE 5.5.—POSTER LIST PREPARED BY THE MONITORING PANEL: SUB-GROUP (E)

SENSORS
Overlay of several technologies Vibration and noise time/frequency analysis Vibration impulse response Thermography Oil analysis Electric current spectra Low cost and good reliability Non-intrusive sensors
PERFORMANCE MONITORS
Smart systems telling the story during measurement Automated interpretation of machine performance via diagram changes
WIRELESS INSTRUMENTATION
Use of RF Use of lasers, etc.
TRENDING
Automated evaluation of seals and bearings Evaluation of rotor components during operation
MODEL-BASED VERSUS NEURAL-NET
Automated optimal shutdown time determination for repairs Automated determination of need for spare parts replacement
MISCELLANEOUS
Multi-level signal processing Fault-smart lubricants “Active interrogation” vibration instruments On-line profilometry (lasers ?) Viscosity measurement changes via MEMS Contamination level via on-line MEMS

6.0 PRIORITIZATION OF PROGRAMS

Whereas the work of the subgroups concentrated on the tribological needs for advanced turbomachinery, and as often as not did not concern themselves with the preference of one project over another, the final session of the Workshop dealt specifically with the issue of prioritization.

6.1 REBS ETC.: Subgroup (A)

The issue whether gas turbine technology is comfortable with its DN capabilities first surfaced during NASA/Army presentation and came up again when prioritizing the programs of subgroup (A). Figure 6.1, presented at the last session portrays the history of past and projected levels of DN in turbomachinery over the last half century. This was accompanied by the following observations. In 1955 the DN value was 1.5 million. The early increase in slope seems to be associated with the helicopter fleet requirements during the Vietnam conflict. Following this period the DN graph leveled off and not even the start of the IHPTET program had an effect on it. In some 40 years the DN has gone up from 1.5 to 2.5 million. At present the demand is close to 4 to 5 million. If past history is any indicator it will take another 40 years to accomplish the latter goal. It would seem then that this is an important tribological limitations and hence the significance of magnetic, foil and other new bearing systems.

The reaction to this prognosis was that the graph does not correspond to reality. A 3 million DN is something that the Air Force and Navy today are quite comfortable with; the GET700 ram engine developed in the 80's runs at about 3 million DN. From Pratt & Whitney came the comment that they have gone as high as 2.8. It is not the REBs that dictate a limit on the rpm but other mechanical components of the engine as, for example, the rotating blades. Nor, was it added, is it likely that the aircraft engine industry would in the foreseeable future require REBs to run at 4 to 5 million DN. It was asserted that even by 2010 there will be no need for REBs running higher than about 4 million DN. This exchange put somewhat of a damper on the immediate need for replacing REBs with advanced bearing systems. Yet when a call went out to have figure 6.1 amended by the people with direct experience in the area-no new data became available that might have radically altered the gist of the graph in figure 6.1.

The listing given in table 5.1 was then scrutinized and the following five priority programs were selected:

1. Race shoulder wear in rolling element bearings so as to understand the mechanism and find proper remedies
2. Lubricants with improved chemistry and thermal stability as well as the overall issue of thermal management
3. Materials. Corrosion and wear resistance, fracture toughness and high fatigue limits all within a given material
4. Contamination. This relates partly to program number 1 above as debris conceivably plays a part in the shoulder wear problem; the other goal is to achieve good filtration and tolerance of internal wear
5. Surface Topography. Determine the effect of ultra-fine finish on a material's resistance to rubs; correlate the condition of surface finish with a component's life expectancy

6.2 Magnetic Bearings: Subgroup (B)

Three priority programs were selected by this panel.

1. Auxiliary Bearings. Depending on the application these would have to fulfill one of the following functions; one-time safe shutdown; start and stop capability when little electric power is available; emergency operation at full speed and load to permit safe landing of aircraft.
2. Electromagnetic Materials and Assembly. Search for materials possessing good magnetic properties at the elevated temperatures and frequencies, including wiring and their insulation.
3. Seals. Depending on the choice of auxiliary bearings, seals would be required capable of accommodating sliding wear at the possible large excursions of the rotor.

6.3 Foil Bearings: Subgroup (C)

At the plenary meeting four programs were selected from the list presented in table 5.3, even though the panel itself had not assigned any priority to their programs. The selections were as follows:

1. Operating Envelope. Determine the upper and lower limits for speed, load capacity and temperature possible for foil bearings; determine their ability to endure shock and vibration in operation, at standstill and during transport.
2. Materials and Coatings. The aim is to find materials capable of operating at high temperature, resist fretting under vibration and tolerate a large number of starts and stops.
3. Load capacity. This requires a basic study, both analytical and experimental, to arrive at a valid definition and quantify load capacity in terms of the operating parameters.
4. Time/Life Endurance. The capabilities of foil bearings are to be verified over a prolonged period of time in actual service.

6.4 Modeling: Subgroup (D)

In discussing the modeling programs a complaint was made about the absence of grease lubricated bearings. The explanation was that in grease lubrication the film is that of oil and the only other effect is churning of the grease. Still the latter presents problems. For example, in cruise missiles what prevents the employment of grease lubricated bearings is exactly the generation of too much heat. It was also argued that in fact grease does cause an influx of particles into the film. It was therefore decided to include this topic in the listing presented in table 5.4. No priority programs emerged for modeling—partly because, as was argued originally, modeling would be tied to the priorities selected in the four other domains.

6.5 Monitoring: Subgroup (E)

Three families of monitoring systems were selected for priority programs

1. Sensors (MEMS, wireless)
2. Trending—a continuous monitoring of performance
3. Modeling—employing the technologies of instrumentation, neural nets, artificial intelligence, fuzzy logic and smart/deterministic models

A summation of all priority programs selected by the five subgroups is given in table 6.1.

TABLE 6.1.—PRIORITY PROGRAMS SELECTED BY THE WORKSHOP*

Area	Program
REB/Seals, lubricants and materials	Cage shoulder wear Lubricants Materials Contamination Surface topography
Magnetic bearings	Auxiliary bearings Electromagnetic materials and assembly Seals
Compliant foil bearings	Operating envelope Materials and coatings Load capacity Time/life endurance
Modeling	Linked to the other priorities
Monitoring	Sensors Trending Modeling

*For particulars of the above program see Sections 5 and 6.

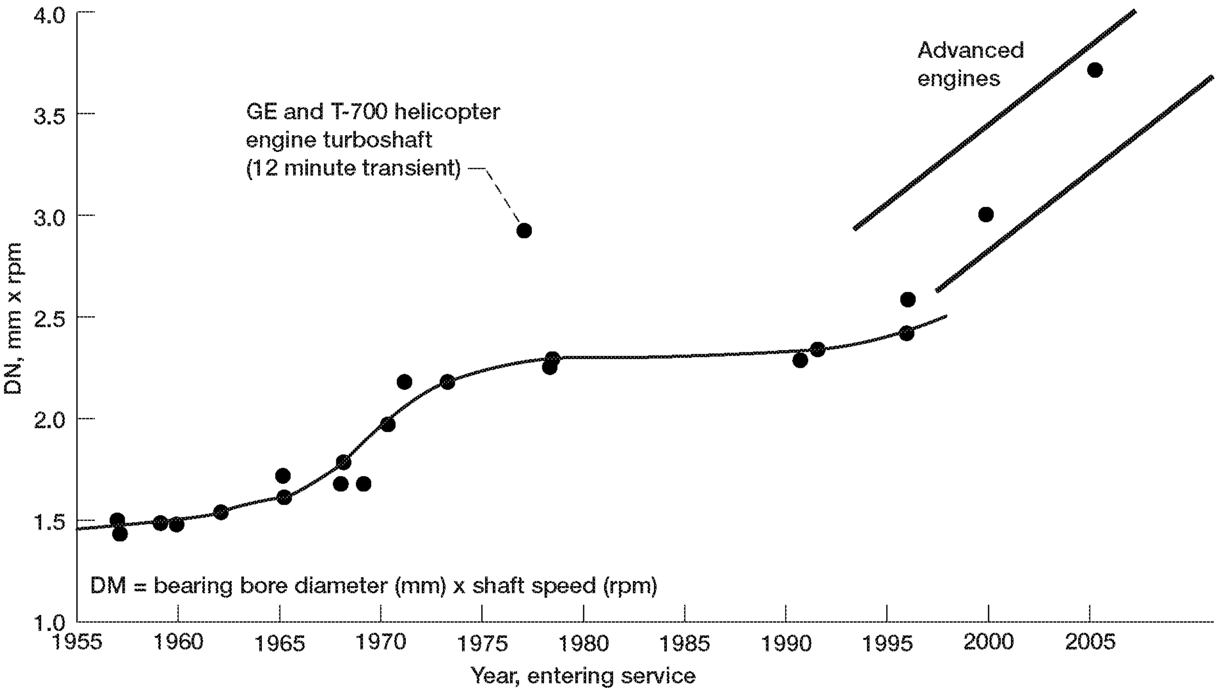


Figure 6.1.—Past and projected DN levels in large gas turbine engines.

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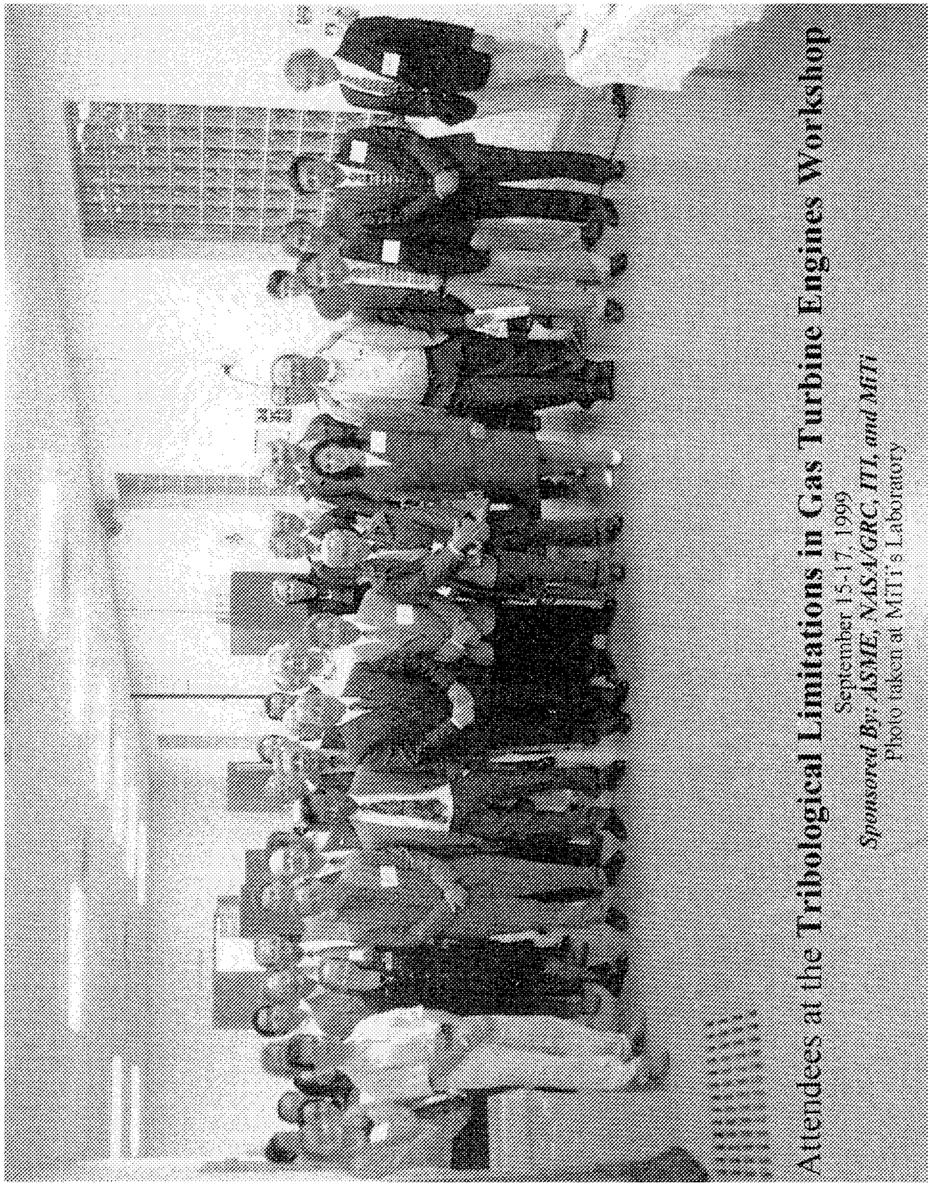
2. Transcript of Workshop Proceedings, Sept. 15–17, 1999, Candyco Transcription Service, Inc., Cliffton Park, New York, Oct. 1999.
3. DARPA, Advanced Magnets for Power Systems, Oct. 15, 1997, Workshop at Washington Dallas Airport Hilton, Herndon, Virginia.

APPENDIX
WORKSHOP ORGANIZATION AND PARTICIPANTS



Attendees at the **Tribological Limitations in Gas Turbine Engines Workshop**

September 15-17, 1999

Sponsored By: ASME, NASA/GRC, ITI, and MiTi

Photo taken at MiTi's Laboratory

Mohawk Innovative
Technology, Inc.

July 13, 1999

Dr. Woodrow Whitlow, Jr.
Glenn Research Center
21000 Brookpark Road
MS 3-5
Cleveland, OH 44135

Subject: Tribological Limitations in Gas Turbine Engines - A Workshop Scheduled for September 15 - 17, 1999 at the Albany, New York Airport Hilton Hotel

Dear Colleague,

It is with great pleasure that I invite you to participate in the subject workshop. The purpose of this workshop is to define and analyze the important tribological challenges facing advanced gas turbine engines, discuss recent related advances and to identify possible approaches and research directions to address the identified limitations. The approach selected for this workshop includes a combination of formal presentations, extensive group discussions and a general reporting and feedback session to prioritize recommendations. Key organizations such as the ASME/Tribology Division, NASA/Glenn Research Center, the Industrial Tribology Institute and Mohawk Innovative Technology, Inc. have recognized that a focused effort will be needed to resolve the identified limitations and have generously agreed to sponsor this meeting. To ensure that the outcome and recommendations of the workshop will be useful to both industry and government, a secretariate and an editorial staff have been selected to compile and publish the proceedings.

This workshop will provide you with a unique opportunity to provide your input into both the definition of the problem and approaches to their resolution. We are expecting a very diverse group of attendees, having already attracted key individuals from industry, government and academia. As you can see from the attached program, we are providing time for presentations by the gas turbine engine manufacturers, leading researchers and government personnel.

Attendance at this workshop is limited and by invitation only, therefore we request your RSVP as soon as possible but not later than August 1st and that you not forward this to other individuals. However, if you have colleagues or other individuals you feel should be invited, please forward their name, address and phone number so that we may attempt to include them in this meeting. A block of rooms has been reserved at the Airport Hilton at a special rate of $105 per night for this meeting and will be given out on a first come first serve basis. Please contact the hotel directly for your reservations. Please contact MiTi via Fax at 518.862.4293 or e-mail at MiTi@albany.net with your RSVP.

I hope that you can accept this invitation and plan to attend. We look forward to a very productive meeting and the opportunity to jointly establish the goals, objectives and directions needed to ensure that the tribological challenges of the future are met.

Workshop Co-Chairs

Hooshang Heshmat, Ph.D.
President/Technical Director
Mohawk Innovative Technology, Inc.

Christopher Della Corte
Acting Branch Chief/Senior Scientist
Materials Science Branch
NASA/Glenn Research Center

Objectives:

Explore limitations of and advances needed for current and future air craft gas turbine engine bearings, including existing rolling element bearings and alternative technologies that may provide design freedom such as air foil bearings, novel seals, rotordynamic analyses and related technologies.

Benefits:

Guidance and direction to maintain U.S. global competitiveness will be provided for focused and accelerated developments and applications of revolutionary technologies in gas turbine engines.

Description:

Early in the development of the gas turbine aircraft engine, tribology played a key supporting role in extending the life and performance of oil lubricated rolling element bearings permitting operation at ever higher speeds, loads and temperatures. A major factor in the success of rolling element bearings has been a clear understanding of the operating conditions and improvements in both bearing materials and lubricants. However, current projections and recent experience are that advancements to existing bearings and lubricants will likely only be incremental at best.

This workshop has, as its goal the exploration of current rolling element bearing technology limitations in aircraft gas turbine engines. Further, this workshop will investigate the design freedom that may result from alternative rotor support technologies, such as compliant foil air bearings, hybrid foil/magnetic bearings, improved seals, rotordynamic analyses and related technologies.

It is expected that the major issues and benefits concerning the adoption of new bearing technologies will be highlighted. Keynote speakers and discussion leaders are being sought for this workshop. The workshop results will be documented in an effort to provide valuable guidance for future research on revolutionary oil-free aircraft engines.

Co - Chairs

Dr. Christopher Della Corte (NASA)

Dr. Hooshang Heshmat (MiTi)

Tribological Limitations in Gas Turbine Engines

September 15-17, 1999

PRELIMINARY
AGENDA

September 15, 1999

Registration	12:30-5:00 PM
Welcome & Introduction	1:00 - 1:20 PM
Overview of Workshop Format	1:00 - 2:00 PM
Tribological Limitations From a Manufacturers Perspective	2:00 - 5:00 PM
AADC	
Allied Signal	
General Electric	
Pratt & Whitney	
Williams International	
Welcome Reception	6:00 - 7:00 PM
Dinner (Provided)	7:00 - 9:00 PM

September 16, 1999

Registration	8:00 - 9:00 AM
Tribological Limitations From a Users Perspective	8:00 -10:00 AM
Air Force	
Army	
NASA	
Navy	
Break	
Working Groups	10:30 - 12:00
Bearings	
Seals	
Friction Induced Vibrations (i.e., Blade Dynamics, etc)	
Lunch (Provided)	12:00 - 1:00 PM

S-O-A & Tribological Limitations From a Researchers Perspective Invited Speakers	1:00 -3:00 PM
Working Groups - Prioritize Tribological Limitations and Directions Blades Bearings Seals	3:15 - 5:00
Open House & Reception at MiTi	5:00 - 6:30 PM
Dinner (Provided)	7:30 - 9:30 PM

September 17, 1999

Working Group Presentations	8:30 - 10:00 AM
Break	10:00 - 10:15
Discuss and Merge Priorities	10:15 - 12:00
Lunch (Provided)	12:00 - 1:00 PM
Recommendations and Plan of Action	1:00 - 2:30
Adjourn	3:00 PM

Tribological Limitations in Gas Turbine Engines

September 15 - 17, 19999
Albany Airport Hilton
Albany, NY

Sponsored By
ASME / Tribology Division
NASA/Glenn Research Center
Industrial Tribology Institute
Mohawk Innovative Technology, Inc.

List of Attendees

Dr. Giri Agrawal
President
R&D Dynamics Corp.
15 Barber Pond Road
Bloomfield, CT 06002
Phone: 860-726-1204
Fax: 860-726-1206
email: agragiri@aol.com

Prof. Adnan Akay
Carnegie Mellon University
Mechanical Engineering Dept.
Pittsburgh, PA 15213
Phone: 412-268-2501
Fax: 412-268-3348
email: akay@cmu.edu

Prof. Thierry Blanchet
Associate Professor
Rensselaer Polytechnic Institute
Department of Mechanical Engineering
Troy, NY 12180
Phone: 518-276-8697
Fax: 518-276-2623
email: blanct@rpi.edu

Mr. Robert Bruckner
Aerospace Engineer
NASA Glenn Research Center
21000 Brookpark Road
Cleveland, OH 44135
Phone: 216-433-6499
Fax: 216-977-7008
email: Robert.Bruckner@grc.nasa.gov

Prof. Michael D. Bryant
University of Texas
Mechanical Engineering Dept.
Austin, TX 78712-1063
Phone: 512-471-4870
Fax: 512-471-7682
email: mbryant@mail-utexas.edu

Mr. Leo Burkhardt
Aerospace Engineer
NASA Glenn Research Center
21000 Brookpark Road
Cleveland, OH 44136
Phone: 216-977-7021
Fax: 216-433-5100
email: leo.burkhardt@grc.nasa.gov

Mr. Scott Cruzen
Director/Advanced Technology
Williams International
2280 West Maple
Walled Lake, MI 48390
Phone: 248-960-2418
Fax: 248-625-5345
email: scruzen@williams-int.com

Dr. Christopher Della Corte
NASA Glenn Research Center
21000 Brookpark Road
Cleveland, OH 44135
Phone: 216-433-6056
Fax: 216-433-5170
email: Christopher.dellacorte@grc.nasa.gov

Mr. Loc Duong
Project Engineer
Pratt & Whitney
400 Main Street (Mail Stop 169-19)
East Hartford, CT 06078
Phone: 860-557-1502
email: DuongL@pweh.com

Dr. Nelson Forster
Senior Mechanical Engineer
US Air Force
1790 Loop Road North
Wright-Patterson AFB, OH 45433
Phone: 937-255-4347
Fax: 937-656-7176
email: nelson.forster@pr.wpafb.af.mil

Mr. Howard Gibson
Materials Engineer
NASA/MSFC
Huntsville, AL 35812
Phone: 256-544-2513
Fax: 256-544-0212
email: howard.gibson@msfc.nasa.gov

Mr. Darrell Grant
Lead Technical Engineer
US Navy
48298 Shaw Road, Unit 4
Building 1461, Air-446
Pax River, MD 20670
Phone: 301-342-0886
Fax: 301-342-0892
email: grantd@navair.navy.mil

Dr. Pradeep Gupta
President
PKG, Inc.
117 Southbury Road
Clifton Park, NY 12065
Phone: 518-383-1167
Fax: 518-371-3833
email: guptap@worldnet.att.net

Mr. David Halsey
Advisory Engineer
Hamilton Sunstrand
4747 Harrison Ave.
Rockford, IL 61125
Phone: 815-394-2071
Fax: 815-397-8720
email: David.Halsey@hs.utc.com

Dr. Hooshang Heshmat
President/Technical Director
Mohawk Innovative Technology, Inc.
1037 Watervliet-Shaker Road
Albany, NY 12205-2033
Phone: 518-862-4290 ext. 12
Fax: 518-862-4293
email: Heshmath@ASME.org

Ms. Crystal Heshmat
Mechanical/Research Engineer
Mohawk Innovative Technology, Inc.
1037 Watervliet-Shaker Road
Albany, NY 12205-2033
Phone: 518-862-4290 ext. 17
Fax: 518-862-4293
email: cheshmat@albany.net

Dr. Said Jahanmir
NIST
Ceramic Machining Consortium
Building 223, Room A 329
Ceramic Division
Gaithersburg, MD 20899
Phone: 301-975-3671
Fax: 301-975-5334
email: said.jahanmir@nist.gov

Prof. Francis E. Kennedy
Dartmouth College
Thayer School of Engineering
Hanover, NH 03755
Phone: 603-646-2094
Fax: 603-646-3856
email: Francis.Kennedy@dartmouth.edu

Mr. Jim Knorr
Mananger
Mech. Comp. Design, Advanced Technolgoy
Allied Signal Engines
111 S. 34th Street
Box 52181 MS 301-127
Phoenix, AZ 85072-2181
Phone: 602-231-7989
Fax: 602-231-3018
email: James.Knorr@alliedsignal.com

Dr. Jorn Larsen-Basse
Program Director
National Science Foundation
4201 Wilson Blvd., Room 545
Arlington, VA 22230
Phone: 703-306-1361
Fax: 703-306-0291
email: jlarsenb@nsf.gov

Mr. Dan Lubell
Rotating Assembly Analysis Engineer
Hamilton Sunstrand
4400 Ruffia Road
San Diego, CA 92123
Phone: 858-627-6064
Fax: 858-627-6195
email: Dr.Lubell@hs.utc.com

Mr. William D. Marscher
Technical Director
Mechanical Solutions, Inc.
1719 Route 10, Suite 205
Parsippany, NJ 07054
Phone: 973-326-9920
Fax: 973-326-9919
email: Bill.Marscher@MechSol.com

Mr. Frank Murray
Senior Res. Engineer (Ret.)
Rensselaer Polytechnic Institute
Mechanical Engineering Dept.
Troy, NY 12180
Phone: 518-276-6977

Prof. Oscar Pinkus
Director
Sigma Tribology Consultants
17 Del Sol Court
Sandia Park, NM 87047
Phone: 505-281-5312
Fax: 505-281-5312

Mr. Ed Rogala
Adv. Tech. Marketing
GEAE
1 Newmann Way
Cincinnati, OH 45215
Phone: 513-243-1932
Fax: 513-243-1667
email: ed.rogala@ae.ge.com

Prof. Farshid Sadeghi
Professor
Purdue University
School of Mechanical Engineering
W. Lafayette, IN 47907
Phone: 765-494-5719
Fax: 765-494-0539
email: Sadeghi@ecn.purdue.edu

Mr. Jonathan A. Scheetz
Program Leader
Advanced Bearing & Seals Technology
General Electric Aircraft Engines
1 Newmann Way M/D BBC6
Cincinnati, OH 45215-1988
Phone: 513-243-7319
Fax: 513-243-2565
email: jon.scheetz@ae.ge.com

Mr. Ron Struziak
Senior Engineer
Hamilton Sunstrand
1 Hamilton Road
Windsor Locks, CT 06096
Phone: 860-654-4142
Fax: 860-654-4011
email: struzia@hsd.utc.com

Dr. Mark J. Valco
Aerospace Engineer
U.S. Army Research Laboratory
21000 Brookpark Road
Cleveland, OH 44135
Phone: 216-433-3717
Fax: 216-433-3954
email: mark.j.valco@grc.nasa.gov

Mr. James F. Walton, II
Vice President of Program Development
Mohawk Innovative Technology, Inc.
1037 Watervliet-Shaker Road
Albany, NY 12205-2033
Phone: 518-862-4290 ext. 14
Fax: 518-862-4293
email: miti1@aol.com

Mr. Dennis Weissert
Engineer
Capstone Turbine Corp.
6430 Independence Ave.
Woodland Hills, CA 91367
Phone: 818-654-1341
Fax: 818-774-0228
email: dwei@capstone.turbine.com

Mrs. Alicia Zysman
Technology Manager/Mech. Systems
Pratt & Whitney
400 Main Street
East Hartford, CT 06231
Phone: 860-565-0329
Fax: 860-565-9059
email: zysmanav@pweh.com

Stenographer:
Ms. Marion Matrazzo
Candyco.
P.O. Box 3242
Saratoga Springs, NY 12866
Phone: 518-587-5010
Fax: 518-587-9560

In the Matter of

Tribological Limitations

In

Gas Turbine Engines

Date: September 15, 1999

Place: Albany Hilton

Time: 1:00 p.m. to 5:00 p.m.

Day No.: 1

TRANSCRIPT OF PROCEEDINGS

AGENDA

Welcome & Introduction	1:00 to 1:20 p.m.
Overview of Workshop Format	1:00 to 2:00 p.m.
Tribological Limitations from a Manufacturers Perspective	2:00 to 5:00 p.m.

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Williams International
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12 Merrall Drive
Clifton Park, New York 12065
(518) 371-8910 * FAX (518) 371-3711

Tribological Workshop

ATTENDEES

Giridhari Agrawal	R&D Dynamics Corp.
Adnan Akay	Carnegie Mellon University
Thierry Blanchet	RPI
Robert Brucker	NASA
Michael Bryant	University of Texas
Leo Burkardt	NASA
Scott Cruzen	William International
Chris Della Corte	NASA
Loc Duong	Pratt & Whitney
Nelson Forster	US Air Force
Howard Gibson	NASA
Darrell Grant	US Navy
Pradeep Gupta	PKG Inc.
David Halsey	Hamilton Sundstrand
Said Jahammir	NIST
Francis E. Kennedy	Dartmouth College
Jim Knorr	Allied Signal
Jorn Larsen-Basse	NSF
Daniel Lubell	Hamilton Standard
William Marscher	Mechanical Solutions, Inc.
Frank Murray	RPI
Oscar Pinkus	SIGMA
Ed Rogala	GEAE
Farshid Sadeghi	Purdue University
Jon Scheetz	GEAE
Ronald Struziak	Hamilton Sundstrand
Mark Valco	US Army
Dennis Weissert	Capstone Turbine
Alicia Zysman	Pratt & Whitney
Hooshang Heshmat	Mohawk Innovative Technologies
James Walton	Mohawk Innovative Technologies
Crystal Heshmat	Mohawk Innovative Technologies

SPEAKERS

EXHIBIT

1 Gas Turbine Engines Tribology Limitations Workshop

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Chris DellaCorte and Oscar Pinkus

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National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

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13. ABSTRACT *(Maximum 200 words)*

The following report represents a compendium of selected speaker presentation materials and observations made by Prof. O. Pinkus at the NASA/ASME/Industry sponsored workshop entitled “Tribological Limitations in Gas Turbine Engines” held on September 15–17, 1999 in Albany, New York. The impetus for the workshop came from the ASME's Research Committee on tribology whose goal is to explore new tribological research topics which may become future research opportunities. Since this subject is of current interest to other industrial and government entities the conference received cosponsorship as noted above. The conference was well attended by government, industrial, and academic participants. Topics discussed included current tribological issues in gas turbines as well as the potential impact (drawbacks and advantages) of future tribological technologies especially foil air bearings and magnetic bearings. It is hoped that this workshop report may serve as a starting point for continued discussions and activities in oil-free turbomachinery systems.

14. SUBJECT TERMS

Gas turbines; Foil bearings; Magnetic bearings; Gas bearings

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