Oil-Free Rotor Support Technologies for Long Life, Closed Cycle Brayton Turbines

John M. Lucero [*] and Christopher DellaCorte[†]
NASA Glenn Research Center, Cleveland, Ohio, 44135

The goal of this study is to provide technological support to ensure successful life and operation of a 50 – 300 kW dynamic power conversion system specifically with respect to the rotor support system. By utilizing technical expertise in tribology, bearings, rotordynamics, solid lubricant coatings and extensive test facilities, valuable input for mission success is provided. A discussion of the history of closed cycle Brayton turboalternators (TA) will be included. This includes the 2 kW Mini-Brayton Rotating Unit (Mini-BRU), the 10kW Brayton Rotating Unit (BRU) and the 125 kW turboalternator – compressor (TAC) designed in mid 1970's. Also included is the development of air-cycle machines and terrestrial oil-free gas turbine power systems in the form of microturbines, specifically Capstone microturbines. A short discussion of the self-acting compliant surface hydrodynamic fluid film bearings, or foil bearings, will follow, including a short history of the load capacity advances, the NASA coatings advancements as well as design model advances. Successes in terrestrial based machines will be noted and NASA tribology and bearing research test facilities will be described. Finally, implementation of a four step integration process will be included in the discussion.

Nomenclature

AC = alternating current
$^{\circ}C$ = degrees Centigrade
DN = diameter $_{\text{bearing}}$ x RPM $_{\text{shaft}}$
$^{\circ}F$ = degrees Fahrenheit
He = Helium
hp = horsepower
kW = kilo watt
RPM = revolutions per minute
Xe = Xenon

I. Introduction

Increased electrical power requirements for long life scientific missions to the moons of Jupiter have generated a renewed interest in advanced dynamic power conversion systems. Space dynamic power conversion systems must be designed for efficiency, reliability, and the ability to operate for extended periods with no maintenance. One candidate power conversion method is a closed cycle Brayton system. This concept has been recently reported by Mason [1] and others [2,3,4]. The Brayton system is a power conversion method utilizing captured energy from a heat source to energize a working fluid which is passed through a single shaft, radial turbo-compressor converting the heat into work. The rotating shaft, which is supported by gas foil bearings, is also a component of a rotary alternator

---

[*] Research Engineer, 21000 Brookpark Road, MS 23-2, Cleveland, Ohio 44135.

[†] Research Engineer, 21000 Brookpark Road, MS 23-2, Cleveland, Ohio 44135.

which delivers high voltage three phase AC to a power distribution module. Figure 1 shows a schematic of the system with the possible location of the bearings.

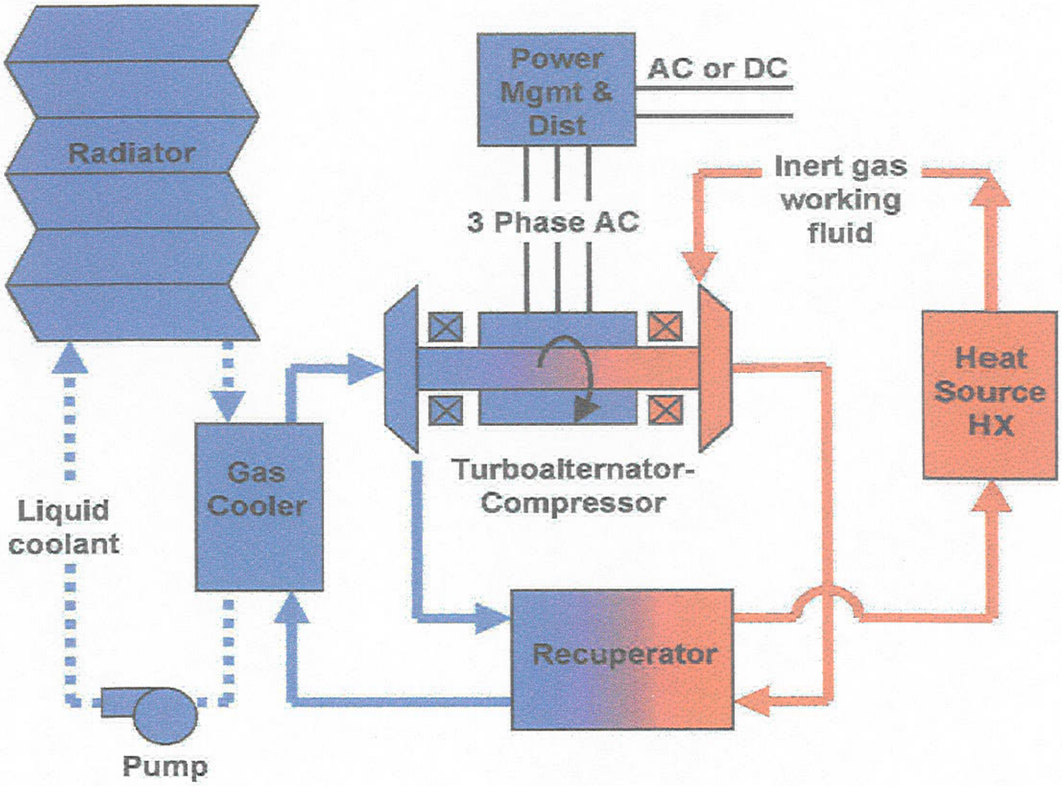

Figure 1: Brayton Cycle

These power systems can also be surface-based operations on the moon and mars. The goal of this study is to provide technological support to ensure successful life and operation of a 50-300 kW dynamic power conversion system. This paper considers the rotor support technology. Efforts in tribology, bearings, rotordynamics, solid lubricant coatings and test facilities will provide valuable input for development and mission success.

II. Background

The development of gas foil bearings, high-temperature coatings and analytical tools for rotor system design will follow. Advances have made it possible to apply gas foil bearings in many applications and with larger capacity systems that were not possible a decade ago. Previously attempted failure causes were due to inadequate bearing load capacity, no high temperature tribological coatings, poor and over simplified analytical models and a risky make it/ break it approach [5,6]. Gas foil bearings are self-acting compliant hydrodynamic bearings, and have been extensively reported [7-11]. Journal foil bearings consist of a metal sleeve that contains a series of thin sheet foils typically made of Inconel 750X, wrapped circumferentially around the inside of the sleeve, that are either smooth or bumpy. Figure 2 shows a simple drawing of the basics components of a journal foil bearing.

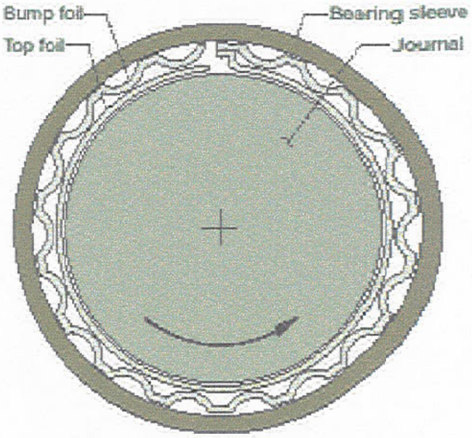

Figure 2: Simple Schematic of a Gas Foil Bearing

The smooth foil, or top foil as it is called, is what the turbine shaft or journal initially rides against before lift-off, and the bump foils provide the compliant "spring" foil support. The foils are often tack welded at one end and are free to grow or flatten out as the boundary layer of the working gas develops (self-acting) and grows thicker with increased journal surface velocity. This ability for the foils to grow and move out of the way also allows the bearings to accommodate misalignment and distortion. Thrust foil bearings are similar in concept and material construction as the journal foil bearings in that they use a top foil and bump foil in the same manner. In thrust bearings the foils are wedge shaped and are circumferentially mounted around one face of the mounting plate. Figure 3 is a photograph of a thrust foil bearing.

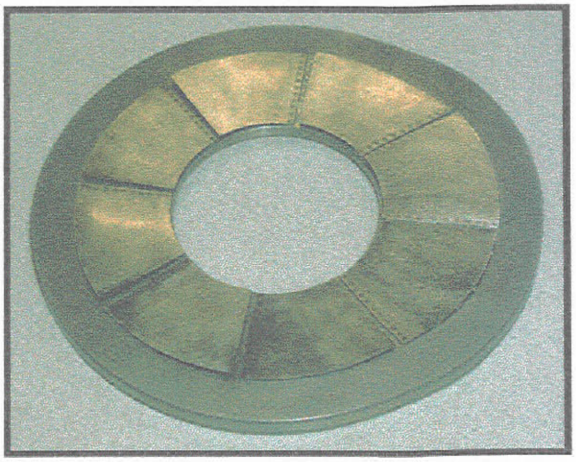

Figure 3: Thrust Foil Bearing

The bearing component has no rotating parts; no conventional rolling elements, like ball bearings, therefore no conventional DN limit. In fact, as surface speed increases, the bearing load capacity increases linearly with it [12]. These bearings require no maintenance and can operate up to 650°C. They also require no external pressurization, thus the term self-acting. The fluid flow inside the bearings is driven by pressure gradients (greater and less than ambient pressure) that develop between the top foil and the rotating shaft due to viscous shear forces and the wedge shaped geometry. Fluid, or gas, is drawn into the bearing in regions where the pressure is less than ambient, usually near where the fluid film is thickest. The fluid is entrained with the rotating shaft into the thinner fluid film region where the pressure increases. This pressure increase causes some of the fluid to leak out of the bearing while the remaining fluid supports the applied load.

Gas foil bearings do not require conventional oil lubrication, tanks, coolers, plumbing or filters. These foil bearings also have a higher power density, lower weight and higher efficiency than conventionally lubricated bearings, thus reducing operating costs. The only time there is contact between the journal and the top foil is during start up and shut down. Therefore, solid lubricant coatings were developed to ease this transition from sliding contact to lift-off of the journal. The shut down transition is similar but in reverse, with the journal floating until the surface speed decreases to the point that the boundary layer of gas collapses under the load and sliding friction occurs again. One such lubricant, PS304, was developed at NASA Glenn to provide the lubricity needed for these events when the surfaces are sliding against each other creating fiction and subsequent wear and is extensively reported [13-20]. Basic failure modes have all but been eliminated by new and improved high load capacity bearing designs, a proven PS304 solid lubricant coating, advances in structural, hydrodynamic and rotordynamic analyses and modeling techniques and a successful stepwise technology integration approach

In the 1960's and 70's closed cycle foil bearing supported Brayton turboalternators (TA) were investigated as possible power plants for extended space missions. Unacceptable contamination of the working fluid with oil-like lubricants and radiation damage to the lubricants dictated a non-conventional rotor support system. It was determined by 1970 that gas lubricated bearings were the best choice for a Brayton TA Compressor. This included the 2 kW Mini-Brayton Rotating Unit (Mini-BRU), and the 10 kW Brayton Rotating Unit (BRU). The 2 kW Mini-BRU and 10 kW BRU have been extensively reported [21, 22]. Also noted is the 125 kW turboalternator compressor (TAC) design that was generated in mid 1970's by AiResearch Manufacturing Company of Arizona [23].

Despite program shifts away from space power projects, the continued development of gas foil bearings in the industry has brought about new capabilities and applications [24-26]. The development of foil bearing supported air-cycle machine was done in the 1970's which provided high reliability and the great benefit of being practically maintenance free. Air cycle machines are in the 50-500 kW range. By 1990, there were units that had been operating at over 100,000 hours mean time between failure (MTBF) [27]. And by 2002, some units had been in service for millions of hours of service [28]. In the 1980's, new foil bearing designs doubled the load capacity [12]. Oil-free turbocompressors were then developed because of their long life, cryogenic capabilities and no process fluid contamination characteristics. By the early 1990's, foil bearing load capacity redoubled leading to turbogenerator designs with long life gas foil bearings to provide the benefits of low combustion product emissions, nearly no maintenance, and very lightweight [12, 26]. By early 2000, with improved load capacity, start/stop capability due to advanced coatings and improved analytical techniques available, a totally oil-free turbocharger was designed and tested successfully. The advanced foil bearing rotor support systems were capable of handling greater static and dynamic loading at temperatures approaching 650°C. This provided a low emission, high temperature solution with mounting orientation freedom. In 2002, hot foil bearings were demonstrated in a drone engine [29]. Terrestrial based oil-free gas turbine power systems in the form of microturbines, specifically Capstone microturbines were introduced in 1999 [25].

Capstone holds the distinction of producing the world's first and only fully oil-free open-cycle gas turbine engines. They are used to power an electrical generator for distributed and back-up power generating systems. Capstone produces 30 kW and 60 kW engines and is now field (beta) testing a new 200 kW engine. They are the experts in the field of oil-free turbines. The traditional turbine engine companies are all exploring the technology in one form or another especially for aircraft auxiliary power units, fuel cell compressors and unmanned aircraft engines. A 30 kW Capstone unit is operating at Glenn Research Center with the advanced coating NASA PS304 applied. Long life testing of this coating system in the Capstone unit is now underway.

III. Current Mission

The current technology focus is a single shaft, radial turbocompressor, on gas foil bearings. The 50-300 kW range turboalternator falls within the historic framework for gas foil bearing supported systems. The new mission will require long life, high temperature, radiation tolerance, and a He-Xe working fluid. As stated previously current air-cycle machines (ACM), 50-500 kW operate for 300,000 hours MTBF. Also, high temperature applications up to 750°C have been successfully developed, i.e. turbocharger and drone engine. The He-Xe environment will require testing and validation of foil bearing performance as well as start/stop capabilities. With the parameters and requirements needed to meet the technology goals, the 100 kW class Brayton TA will probably require 50-100 millimeter diameter journal bearings.

IV. Challenges

First, the differences between closed and open systems and how they affect the current mission will be discussed. In an open system, mechanical operation failures were attributed to thermal barrier coating degradation due to oxidation, degradation, and corrosion or ingested particles. This is not a problem in a closed system. Thermal environmental barrier coatings govern the life and maintenance of hot section components. However, the historical development of closed cycle engines demonstrates that thermal coatings are not needed in the current mission temperature range. Other possible failure modes for hot section components in an open system include thermal mechanical fatigue and creep. In the current closed system, the working fluid is an inert gas, so oxidation is not an issue and there is no water vapor to contend with. Maintenance intervals are not affected by change out of filters in a closed system.

The real challenges that will be faced, such as no bearing performance data and limited system level experience using He-Xe as the working fluid, will be addressed. Bearing performance data in He-Xe gas is required. Radiation environment considerations are being addressed by irradiating coupons of representative materials (Inconel 750X, PS304 sprayed coupons), determining how long until they aren't "hot" anymore, and then testing the coupons. Fatigue considerations for such a long life mission are another challenge. Currently, only the shaft rotates in a foil bearing system. However, fatigue issues such as creep and weld failure must be considered. The previously irradiated coupons will be used in the creep tests. The welds in foil bearings can be eliminated by design changes and such work is already underway. The effects of cavity pressure and temperature on bearing performance must be investigated as well as the tribological compatibility of candidate coatings in the He-Xe closed-cycle environment. And finally, the launch load, starting torque and load capacity data input for preliminary design are needed.

V. Previous successes and current NASA Test Facilities

Previous NASA success/experience, including successful experiences in a terrestrial based machine follows. Renewed foil bearing and tribological coating research and testing have been underway at NASA Glenn since 1985. The high temperature coating NASA PS 304 has been developed and tested in a 650°C environment and exceeded over 100,000 start/stop cycles with no appreciable wear. Successful NASA Glenn experience in oil-free technology integration include the world's first oil-free turbocharger rated at 110 kW (150 hp), and a 300 kW (400 hp) drone engine hot bearing test. Also, the NASA PS304 coating has been operating in a 30 kW Capstone microturbine for the past 5 years (~10,000 hours).

The facilities that are available to obtain the required data for establishing feasibility have been built. The Journal Foil Bearing Test Facilities (including the High-Speed Foil Bearing Rig, the Ambient Pressure Foil Bearing Test Rig and the Endurance Start/Stop Rig), Thrust Foil Bearing Test Rig, the Rotordynamic Foil Bearing Simulator Test Rig and the High Temperature Pin-on-Disk Rig. Also, a Coating Research Deposition Research Facility has been developed. Finally, a 30 kW Capstone microturbine with PS304 coated shaft is the subject of coating endurance testing in high temperature turbomachinery.

The High-Speed Journal Bearing Rig is designed to test up to 700°C and up to 70,000 RPM and is extensively reported[25]. Figure 4 shows the rig with the heater case open.

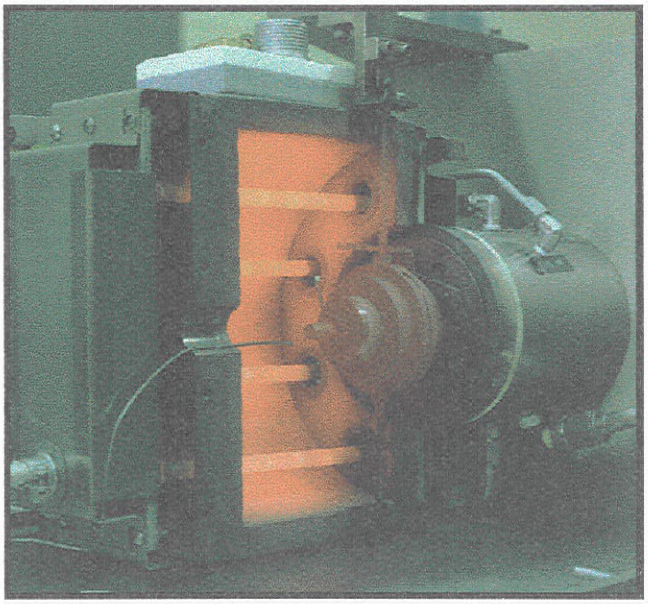

Figure 4: High Speed Journal Bearing Test Rig

This rig is primarily used to determine journal bearing displacements/vibrations, load capacity, operating torques, and bearing performance related to (but not limited to) cooling flow issues and radial clearance.

The Ambient Pressure Foil Bearing Test Rig (Figure 5) is used to test journal bearings in a controlled atmosphere to simulate either near vacuum conditions or ambient pressures up to 2 atmospheres. Thus, the rig can be backfilled with an inert gas to simulate a closed-cycle application.

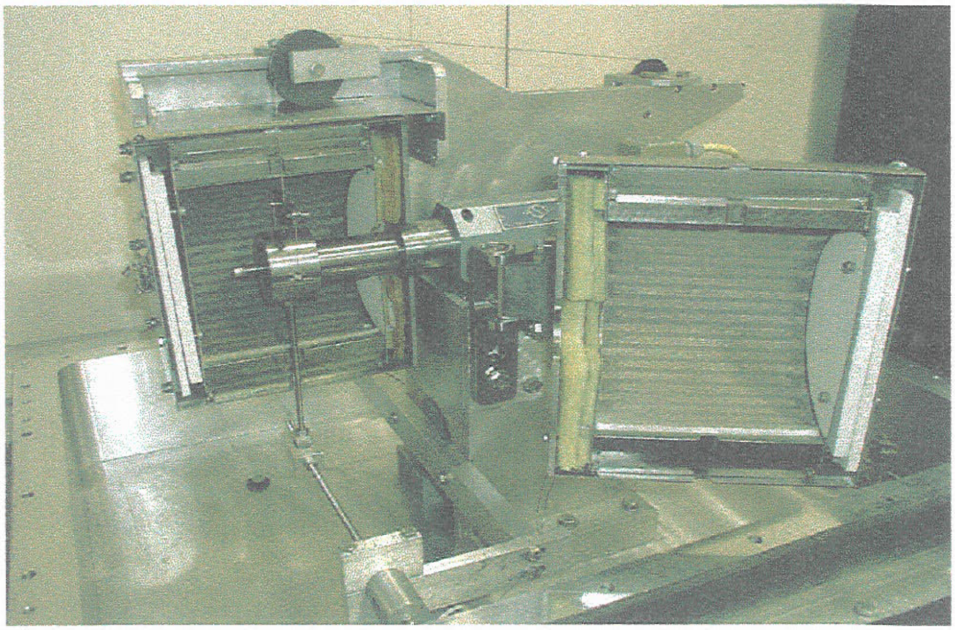

Figure 5: The Ambient Pressure Foil Bearing Test Rig

This rig can operate up to 700°C and 30,000 RPM. The information collected on this rig includes starting torque, load capacity and bearing performance at various ambient conditions. Preliminary analytical studies suggest that the bearing load capacity increases indirectly with increasing ambient pressure and decreases with decreasing fluid pressure. Preliminary data suggests this is true.

The Endurance Rig is used to test start/stop life up to 700°C in half-bearing coupons run on NASA PS304 coated journals or any kind of tribological coating of interest, either on the journal or on the foils themselves. This rig can operate up to 15,000 RPM with temperatures up to 700°C.

The Thrust Bearing Test Rig (Figure 6) operates up to 80,000 RPM and 600°C. This rig evaluates bearing power loss, load capacity and starting torques in 75-100 millimeter thrust bearings. The shaft is properly aligned axially using a magnetic bearing and is supported radially by 2 journal bearings. The test thrust bearing is mounted on one end and is loaded axially to simulate engine thrust loads.

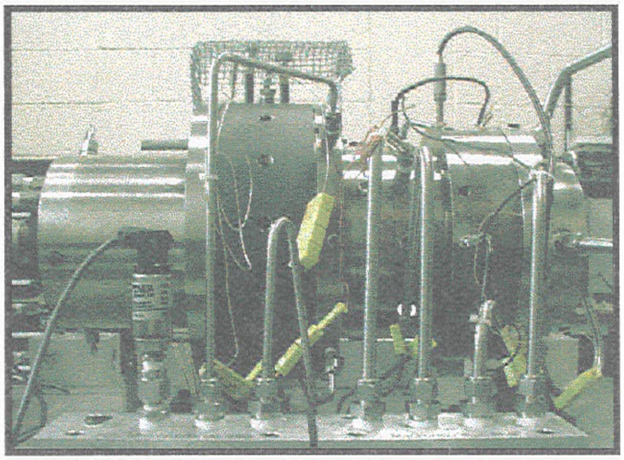

Figure 6: Thrust Foil Bearing Test Rig

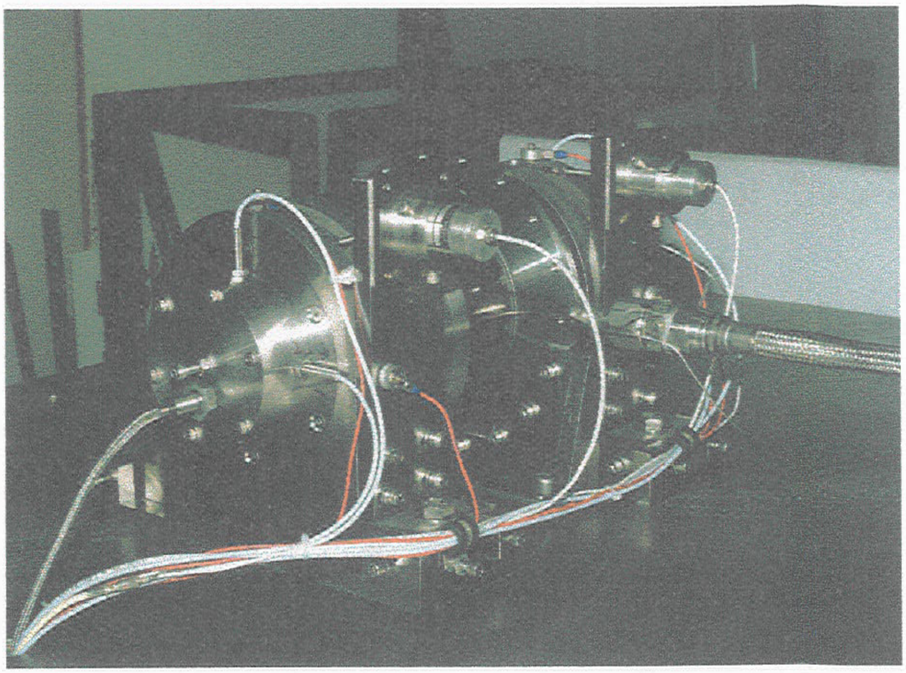

Figure 7: Rotordynamic Journal Foil Bearing Simulator Rig

The Rotordynamic Bearing Simulator Rig is designed to operate up to 62,000 RPM at room temperature. Figure 7 shows the Rotordynamic Rig.

The rig simulates shafts up to 100 millimeters or larger in diameter and 1.3 meters in length. It is used to physically model the rotordynamics of aircraft engine shafting and test under various conditions of misalignment and simulated compressors/turbines by using disk masses in various locations. It is highly instrumented to obtain data that is used to predict the onset of rotordynamic system instability.

The High Temperature Pin-on-Disk Test Rig is used to test candidate tribologically coated disks sliding against candidate material in the shape of a pin. This rig is used to evaluate coating and mating part torques and friction coefficients and determine the associated wear rate for the spinning rubbing parts.

The Coating Research Deposition Research Facility and the 30 kW Capstone microturbine are shown in Figures 8 and 9 respectively.

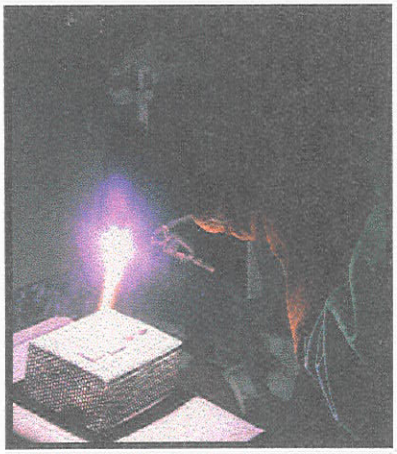

Figure 8: Coating Research Deposition Research Facility

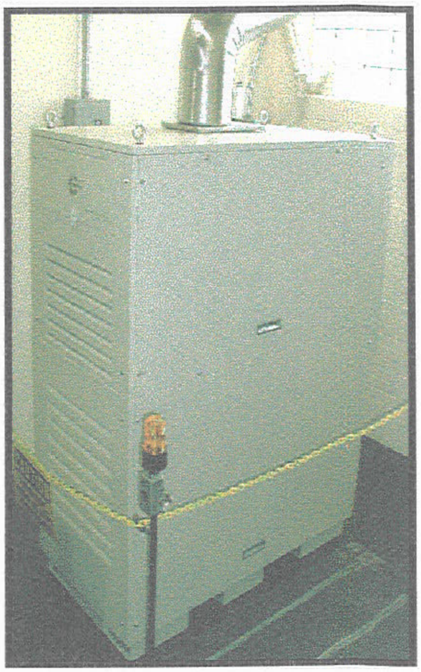

Figure 9: 30 kW Capstone Microturbine

VI. Approach

The four step Integration approach will be discussed here. The process includes:

1. Rotor System Conceptual Design and Feasibility Study
2. Bearing development process
3. Rotor system simulation
4. Oil-free technology demonstration.

The Rotor System Conceptual Design and Feasibility Study is accomplished by using the "Rule of Thumb" bearing sizing [12], rotordynamic analyses (DyRobes, etc.), thermal and structural analyses, and secondary flow analyses thrust balancing. The bearing development process includes bearing testing at speed, load, and temperature. The rotor system simulation is accomplished by simulated rotor testing. Finally, engine system testing accomplishes the oil-free technology demonstration. This approach has been used successfully in the oil-free turbocharger project and is practiced by industry in the turboalternator and turbocompressor projects.

VII. Conclusions

GRC has relevant and valuable experience in the successful development of high speed rotating systems. Expertise in tribology, rotordynamics and bearings will facilitate a successful mission. Unique extreme conditions test facilities are to be employed in the determination of key technical questions. Research in foil bearings and high temperature solid lubricants directly supports NASA's future work in space power and propulsion.

References

1. Mason, L.S., "A Power Conversion Concept for the Jupiter Icy Moons Orbiter", AIAA-2003-6007, August 2003.
2. Mason, L.S., "A Comparison of Brayton and Stirling Space Power Systems for Power Levels form 1 Kilowatt to 10 Megawatts," NASA/TM-2001-210593, January 2001.
3. Mason, L.S., Shaltens, R.K., and Espinosa, W.D., "Experimental Data for Two Different Alternator Configurations in a Solar Brayton Power System", NASA TM-107509, July 1997.
4. Hervol, D., "Experimental Results from a 2 kW Brayton Power Conversion Unit", NASA/TM-2003-211999, January 2003
5. Suriano, F.J., "Gas Foil Bearing Development Program," U.S. Airforce Report #AFWAL-TR-81-2095, September 1985.
6. Advanced Gas Turbine (AGT) Technology Development Project-Final-Report, NASA CR-180891, December 1987, T. Strom Program Manager.
7. Ma, J.T.S., "An Investigation of Self-Acting Foil Bearing", ASME, Journal of Basic Engineering, pp. 837-846.
8. Heshmat, H., Shapiro, W., and Gray, S., "Development of Foil Journal Bearings for High Load Capacity and High Speed Whirl Stability," ASME Journal of Lubrication Technology, vol. 104, no.2, pp. 149-156, 1982
9. DellaCorte, C., Valco, M.J., Radil, K.C., and Heshmat, H., "Performance and Durability of High Temperature Foil Air Bearings for Oil-Free Turbomachinery, NASA/TM-2000-209187.
10. Heshmat, H., Walowit, J.A., and Pinkus, O., "Analysis of Compliant Foil Gas Thrust Bearing", ASME Journal of Lubrication Technology, 1981.
11. Heshmat, H. Walowit, J.A. and Pinkus, O., "Analysis of Gas Lubricated Foil Journal Bearing", ASME Journal of Lubrication Technology, 1981.
12. DellaCorte, C., and Valco, M.J., "Load Capacity Estimation of Foil Air Journal Bearings for Oil-Free Turbomachinery Applications", NASA/TM-2000-209782, and STLE Tribology Transactions, 43(1), October 2000.
13. DellaCorte, C., and Wood, J.C., "High Temperature Solid Lubricant Materials for Heavy Duty and Advanced Heat Engines", NASA/TM-106570, September 1994.
14. Wagner, R.C., and Sliney, H.E., Effects of Silver and Group II Fluorides Addition to Plasma Sprayed Chromium Carbide High Temperature Solid Lubricant for Foil Gas Bearings to 650°C, NASA/TM-86895, 1985, ASLE, Lubrication Engineering (42), vol. 10, pp. 594-600, 1986.
15. DellaCorte, C., and Fellenstein, J.A., "The Effects of Compositional Tailoring on the Thermal Expansion and Tribological Properties of PS300: A Solid Lubricant Composite Coating", NASA/TM-107332, 1996.
16. DellaCorte, C., "Composition Optimization of Cr3C2 Based Solid Lubricant Coatings for Foil Gas Bearings at Temperatures to 650°C", NASA CR-179649, July 1987.
17. DellaCorte, C., "The Evaluation of a Modified Chrome Oxide Based High Temperature Solid Lubricant Coating for Foil Gas Bearings", NASA/TM-1998-208660.
18. DellaCorte, C., Edmonds, B.J., and Benoy, P.A., "Thermal Processing Effects on the Adhesive Strength of PS304 High Temperature Solid Lubricant Coatings", NASA/TM-2001-210944.

19. DellaCorte, C., Fellenstein, J.A., and Benoy, P.A., "Evaluation of Advanced Solid Lubricant Coatings for Foil Air Bearings Operating at 25 and 500°C", STLE Tribology Transactions, vol. 42, no. 2, pp. 338-342, April 1999.
20. Wagner, R.C., "Experimental Test Program for Evaluation of Solid Lubricant Coatings as Applied to Compliant Foil Gas Bearings to 315 C", NASA CR-17483, 1985.
21. Davis, J.E., "Design and Fabrication of the Brayton Rotating Unit", NASA CR-1870, March 1972.
22. Dobbler, F.X., et al., "Analysis, Design, Fabrication and Testing of the Mini-Brayton rotating Unit (Mini-Bru)", NASA CR-159441, April 1974.
23. Ellison, W.R., "Design and Simulation of a Foil Bearing Brayton Turbine-Alternator-Compressor (TAC)", NASA CR-121182, April 1973.
24. Emerson, T.P., "The Application of Foil Air Bearing Turbomachinery in Aircraft Environmental control Systems", ASME Proceeding of the Intersociety Conference on Environmental Systems, 780-ENAS-18, July 1978.
25. Capstone Microturbine Corporation, Chatsfield, CA, press release, 2000.
26. Heshmat, H., Walton III, J.F., DellaCorte C., and Valco, M.J., "Oil-Free Turbocharger Paves the Way to Gas Turbine Engine Applications", ASME 2000-210941, 2000.
27. Agrawal, G.L., "Foil Gas Bearings for Turbomachinery," SAE Technical Paper Series, 901236, 20th Intersociety Conference on Environmental Systems, Williamsburg, VA, July 1990.
28. DellaCorte, C., Pinkus, O., "Tribological Limitations in Gas Turbine Engines: A Workshop to Identify the Challenges and Set Future Directions," NASA/TM-2000-210059/REV1, August 2002.
29. Mohawk Innovative Technology Inc., Albany, NY, press release 2002.