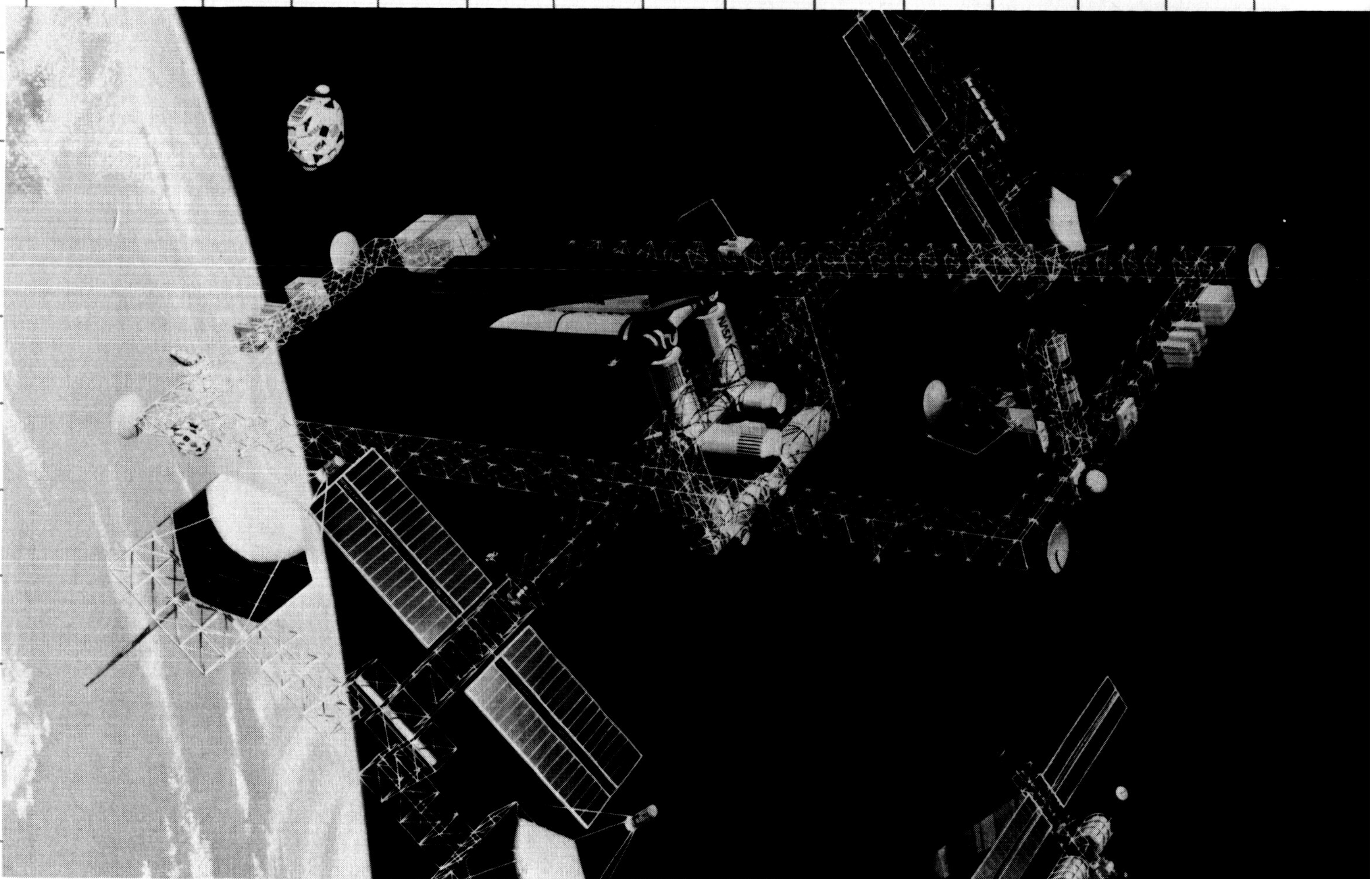
ANNUAL REPORT 1986

NASA Technical Memorandum 88868

RESEARCH & TECHNOLOGY



LEWIS Your Investment in the Future 45th ANNIVERSARY

National Aeronautics and Space Administration

Lewis Research Center

Contents

Introduction

This report selectively summarizes the NASA Lewis Research Center's research and technology accomplishments for fiscal year 1986, the 45th anniversary year of the Center. The report is organized into five major sections covering aeronautics, aerospace technology, space communications, space station systems, and computational technology support. A table of contents by subject has been developed to assist the reader in finding articles of special interest.

The results of all research and technology work performed during the fiscal year are contained in Lewis-published technical reports and presentations prepared by members of the Lewis staff or by contractors. In addition, university grants have enabled faculty members and graduate students to engage in sponsored research projects that are reported at technical meetings or in technical journals. For the reader who desires more information about a particular subject, a Lewis contact has been identified with each article.

Among the articles is a summary of the Lewis Distinguished Paper for 1985–6. Research & Development Magazine selected four Lewis products for IR-100 awards in 1986. All are described and identified herein.

As is evident from the contents of this report, 1986 was a year in which a broad range of research and technology programs were pursued by the Center. For general information about this report, contact Robert W. Graham at (216) 433–5828 or FTS 297–5828.

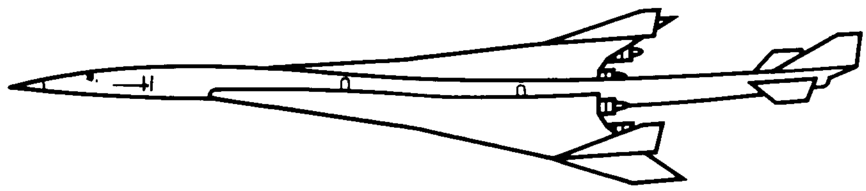
Aeronautics

Advanced Planning and Analysis

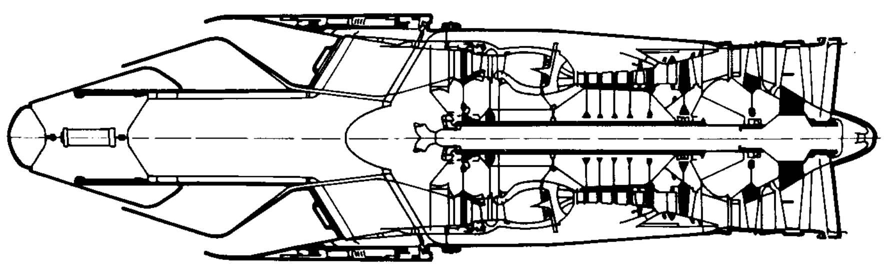
Advanced Supersonic Transport Propulsion

General Electric has been under a 1-year contract to Lewis to determine the mission benefits, cycle parameters, and associated enabling technologies for 21st century transport aircraft engines based on revolutionary rather than evolutionary technology advancements. Included in the study was a supersonic transport carrying 290 passengers and cruising at Mach 2.6 over a range of 5000 nautical miles. An advanced variable-cycle engine with an extremely high turbine inlet temperature of 4100 °F and an overall pressure ratio of 38 would provide the propulsion.

Study results show that this propulsion system has the potential for a 22 percent saving in fuel and an 18 percent reduction in direct operating cost (based on $1.50/gal fuel cost) relative to current technology. These benefits result from the advanced engines achieving an 8 percent improvement in specific fuel consumption and a 40 percent reduction in weight. This could result in an economically viable supersonic transport with a direct operating cost about the same as that of current wide-body subsonic transports. The key technologies required to produce these benefits are lightweight high-temperature materials and lightweight structural concepts.



Supersonic transport



Advanced variable-cycle engine

Lewis contact, Gerald Knip
((216) 433-5640)
Headquarters program office, OAST

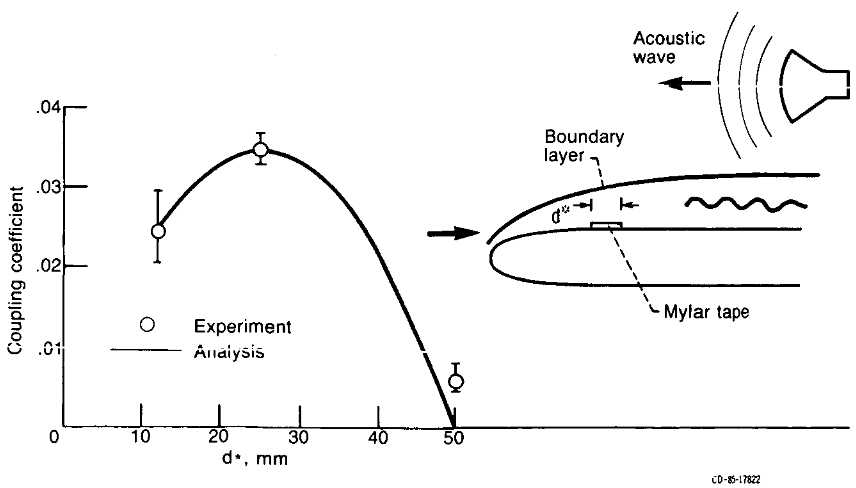
Fundamental Propulsion and Related Research

The successful operation of the liquid-droplet radiator being developed at Lewis depends on being able to break up a capillary jet into very uniform drops. These drops develop from the "pinching off" of a spatially growing varicose instability wave at the position where its amplitude becomes sufficiently large. Uniform drops are obtained by forcing the instability wave, which is a natural oscillation mode of the system, with a piezoelectric crystal within the nozzle. Analysis shows that this forcing usually produces neutral (i.e., nongrowing) disturbances at the nozzle exit that develop into spatially growing waves as they propagate downstream because of the gradual relaxation of the mean velocity profile. The neutral waves can amplify nonlinearly by a so-called direct resonance that can occur in certain parameter ranges. Expressions were obtained for a "coupling coefficient" that measures the effectiveness of the coupling between the imposed disturbance and the instability wave. They show how this coupling changes with various parameters that can be controlled by the experimenter.

It has long been known that transition to turbulence in boundary layers is strongly affected by the precise nature of the free-stream-disturbance environment. We now believe that transition is the result of a chain of events that begins when the external disturbance environment excites spatially amplifying Tollmien-Schlichting waves in the boundary layer. A major problem with this scenario has been to explain how the usually long wavelengths of the free-stream disturbances can be made to match the short Tollmien-Schlichting wavelength. We have shown that a region surrounding the minimum skin-friction point on bodies at moderate angle of attack can introduce short scales into the boundary layer flow and that these short scales can then "scatter" the long wavelength free-stream disturbances into the short Tollmien-Schlichting waves. These short scales are produced by the boundary layer flow itself and are not externally imposed by the prescribed geometry.

We have also shown that short scales can be produced by a change in wall curvature with no change in wall slope. This situation occurs in most laboratory experiments designed to investigate this phenomenon. The analysis, when applied to one of the better known of such experiments, was in good agreement with the measurements.

Lewis contact, Dr. Marvin E. Goldstein ((216) 433-5825)
Headquarters program office, OAST



Effect of outside disturbances on boundary layer Tollmien-Schlichting waves

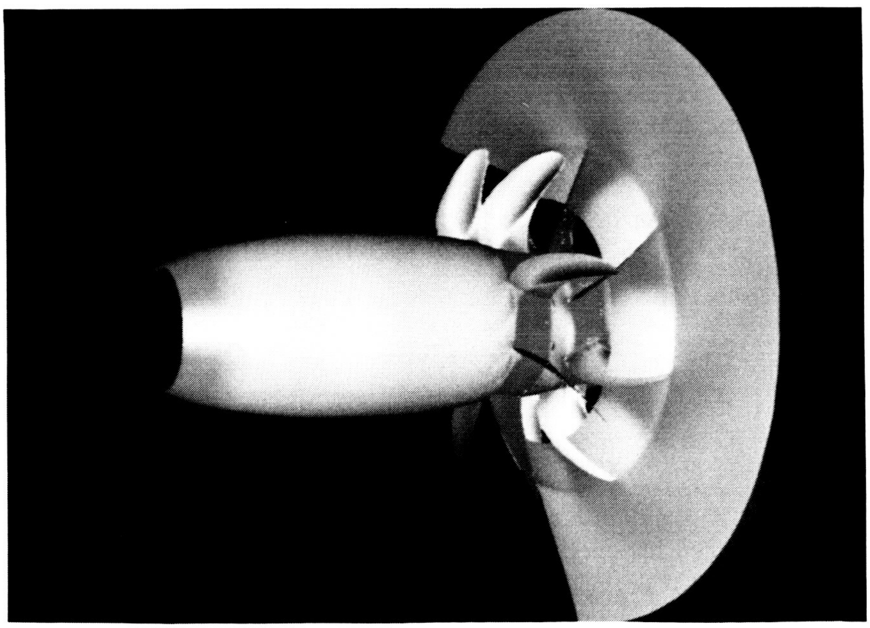
Simulation of Multistage Turbomachinery Flows

Lewis has formulated a flow model for use in simulating multistage turbomachinery flows that is compatible with today's supercomputers and those under development. This model, called the "average passage" flow model, describes the three-dimensional, time-averaged flow field in a typical blade passage of a multiple-blade-row machine. A computer code has been written to solve the inviscid form of the average-passage equation system. This code takes full advantage of today's multiprocessor central processing units by assigning a processor to each blade row of a multistage configuration.

A number of turbomachinery configurations have been analyzed with the inviscid average-passage flow code, including several counterrotating propeller configurations designed by General Electric and Hamilton Standard, the first stage of the space shuttle main engine fuel turbine, a high-speed fan stage, and a supersonic throughflow rotor. All of these simulations yielded new insight into the nature of the flows within multiblade machinery.

We successfully executed a recent request by Sverdrup Technology, Inc., Tullahoma, Tennessee, in behalf of the Air Force, to perform a simulation of a high-speed counterrotating propeller in a free-jet wind tunnel. The object of this simulation was to assess the effect of the finite-diameter jet on propeller performance relative to its performance in free air. The multiple-blade-row code provides a means of quantifying the difference and correcting free-jet wind tunnel performance measurements. We are working to include the effects of viscosity in the code.

Lewis contact, Dr. John J. Adamczyk ((216) 433-5829)
Headquarters program office, OAST

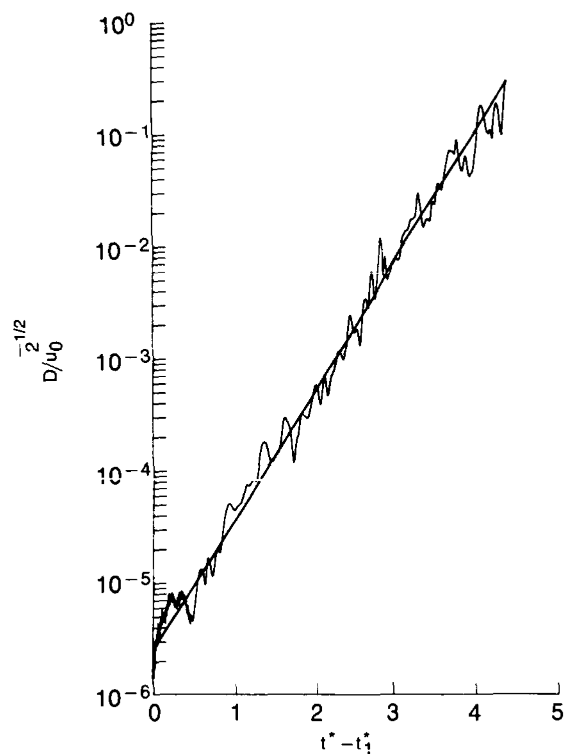


Simulation of radiated pressure field produced by counterrotating propeller

Characterization of Turbulence

Most fluid flows, both those occurring in nature and those that are man made, are turbulent. Lewis is working to characterize fluid turbulence and has numerically obtained turbulent solutions of the equations of fluid motion. The nonlinear terms in the equations have a randomizing effect, and the solutions are chaotic in the sense that the instantaneous values are extremely sensitive to small changes in initial conditions. When the growth with time of the difference between initially neighboring solutions is plotted semilogarithmically, the divergence of neighboring solutions is exponential (linear on the semilog plot). The mean slope, the Liapunov characteristic exponent of the flow, is a measure of the chaoticity of the turbulence. A positive Liapunov exponent indicates a chaotic flow.

Lewis contact, Robert G. Deissler ((216) 433-5823)
Headquarters program office, OAST



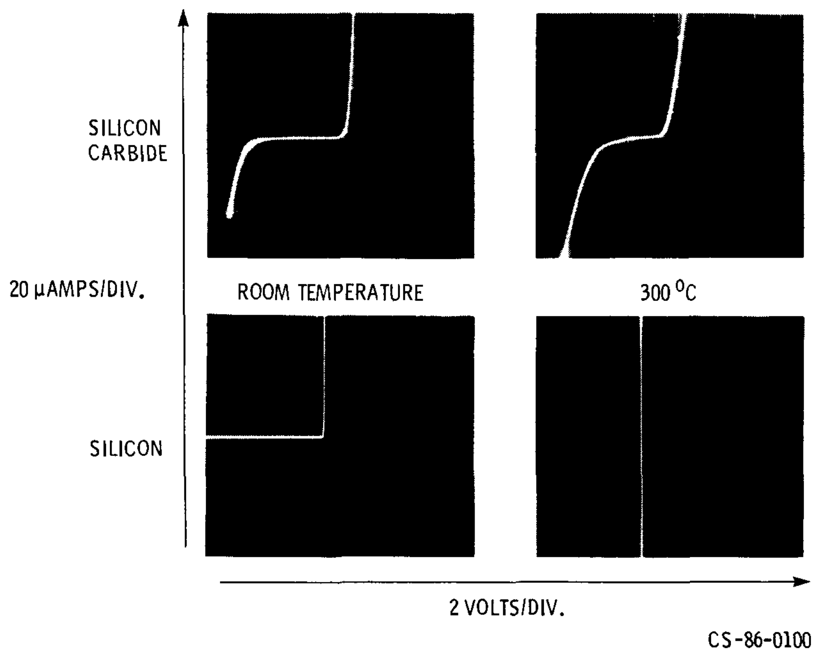
Growth with time of distance between initially neighboring turbulent solutions

Instrumentation and Control Technology

Ion-Implanted Silicon Carbide Diode for High-Temperature Applications

Silicon carbide (SiC) devices have the potential for performance at temperature, power, and frequency levels that are impossible to achieve with current semiconductor devices. Benefits include improved (and more reliable) instrumentation and controls for advanced propulsion systems, significant weight reduction for large space power systems, and higher frequency devices for space communications.

For many years the development of SiC devices has been hindered by the lack of suitable crystal substrates for device fabrication. Lewis has made progress in crystal growth over the last several years, and crystals are now of sufficient quality that prototype device development has begun. Crystals grown at Lewis are being used at Case Western Reserve University (CWRU) in a grant program aimed at developing two fundamental devices; diodes and metal-oxide-semiconductor field-effect transistors.



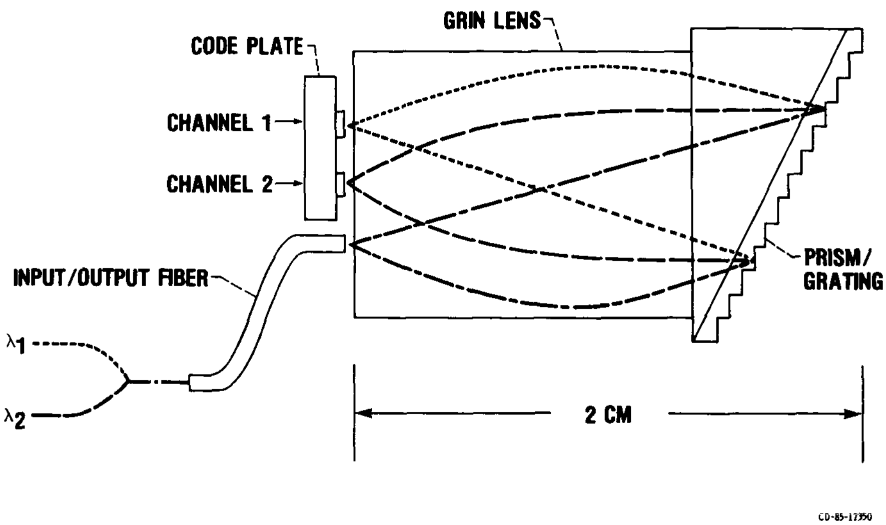
Current-voltage curves of SiC and Si diodes

The CWRU group recently achieved the fabrication of an SiC diode with a planar structure. In this process boron atoms are ion implanted through windows in an oxide mask to form implanted regions at selected areas. The oxide mask is then removed, and the structure is thermally annealed at 1350 °C to reduce damage and to electrically activate the implanted atoms. Current-voltage curves demonstrate that the SiC diode retains diode characteristics at 300 °C; the conventional silicon diode does not. As fabrication procedures are modified and crystal quality continues to improve, SiC diode characteristics are expected to continue improving to the point that the devices will be useful even at much higher temperatures (600 °C).

Lewis contact, J. Anthony Powell ((216) 433-3652)
Headquarters program office, OAST

Wavelength-Multiplexed Optical Encoder

The combination of fiber optic waveguides and passive optical sensors has the potential to make advanced aircraft digital control systems more reliable, smaller, and lighter. One optical sensor that has been developed measures the position of an actuator by reading a digitally coded plate that moves with the actuator. Various schemes have evolved to permit optical encoding with the most desirable optical link configuration—a single fiber for both input and output. Until recently the most successful scheme used relatively long delay lines to temporally separate the signals from each binary column. This method tends to be costly and results in a sizable sensor.



Wavelength-multiplexed optical encoder

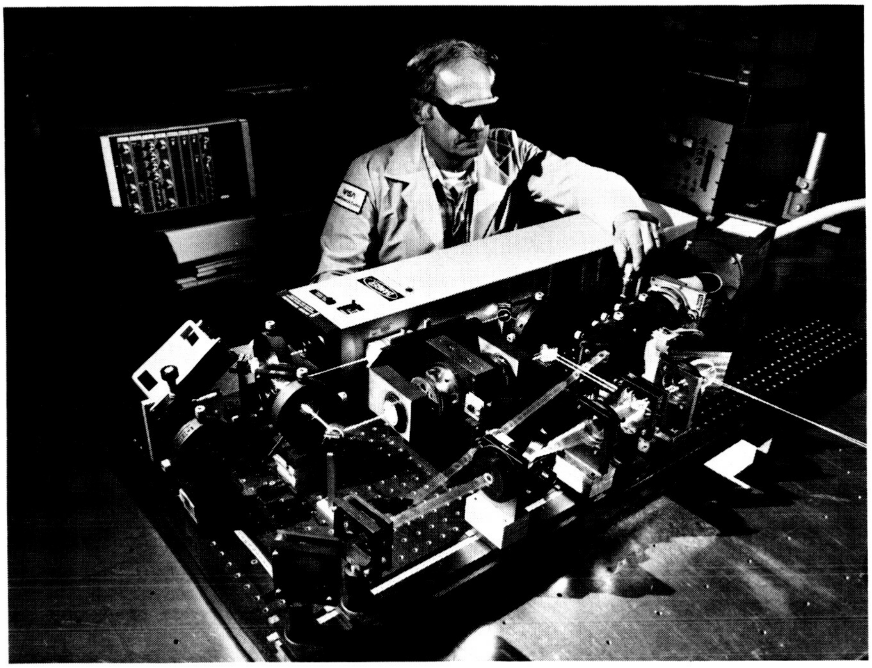
Through an interactive grant with John Carroll University, Lewis is developing a wavelength-multiplexed position encoder. The design employs a light-emitting diode to provide broadband light, which is transmitted over a single fiber to the sensing element. In the sensing element a graded index (grin) lens and prism grating disperse the incoming spectrum into a number of relatively narrow wavelength bands, with each band covering a specific column of the encoder plate. Depending on its position the encoder absorbs or reflects the various wavelength bands and collects those that are reflected through the same grin lens and prism grating system. The combined wavelength bands are returned via the input-output fiber and directed to a remote signal-processing module. The module contains a second grating, which disperses the spectrum across a linear array of photodiodes. Each photodiode represents one column of the encoder plate. The exact position of the encoder plate is determined by the presence or absence of each wavelength band impinging on the photodiode array. Thus the entire digital word, representing the actuator position, is identified from the linear array.

Proof-of-concept demonstrations have been completed, and a prototype for engine testing is being developed.

Bibliography

Fritsch, K.; and Beheim, G.: Wavelength-Division Multiplexed Digital Optical Position Transducer. Opt. Lett., vol. 11, no. 1, Jan. 1986, pp. 1-3.

Lewis contact, Robert J. Baumbick
((216) 433-3735)
Headquarters program office, OAST



Three-component laser anemometer

Laser Anemometer for Three-Component Velocity Measurements

Validation of computer models for the highly three-dimensional flow encountered in modern turbine engines requires accurate measurements of all three velocity components in benchmark research experiments. Turbomachinery facilities rarely permit more than a single, small viewing port to the internal flows of the rig. In this application therefore the use of a conventional fringe laser anemometer to measure all three components, especially the radial one, is not feasible. Since laser anemometry is an otherwise excellent technique for nonintrusively mapping flow-field velocities, Lewis has designed and built a new three-component laser anemometer system. The system uses the fringe technique for the axial and circumferential velocities with a cofocal Fabry-Perot interferometer to measure the radial component. The anemometer uses a single argon ion laser and is mounted on a computer-controlled positioning system that controls the probe volume location.

The system was installed in a full-annular turbine stator cascade facility for three-dimensional code verification. Data from the facility have been obtained with the anemometer system to illustrate the system capabilities. These preliminary data agree well with theoretical calculations of velocity components.

Lewis contact, Dr. Richard G. Seasholtz
((216) 433-3754)
Headquarters program office, OAST

Thin-Film Sensors Laboratory

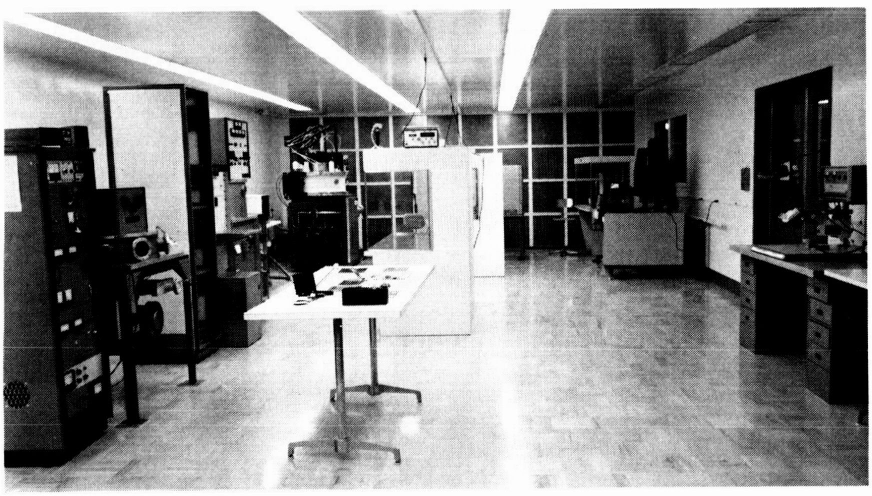
Thin-film sensors offer great advantages for instrumentation to be used in turbine engine testing because of their minimal intrusiveness. Thin-film thermocouples and strain gauges can be deposited directly on airfoils and provide data with no disturbance to the airflow or to the blade thermomechanical properties.

Lewis has established a Thin-Film Sensors Laboratory for in-house research and development of these sensors. The in-house work will complement and extend contract and grant work on thin-film sensors sponsored by Lewis in recent years. Some of this contract work has established the technology for thin-film (5 to 10 μm thick) thermocouples. Thin-film thermocouples deposited onto the surface of turbine blades have operated successfully in turbine engine tests to 1800 °F. Other contract work has developed thin-film strain gauges for measuring vibrational stresses in compressor blades. Work done on a grant at the University of California, Los Angeles, has been directed at improving procedures for forming the required electrically insulating film on the substrate surface and at improving the adherence of the sensor films.

The ongoing work at Lewis has three major goals: (1) to develop thin-film thermocouples for use on the turbine blades of the space shuttle main engine (SSME) turbopumps, (2) to develop high-temperature, thin-film strain gauges for measuring strain on turbine engine components under nonisothermal test conditions, and (3) to develop thin-film sensor technology for use on high-temperature ceramic and ceramic composite materials. Test thermocouples on SSME turbine blade material samples have been successfully cycled from a 2000 °F furnace into liquid nitrogen.

The laboratory is housed in a clean room. The environment of the clean room is carefully controlled to eliminate dust particles and to maintain the temperature and humidity at specified levels. The laboratory contains three vacuum sputtering systems for depositing the thin films, photolithography equipment for creating the geometric patterns for the sensors, and a welder for connecting fine wires to the thin films.

Lewis contract, David R. Englund
((216) 433-3729)
Headquarters program office, OAST



Thin-Film Sensors Laboratory

Internal Fluid Mechanics

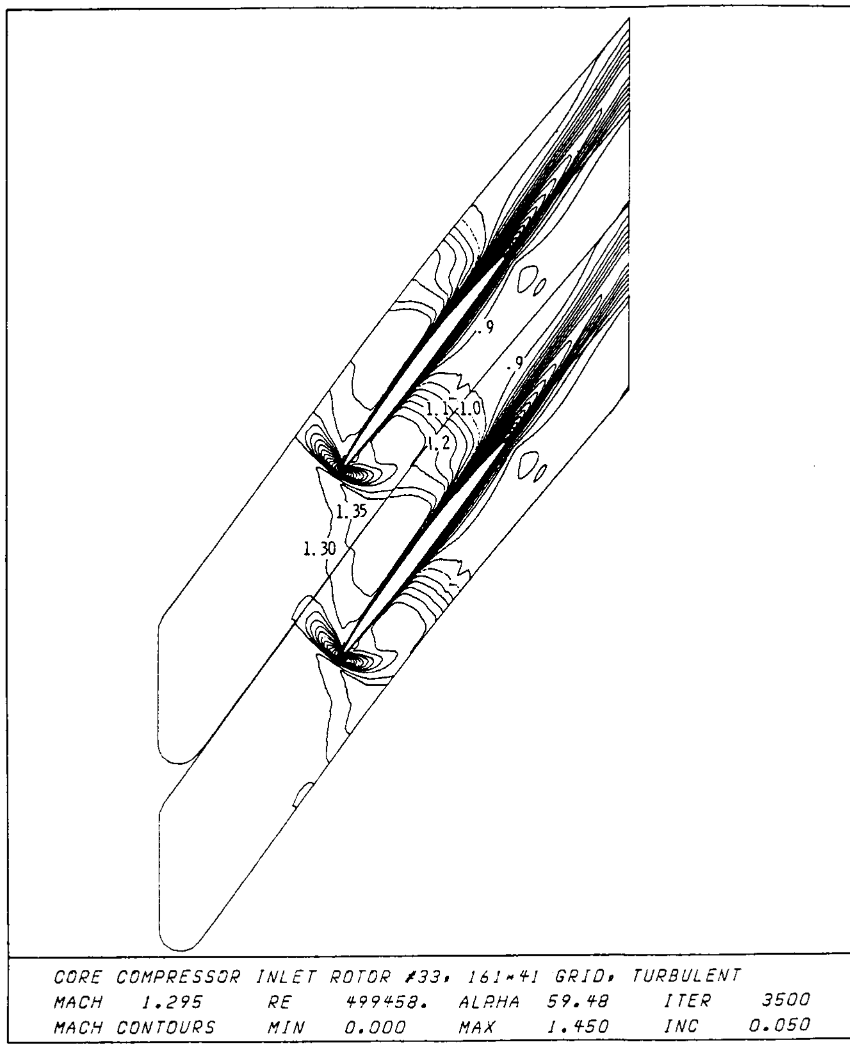
Quasi-Three-Dimensional Viscous Flow Analysis for Turbomachinery

Lewis has developed a fast computational method for analyzing viscous blade-to-blade flows in turbomachinery. This is the first analysis to include the quasi-three-dimensional effects of rotation, radius change, and variable stream-surface thickness. It is applicable to a wide range of turbomachinery.

The method solves unsteady Euler or thin-layer Navier-Stokes equations written in finite-difference form and uses an eddy viscosity model for turbulent flows. The explicit Runge-Kutta method is made efficient by vectorization, a variable time-step, and a multigrid method.

Results have been computed for an axial compressor, an axial turbine, a centrifugal impeller, and a radial diffuser. They show that the method can predict subtle viscous flow phenomena in diverse types of turbomachines and that it is fast enough to be a practical design tool.

Lewis contact, Dr. Rodrick V. Chima ((216) 433-5919)
Headquarters program office, OAST



Viscous flow analysis of axial compressor

Algorithm Development for High-Speed Flows

Recent interest in the aerospace-plane and other hypersonic vehicles has revitalized research on high-speed propulsion systems. In designing hypersonic propulsion systems the computational analysis of high-speed flow past an inlet plays a critical role. Such analysis requires a robust and stable baseline algorithm as well as an efficient method of capturing strong oblique shock waves without spurious oscillations. It is desirable to solve the full Navier-Stokes equations with slip effects and chemical reaction. The Euler equations that represent the hyperbolic conservation law can be a useful testbed for evaluating a shock-capturing numerical method.

Lewis is developing a new time-marching method. The new algorithm is an implicit scheme based on lower-upper (LU) factorization. The finite-volume method is augmented by a controlled blend of first- and third-order dissipative terms that give an upwind bias. A new total variation-diminishing scheme is also being developed. The LU implicit scheme has been successfully applied to high-Mach-number inlet flows ranging from Mach 2 to Mach 22. This is the first successful demonstration of the new algorithm at high Mach numbers.

Lewis contact, Dr. Peter M. Sockol ((216) 433-5821)
Headquarters program office, OAST

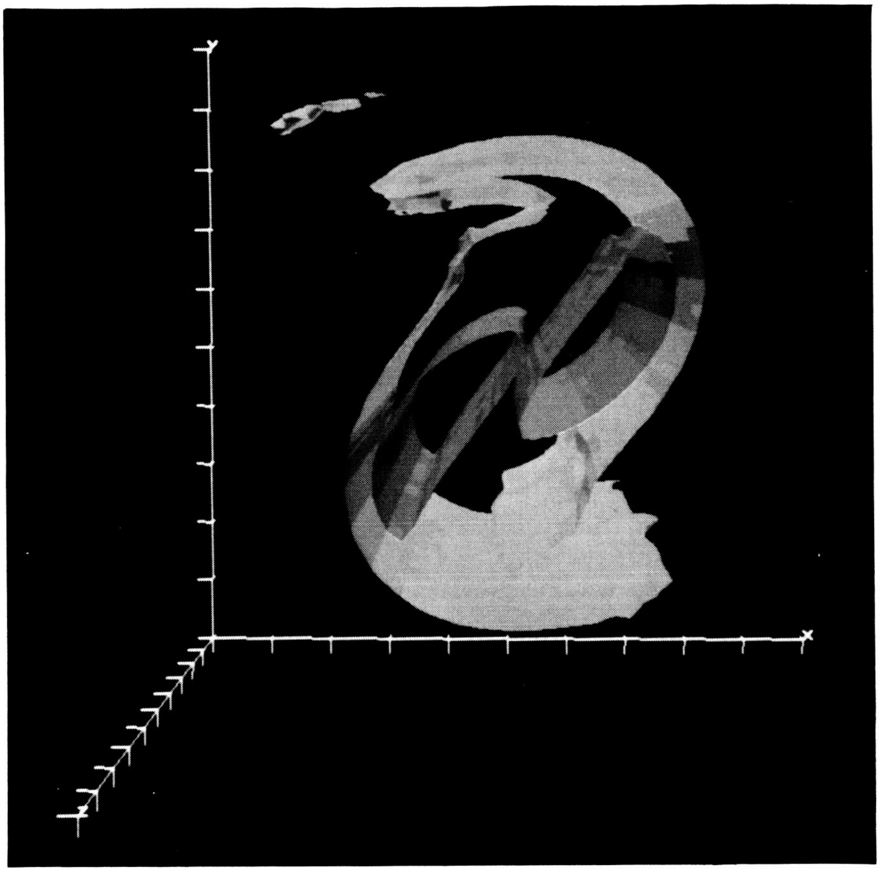
Numerical Simulation of Forced Mixing

The control of turbulent mixing in reacting flows has a number of important applications. In the combustor of a gas turbine engine the desire to burn stoichiometrically in smaller volumes requires intense and rapid mixing. Combustion instabilities, or rumble, in afterburners can be modified by controlled turbulent mixing. Theoretically any process involving the mixing of two fluids can be significantly affected by turbulence control strategies.

Experimental studies have revealed that acoustic forcing at the proper frequencies can greatly enhance turbulent mixing. Many parameters interact in these experiments, making it difficult to unambiguously determine the flow phenomena responsible for the change in chemical mixing. To improve our understanding of the physical processes occurring in these flows, Lewis has been conducting fundamental numerical investigations of forced-flow mixing. All of the physical processes occurring in a flow experiment can be represented (or approximated) on a computer. Until very recently, however, computers have not been powerful enough to examine these flow fields in the detail needed to fully resolve the wide range of turbulent scales naturally occurring in a laboratory experiment. With the advent of the new National Aerodynamic Simulator (NAS) this restriction is being removed.

Three-dimensional computer simulations of forced turbulent mixing layers have been run on the NAS. Three-dimensional computer graphics are used to qualitatively follow the evolution of both the small-scale vorticity and the large-scale structures. Early findings have shown that the development of small-scale streamwise vorticity is enhanced by large spanwise structures that evolve from forcing the flow. These small-scale features contribute significantly to turbulent mixing. Under certain types of forcing large-scale structures coalesce, leading to the destruction of the small-scale vorticity. Thus the numerical simulations are indicating how turbulent mixing is enhanced or reduced depending on the evolution of forced vortical structures. Control of these important processes may lead to more efficient combustion in gas turbine engines and perhaps in the propulsion system of the future national aerospaceplane.

Lewis contact, Russell W. Claus
((216) 433-5869)
Headquarters program office, OAST



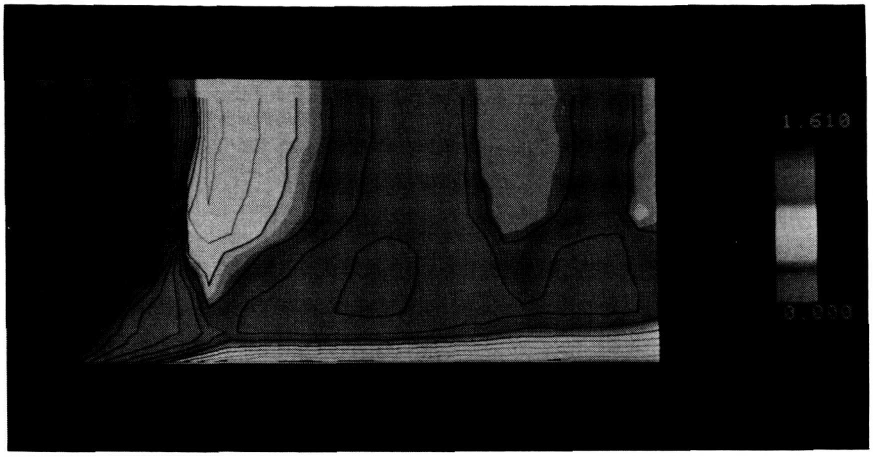
Three-dimensional computer graphic of forced mixing

Shock-Boundary Layer Interactions

Normal shock-boundary layer interactions occur in a number of important high-speed flow applications including transonic flows over wings and bodies, flows in turbomachinery, and flows in supersonic and hypersonic engine inlet systems. Designing improved high-speed flow components requires an understanding of the interaction flow physics and the ability to accurately compute the interaction. Experimental research on these interactions has been limited either to two-dimensional axisymmetric interactions or to measurements along the center plane of rectangular flow geometries.

An experimental program has recently been completed in the Lewis 1- by 1-Foot Supersonic Wind Tunnel in which a normal shock was stabilized across the tunnel test section at free-stream Mach numbers of 1.6 and 1.3. This shock interacted with the naturally occurring tunnel wall boundary layers. The interaction was measured with schlieren and surface oil flow visualization techniques. Three-dimensional laser anemometer surveys were also performed in selected geometric regions throughout the interaction. The complete data set for each Mach number included at least 10 measurement locations.

The laser anemometer results at Mach 1.6 showed a strong shock-boundary layer interaction generating a bifurcated shock. The flow followed one-dimensional normal shock relations only in the center of the tunnel. Flow passing through the bifurcated regions of the shock experienced two oblique shocks and remained supersonic deep into the boundary layer. At Mach 1.3 a weak interaction occurred, the shock did not bifurcate, and the flow was relatively two-dimensional throughout the test section. These results constitute important test cases for numerical flow-field prediction codes, since a small



Mach number contours through shock-boundary layer interaction at upstream Mach number of 1.6

change in Mach number for a fixed, simple geometry resulted in several fundamental changes in the flow physical features.

Lewis contact, Dr. Warren R. Hingst ((216) 433-5923)
Headquarters program office, OAST

Propulsion Systems

Centrifugal Compressor Scaling

A problem confronting the designers of small compressors is the reduction in efficiency that occurs as flow size is reduced. Several factors—Reynolds number, surface roughness, tip clearance, blade thickness, fillet radius, and secondary flow—are known to contribute to the efficiency loss, but the variation in loss that results from a change in each factor is not well known. Controlled experiments are needed to develop mathematical models that can be used to predict and minimize these losses. The Centrifugal Compressor Scaling Program will provide a data base for model development and code verification by determining the loss variation associated with each factor.

A 25-lb/sec centrifugal compressor was directly scaled down to a 10-lb/sec compressor. It was also scaled down to a 2-lb/sec compressor, but the directly scaled blade thickness had to be increased in order to maintain a structurally sound compressor. To maintain a link to the original compressor, the 2-lb/sec compressor was then directly scaled up to the 10-lb/sec size. The efficiency loss caused by the increased blade thickness will be determined by comparing the performance of the two 10-lb/sec compressors.

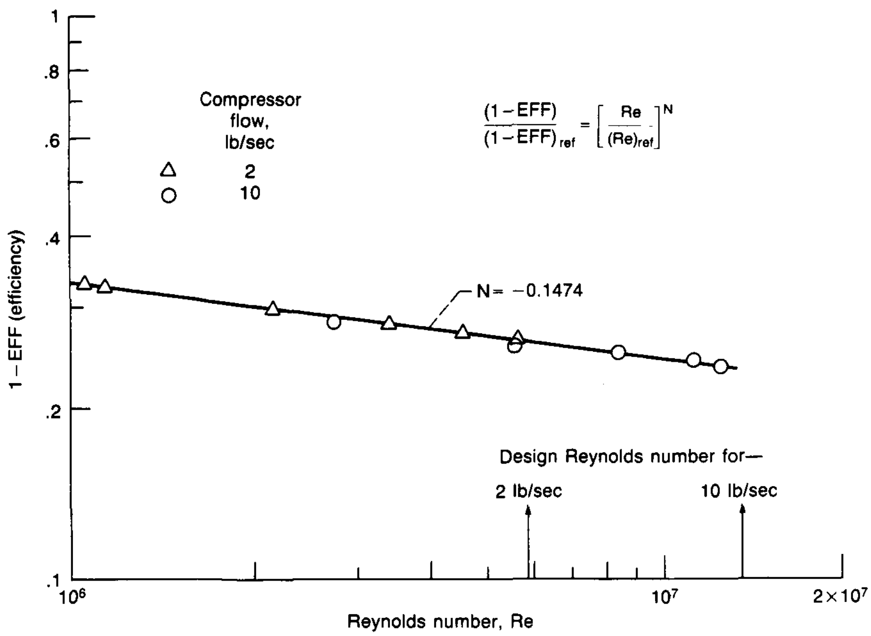
During 1985, performance tests were completed on the 2-lb/sec and 10-lb/sec compressors that are direct scales of each other. For the 2-lb/sec machine, impellers with different surface roughnesses were also tested. Testing was done over a range of blade tip clearances and impeller Reynolds numbers. Data obtained at design values of tip clearance and surface roughness show that the difference in loss between the compressors is due only to the inherent Reynolds number difference between them. Thus the scaling laws hold. The performance loss caused by off-design tip clearance and impeller surface roughness was also measured. These data provide a basis for validating advanced mathematical codes.

Bibliography

Cargill, G.: Scaled Centrifugal Compressor Program. NASA CR-174912, 1986.

Kenehan, J.G.: Scaled Centrifugal Compressor, Collector and Running Gear Program. (GR-21-4269, Garrett Turbine Engine Co.; NASA Contract NAS3-22431.) NASA CR-168167, 1983.

Lewis contact, Gary J. Skoch
((216) 433-3396)
Headquarters program office, OAST

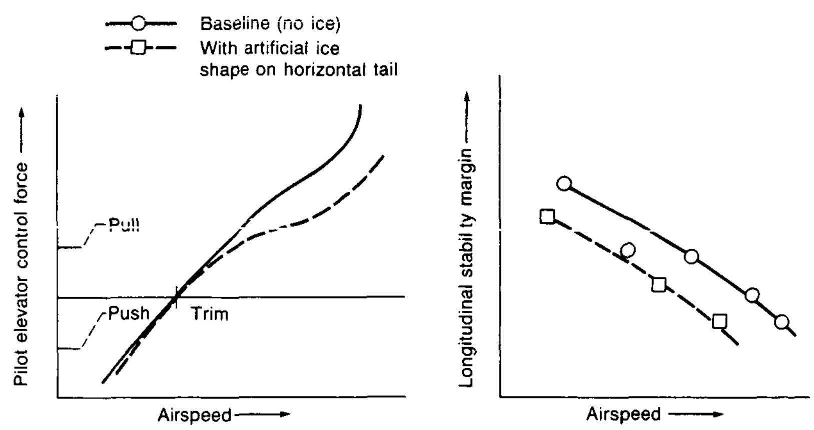


Effect of Reynolds number on centrifugal compressor performance

Aircraft Performance and Handling Changes in Icing

A major goal of NASA icing research is to develop analytical and experimental methods for predicting changes in aircraft handling due to icing. This technology will have direct application in aircraft design, in designing advanced flight control systems for relaxed-stability aircraft, in analyzing failure effects modes, in developing simulator software for pilot training, and in determining aircraft certification criteria for improved operational safety. Little or no quantitative data existed that would be useful for such engineering analyses.

To begin to acquire this required data base, Lewis conducted two flight test programs using the NASA research aircraft, a deHavilland DHC6 Twin Otter. Clear-air flight tests with artificial ice shapes attached to the horizontal tail of the Twin Otter measured changes in the aircraft's static stability margin. Using classical techniques we found that the simulated ice shapes weakened pilot longitudinal control forces and thus reduced the static longitudinal stability of the airplane. Dynamic flight maneuvers were performed in natural icing conditions, and data



Reduction in pilot elevator control force and longitudinal stability due to ice shape on tail were obtained with a compatible data acquisition system provided under contract to Lewis by Kohlman Systems Research, Lawrence, Kansas. These tests identified a degradation due to tail icing in the primary elevator control power derivatives, which in turn are related to the longitudinal flying qualities of the aircraft. Degradations of 8 to 9 percent were measured in the cruise configuration, with slightly greater degradation in the takeoff and landing approach configuration.

Lewis and Kohlman Systems Research will further analyze the flight data. Results of these analyses should point out the limitations of current methods in identifying those parameters that degrade aircraft flying qualities due to icing.

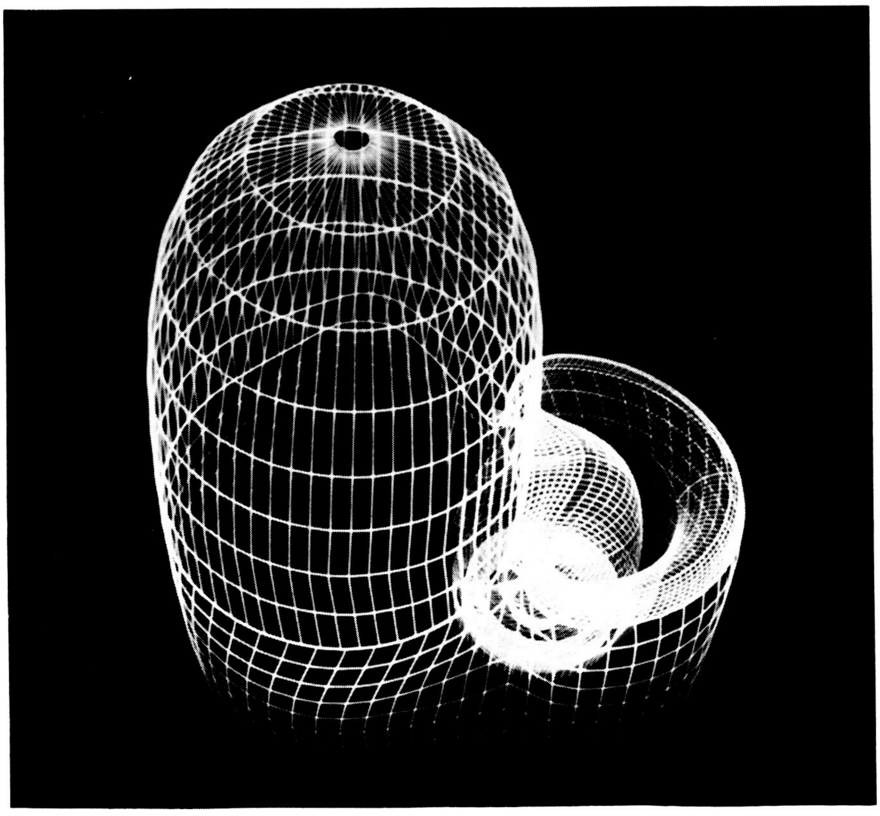
Bibliography

Ranaudo, R.J., et al.: The Measurement of Aircraft Performance and Stability and Control After Flight Through Natural Icing Conditions. AIAA Paper 86-9758, Apr. 1986.

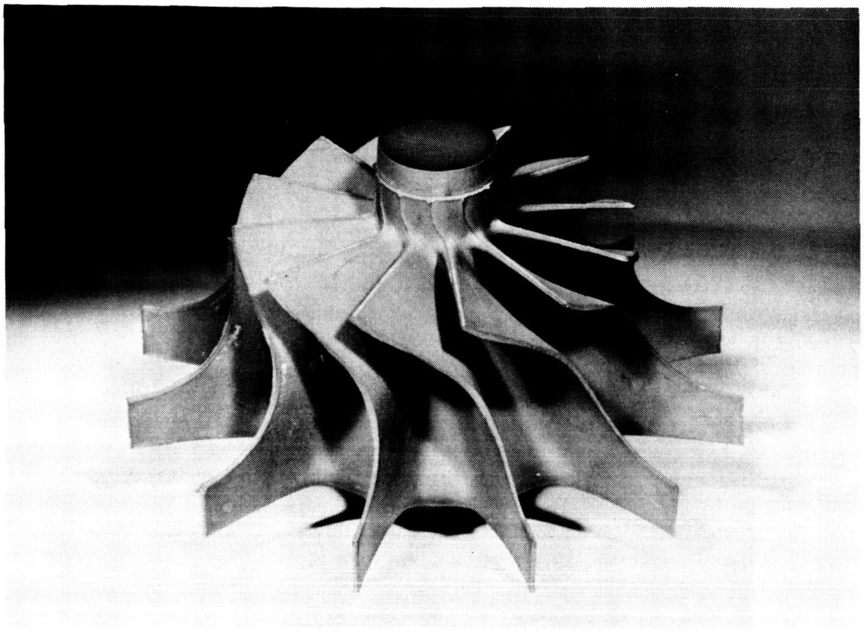
Lewis contact, Dr. Robert J. Shaw ((216) 433-3942)
Headquarters program office, OAST

Three-Dimensional Analysis of Water Droplet Trajectories

Lewis is working to develop and validate a series of computer codes that will predict what happens to an aircraft (fixed or rotary wing) when it flies through an icing cloud. These codes should help reduce the time and cost of designing and certifying all-weather aircraft. Droplet trajectory analysis provides the first indication of a component's susceptibility to icing. Until recently trajectory analyses could be performed only for simple two-dimensional and axisymmetric geometries. But now advanced methods have been developed for predicting three-dimensional trajectories for complex configurations such as three-dimensional inlets (e.g., the JVX/V22) and even for complete aircraft configurations.



Wire mesh model of JVX inlet used for three-dimensional trajectory analysis



AGT *100 silicon nitride rotor*

Lewis is conducting a complementary experimental validation program in the Icing Research Tunnel to measure local droplet impingement characteristics for a number of airfoil, swept-wing, and inlet configurations. We are comparing this experimental data base with the predictions of the various droplet trajectory codes.

Boeing Military (Wichita) is developing the three-dimensional trajectory analysis code, and the experimental data base is being acquired as part of a joint NASA/FAA/Boeing/Wichita State cooperative program. Atmospheric Science Associates developed the trajectory code for analyzing complete aircraft configurations.

Bibliography

Kim, J.J.: Particle Trajectory Computation on a 3-Dimensional Engine Inlet. Ph.D. Thesis, Wichita State Univ., KA, 1986.

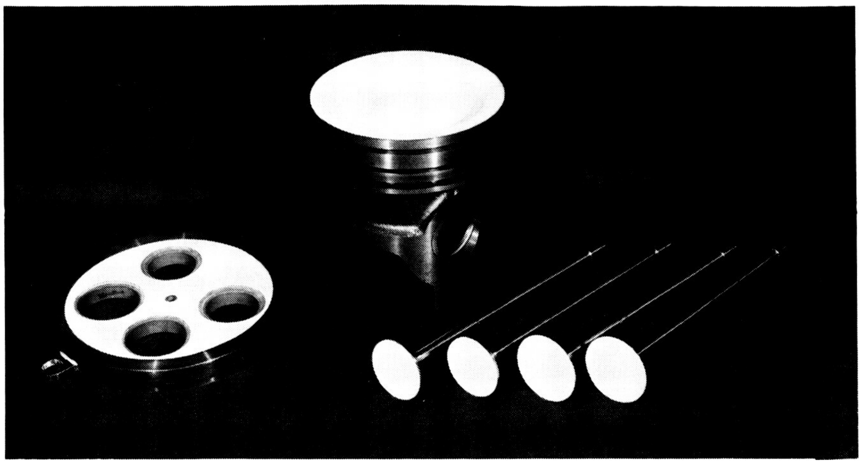
Norment, H.G.: Calculation of Water Drop Trajectories To and About Arbitrary Three-Dimensional Lifting and Nonlifting Bodies in Potential Airflow. NASA CR-3935, 1985.

Papadakis, M., et al.: An Experimental Method for Measuring Droplet Impingement Efficiency on Two- and Three-Dimensional Bodies. AIAA Paper 86-0406, Jan. 1986.

Lewis contact, Dr. Robert J. Shaw ((216) 433-3942)
Headquarters program office, OAST

Ceramic Components for Gas Turbine Engines

As part of the Department of Energy's Automotive Technology Development Program, Lewis is working to develop a technology base applicable to small advanced gas turbine engines. These high-temperature engines with all-ceramic hot-flow-path components offer the potential of significant fuel savings over conventional internal combustion engines and have emission levels that meet or surpass current or proposed Federal standards. Technology development contracts are in place with the Allison Gas Turbine Division of General Motors Corporation and with the Garrett Turbine Engine Company. Development of ceramic components is critical to the overall success of the program, and significant progress has been made in the technology. Ceramic static components have been undergoing extensive analysis, design modification, and engine environmental testing at temperatures to 2100 °F. Continued efforts in fabrication development have produced ceramic rotors with excellent dimensional control and surface finish. These rotors have been successfully spin tested at room temperature to 137 000 rpm (150 percent of rated speed) and are in the initial phases of engine environmental testing. All activities are progressing toward testing a complete set of ceramic components in a testbed engine by the end of 1986.



Thermal-barrier-coated components for low-heat-rejection diesel engines

Bibliography

Proceedings of the Twenty-Third Automotive Technology Development Contractors' Coordination Meeting. SAE P-165, Society of Automotive Engineers, 1986.

Lewis contact, Paul T. Kerwin
((216) 433-3409)
Headquarters program office, OAST

Ceramic Components for Low-Heat-Rejection Diesel Engines

One of the Department of Energy programs for which Lewis is providing technology support is the program to develop advanced low-heat-rejection (LHR) diesel engines. In the LHR configuration engine cooling is drastically reduced so that more heat is retained in the engine and the operating temperature rises. This improves engine performance and raises exhaust temperatures, making more energy available for recovery through exhaust waste heat utilization. The key to success in this program for both the basic engine and the waste heat recovery system is the development of materials and lubricants that can withstand the thermal and mechanical stress imposed by high-temperature operation.

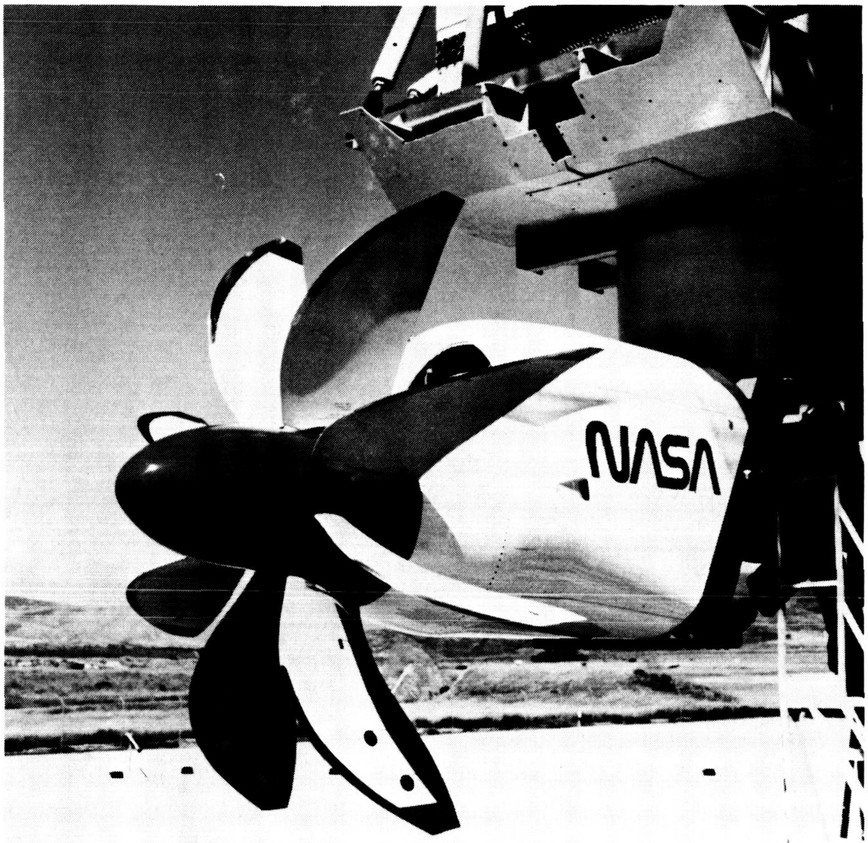
The development of ceramic insulation systems for heat retention and metal protection of the in-cylinder components is continuing, with emphasis on plasma-sprayed zirconia thermal barrier coatings. Two parallel technology contracts have been issued to Caterpillar Inc. and Cummins Engine Company with the objective of insulating these component surfaces with thick zirconia coatings. This work builds on an effort completed last year in which a thinner coating was run for 24 hours in an engine. The significant technology base developed at Lewis for thick (>100 mils) sprayed-zirconia turbine tip seals will also be adapted to help meet the diesel requirements.

The high-temperature operating environment also presents difficult tribological problems at the interface between piston ring and cylinder liner, where the operating limits of conventional lubricants can easily be exceeded. Two independent contracts using pin-and-disk friction and wear apparatus found that the best-performing unlubricated materials, at temperatures to 1200 °F, were nickel-molybdenum-based titanium carbide, titanium carbide, and silicon carbide. The materials exhibited excellent wear characteristics, but although the friction coefficients were good (approximately 0.24) for unlubricated materials, they were too high for practical applications. In a recently completed follow-on effort Southwest Research Institute found that titanium carbide and nickel-molybdenum-based titanium carbide run unlubricated on partially stabilized zirconia and silicon nitride ion-implanted with either cobalt or titanium nitride exhibited friction coefficients as low as 0.09. This is competitive with liquid-lubricated pairs. In a soon-to-start phase they will attempt to run ceramic piston rings and ion-implanted cylinder liners in a single-cylinder engine test.

Bibliography

Proceedings of the Twenty-Third Automotive Technology Development Contractors' Coordination Meeting. SAE P-165, Society of Automotive Engineers, 1986.

Lewis contact, James C. Wood ((216) 433-3419)
Headquarters program office, OAST



Propfan propulsion system during static test

IR-100
Large-Scale Propfan Engine Testing

A new large-scale advanced turboprop, or propfan, designed to be a fuel-saving replacement for the turbofan engine at high subsonic cruise speeds, has completed rigorous ground testing. This unusual 9-ft-diameter propeller, designed and built under contract by Hamilton Standard Division of United Technologies Corp., contains eight highly loaded thin, wide-chord, swept, scimitar-like blades mounted on an area-ruled spinner. This test article is the precursor of advanced turboprop designs that will use 15 to 30 percent less fuel than comparable advanced turbofan engines (50 to 60 percent less than today's turbofan fleet) with no sacrifice in cruise speed.

A series of three contracted ground tests with this propfan was completed in the past year. A static test with the propfan mounted on a variable-speed electric drive motor was conducted at Wright-Patterson Air Force Base (WPAFB). This test was followed by high-speed wind tunnel testing to and beyond Mach 0.8 with the test propfan again driven by a facility drive motor. Finally the propfan was powered by a nacelle-enclosed turboshaft drive system in a static test on an outdoor test stand at Brown Field in California. This drive system will be used to flight test the large-scale propfan on a testbed-modified Gulfstream II airplane.

In the WPAFB static testing, performed by Hamilton Standard under contract, propfan full rated power was achieved at 112 percent of full rated speed. The maximum allowable blade angle was limited by tip stall buffet, but model wind tunnel testing at Lewis indicates that these problems are eliminated as inflow velocity increases to about 50 mph. No blade critical speed problems were observed, and strain gauge data agreed quite well with analytical predictions.

Contracted high-speed wind tunnel testing by Hamilton Standard verified the structural integrity of the large-scale propfan at simulated flight speeds. Because of the power limitations of the facility drive system the propfan was tested not only in its complete eight-blade configuration but also with some of the blades removed to assess the effect of increased power loading on individual blades. There was no sign of whirl flutter or classical blade flutter, nor was there any sign of approaching the predetermined blade stress limits in any of these tests.

The propfan propulsion system was statically tested at Brown Field, a Rohr Industries Facility, under contract with Lockheed-Georgia Co. This test served as a functional checkout for the complete propulsion system to be used in the Gulfstream II flight test and verified the safe and stable operation of the various propulsion components with the propfan and engine control systems to be used in flight. This test further verified the structural integrity of the highly instrumented propfan and characterized both near-field and far-field acoustics before the flight test.

Research & Developement magazine has selected the propfan engine along with the unducted-fan engine, to receive an IR-100 award as one of the 100 most significant technical developments of 1986.

Bibliography

Whitlow, J.B., Jr.; and Sievers, G.K.: Fuel Savings Potential of the NASA Advanced Turboprop Program. NASA TM-83736, 1984.

Lewis contact, Gilbert K. Sievers ((216) 433-3898)
Headquarters program office, OAST

Advanced Propeller Model Testing

A 2-ft-diameter aeroelastic model of the large-scale single-rotation propfan being evaluated by NASA was successfully tested in Lewis wind tunnels. Although high-speed flutter was predicted at around Mach 0.8 at the high-density conditions in the 8- by 6-Foot Supersonic Wind Tunnel, the model was stable to Mach 0.9 at rotational speeds well beyond the design

Unducted-fan model in Lewis 8- by 6-Foot Supersonic Wind Tunnel

point, thus indicating the conservatism of the design methodology. The tests in the acoustically lined 9- by 15-Foot Low-Speed Wind Tunnel revealed no evidence of stall flutter and allowed further definition of the stall buffet boundaries, thus verifying at model scale a condition observed statically in the test of the 9-ft-diameter propfan at Wright-Patterson Air Force Base. Acoustic test data from this tunnel indicate that peak tone levels are significantly influenced by the amount of wing sweep at angle of attack and that the peak tone of the isolated propeller is similarly influenced by the angle of attack of its axis with respect to the upstream flow.

High-speed tests of a 5- by 5-blade counterrotating model typical of a geared tractor propfan configuration were also completed in the United Technologies Research Center (UTRC) 8-ft tunnel under a contract with Hamilton Standard. A maximum net propulsive efficiency of 86.5 percent was obtained at Mach 0.75 cruise conditions—approximately 7 points higher than that obtained for the single-rotation propfan at similar disk power loading and tip speed. The higher efficiency reflects the recovery of much of the swirl loss experienced with single rotation. Data were obtained over a range of Mach numbers, tip speeds, and blade angles. The measured data indicate a strong effect of front and rear blade angle combination on efficiency. Acceptable vibratory stresses and flutter-free operation were obtained over the Mach number range investigated. This counterrotating model was also tested later in the UTRC acoustic research tunnel. Preliminary analysis of the acoustic data indicates that noise levels are not very sensitive to rotor spacing, within practical limits.

Nine unducted-fan counterrotating models were also evaluated in the Lewis supersonic wind tunnel. Parametric model variations included blade sweep, airfoil shape, blade loading, afterbody shape, forebody shape, number of blades, clipped aft blades, and rotor spacing. Propulsive efficiencies several points below expectation were obtained for all configurations at high speeds. Flutter was encountered with three of the nine configurations, but the onset of flutter was less abrupt than with single-rotation configurations. Preliminary acoustic results from these models at cruise conditions indicate that their noise level is about 6 dB higher than that for the single-rotation propfan. Peak cruise noise levels for the nine configurations fell within a 4-dB band.

Bibliography

Whitlow, J.B., Jr., and Sievers, G.K.: Fuel Savings Potential of the NASA Advanced Turboprop Program. NASA TM–83736, 1984.

Lewis contact, Gilbert K. Sievers
((216) 433–3898)
Headquarters program office, OAST

Unducted-fan demonstrator engine on static test stand

IR–100 Unducted-Fan Engine Testing

In the past year the General Electric Co. began static proof-of-concept tests of a 25 000-lb-class unducted-fan demonstrator engine at their Peebles, Ohio, outdoor test site. Development of this advanced counterrotation pusher-propeller propulsion system was partially funded by Lewis. The unducted fan is unique in that its propellers are directly driven by the multi-stage power turbine without the need for gearbox speed reduction. The propulsor section, which includes the counterrotation power turbine and directly attached thin, swept propeller blades, is mechanically uncoupled from the upstream F-404 military turbofan engine, which supplies the hot gases used to drive the power turbine. The advantage of this, as well as other more conventional, geared counterrotation systems, is their capability to reduce the rotational, or "swirl," energy losses associated with single-rotation propellers.

During the initial GE tests measured thrust and specific fuel consumption were close to prediction, and the control system and propeller pitch change mechanism functioned as designed. Approximately 5¾ hours into the test a power turbine failed. All stages of the power turbine were rebuilt with pin dampers to reduce vibratory response. Blade tip clearances were also increased to prevent the recurrence of rubs, which were observed before and during the stall/failure event. Ten days after engine testing resumed with the rebuilt power turbine one of the composite shells from an aft-stage propeller blade was thrown because of a spar-shell bond failure. The spar was retained in its mount but was cracked at one of the fabricated joints. The blade construction was then modified to reduce stress concentrations at the bond joints, to eliminate the spar weld line, and to reduce vibratory stresses by blade detuning. The modified blades were subjected to rigorous fatigue and whirligig testing before being installed on the engine for accelerated endurance testing. The blades were inspected ultrasonically for debonding each day during testing. After the successful completion of the accelerated static endurance testing the demonstrator engine was inspected and refurbished for installation as a prime powerplant on the Boeing 727 testbed aircraft to be used in planned flight tests.

Research & Development magazine has selected the unducted-fan engine, along with the propfan engine, to receive an IR-100 award as one of the 100 most significant technical developments of 1986.

Bibliography

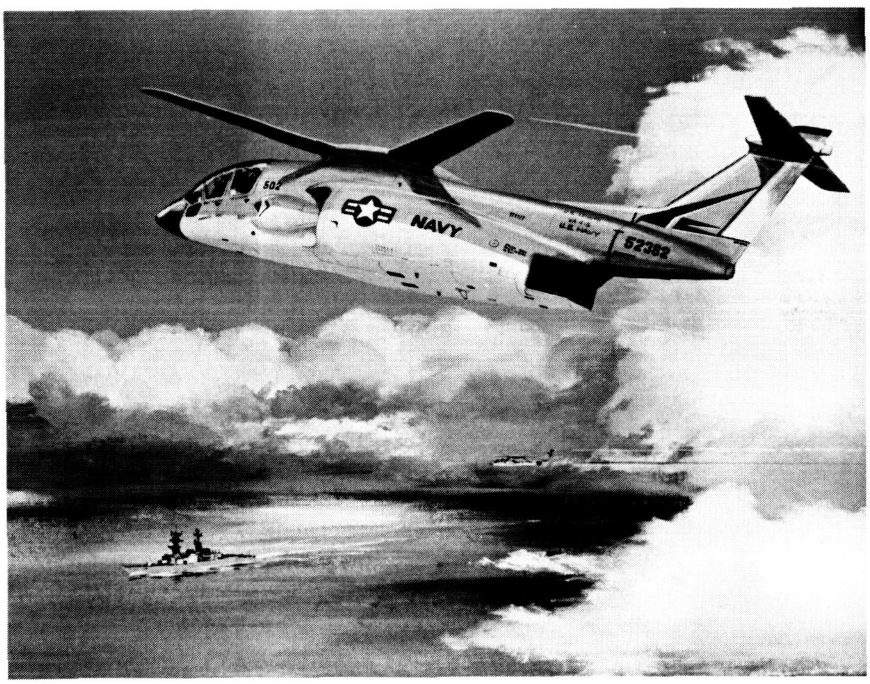
Whitlow, J.B., Jr., and Sievers, G.K.: Fuel Savings Potential of the NASA Advanced Turboprop Program. NASA TM-83736, 1984.

Lewis contact, Gilbert K. Sievers ((216) 433-3898)
Headquarters program office, OAST

Performance and Dynamics of Convertible Engine

Modern rotorcraft are capable of performing a wide variety of tasks, but their inability to reach high forward speeds restricts their use. Because of interest by both the civilian and military sectors in achieving higher speeds new engine concepts that can efficiently supply power for both forward and vertical flight are being sought. One promising concept called the convertible engine supplies power via reduction gears and shafting to a rotor during vertical flight but performs as a turbofan during high-speed forward flight. Over the past two years a Lewis program has experimentally validated the technology for such an engine.

In operation a new high-speed rotorcraft, such as the X-wing, would use convertible engines to take off or land vertically with a four-blade, X-shaped lifting rotor. After achieving sufficient altitude and forward speed the engines would convert smoothly from powering the rotor to a forward thrust or turbofan mode. The transmission would be disengaged and the rotor blades locked into a fixed position, their



Convertible engine rotorcraft

airfoil configuration imparting lift for normal cruise. For landing the same "conversion" would be performed in the reverse order.

The experimental program was jointly sponsored by NASA and the Defense Advanced Research Projects Agency (DARPA). Under a Lewis contract the General Electric Co. modified a TF-34 turbofan engine by adding variable inlet guide vanes (VIGV) and an output shaft so that it could operate in either the shaft-power or turbofan mode, or in any combination of the two modes, and be able to convert from one mode to the other without shutting off. The engine was tested at Lewis in a special outdoor test facility to evaluate its steady-state and dynamic performance characteristics. In 1985 Lewis demonstrated the first transient conversions between shaft power and fan thrust. This year we evaluated an improved fan hub design and mapped steady-state and dynamic (transient) performance and stability over the full operating envelope. The main conclusion of this year's work was that the VIGV convertible engine is inherently stable and controllable in all its operating modes.

This type of engine can reduce direct operating cost by 20 percent over separate engines for advanced rotorcraft concepts such the X-wing, the advancing blade, and the folding tilt rotor. The engine test program at Lewis represented the first successful operation of a 5000-hp-class convertible engine in both fan and shaft modes and the first dual-mode operation for the VIGV concept. A new breed of high-speed civil rotorcraft using convertible engines would combine jet transport comfort and performance characteristics with vertical takeoff and landing features. For military applications this type of vehicle would be a highly maneuverable, agile attack and reconnaissance aircraft with high subsonic speed and long range. The highly successful completion of this convertible engine program has demonstrated a viable propulsion concept for future advanced rotorcraft.

Bibliography

Abdalla, K.L.; and Brooks, A.: TF-34 Convertible Engine System Technology Program. Proceedings, American Helicopter Society, 38th Annual Forum, 1982, pp. 163–169.

Lindsay, Howard: TF-34 Convertible Engine System Technology Program. (General Electric; NASA Contract NAS3-22752.) NASA CR-179453, 1986.

McArdle, Jack G.; Barth, Richard L.; and Burkardt, Leo A.: Steady-State Performance of a Turbofan/Turboshaft Convertible Engine with Variable Inlet Guide Vanes. NASA TP-2673, 1986.

Lewis contact, Kaleel L. Abdalla ((216) 433-3961)
Headquarters program office, OAST

Low-Noise Spiral-Bevel Gears

Spiral-bevel gears are used to transmit motion between intersecting shafts. The most important application for these gears in aviation is in helicopter transmissions. The spiral-bevel gears in most helicopter applications run at high speed and transfer high power from the engine through reduction gears to the main rotor. In many helicopters, because the transmission is close to the passenger compartment, gear noise is a problem. Measurements have determined that the spiral-bevel gears are the single largest contributor to the noise in the passenger compartment. Therefore Lewis is working to reduce bevel gear noise.

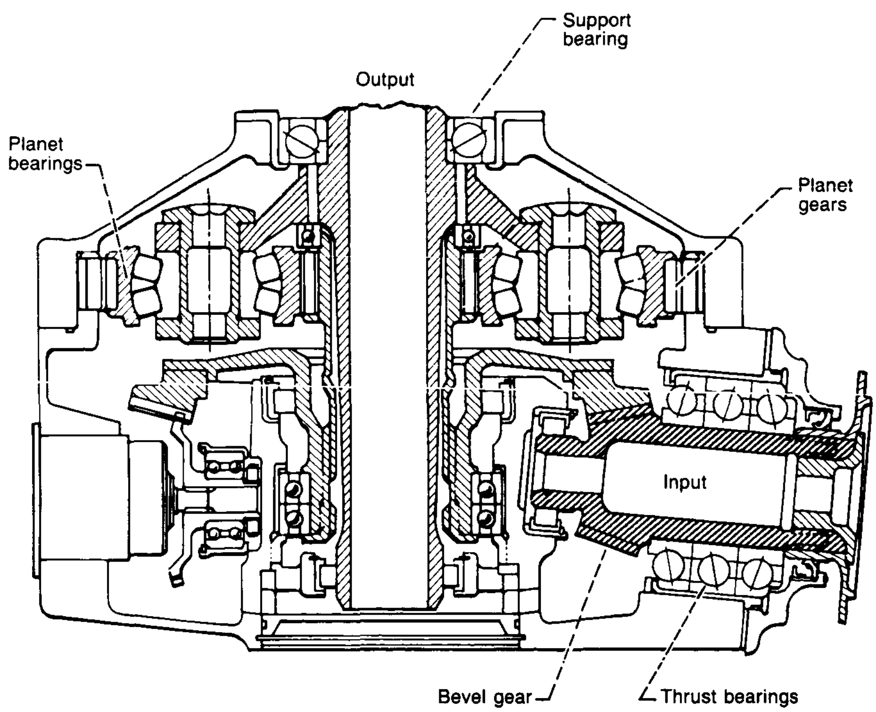
The time-varying deviations in the gear ratio, called kinematic errors, are the source of the noise. The kinematic error can be reduced if the spiral-bevel gears are manufactured with the correct settings on the gear-generating machinery. A mathematical procedure has been developed to determine the machine settings that will generate more smoothly running gears that produce less noise and vibration. An added benefit is that since the gears run more smoothly they will have a longer useful life.

This work is being performed through a grant at the University of Illinois at Chicago as well as at Lewis. The university research program has focused on analysis of the gear-manufacturing process. The work at Lewis will combine the analytical computer programs with three-dimensional computer graphics for full visualization of the tooth contact patterns and meshing simulation.

Bibliography

Litvin, F.L., et al.: Generation of Spiral Bevel Gears with Zero Kinematical Errors and Computer Aided Tooth Contact Analysis. NASA TM-87273, 1986.

Lewis contacts, Robert F. Handschuh ((216) 433-3969) and Dr. John J. Coy ((216) 433-3915)
Headquarters program office, OAST

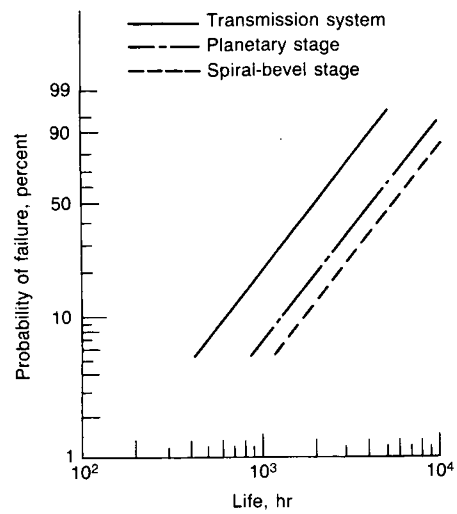


Cross section of OH-58 helicopter transmission

Computer Program for Life and Reliability of Helicopter Transmissions

Life and reliability are important issues in the design, development, and field operation of helicopter transmissions. Light weight and high power capacity must be balanced with requirements for long life and low maintenance costs. Gear and bearing lives are major factors in total transmission system life. Analytical models for predicting transmission life and for comparing competing and alternative designs were only recently developed under NASA/Army sponsorship. Analytical studies were successful in applying these models to transmissions. The work was laborious and only a few transmissions were studied, the results being published in NASA reports. A need was perceived for a more general, computerized model capable of efficiently analyzing a large variety of transmission designs.

A computer program was developed through a grant with the University of Akron that can analyze an extremely wide variety of configurations composed of spiral-bevel gear meshes and planetary gear meshes. Spiral-bevel reductions may have single or dual input pinions, and gear shafts may be straddle mounted or overhung on the support bearings.



Predicted transmission life

The planetary reduction has the sun gear as input, the planet carrier as output, and the ring gear remaining stationary. The planet gears may be plain or stepped and the number of planets may vary.

The program determines the forces on each bearing and gear for a given transmission configuration and loading. The life of each bearing and gear is determined by using the fatigue life model appropriate to that component. Transmission system life is determined from the component lives by using rigorous methods of probability and statistics. The transmission life for a given level of reliability can then be found. Program output consists of component and total system lives and dynamic capacities. From the life predictions the mean time between failures can now be calculated by using rigorous statistical methods.

Bibliography

Lewicki, D.G., et al.: Fatigue Life Analysis of a Turboprop Reduction Gearbox. ASME Paper 85-DET-10, Sept. 1985.

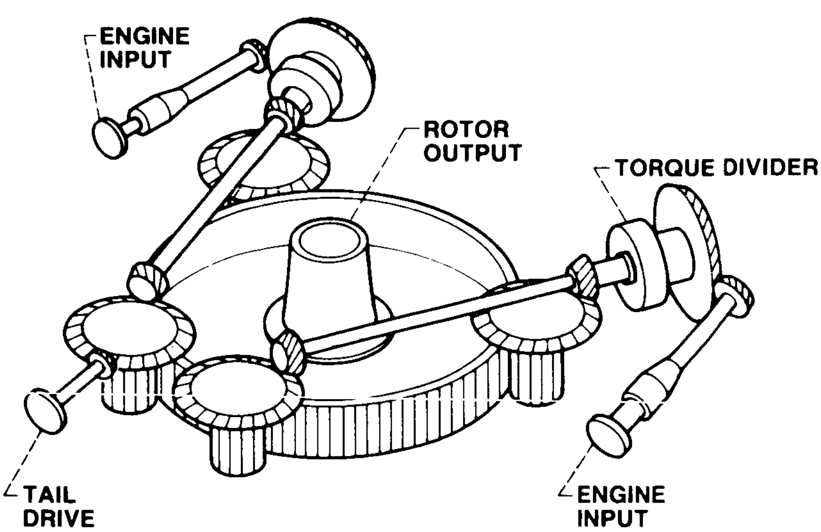
Savage, M.; and Brikmanis, C.K.: System Life and Reliability Modeling for Helicopter Transmissions. NASA CR-3967, 1986.

Lewis contact, David G. Lewicki
((216) 433-3970)
Headquarters program office, OAST

Increased Power-Weight Ratio for 3600-hp Helicopter Transmission

The power transmission of a helicopter contributes significantly to the weight of the vehicle. Conventional planetary transmissions have a power-weight ratio of about 1.3 N/kW (0.40 lb/hp). Improvements to this ratio allow either more carrying capacity or a longer flight range for a helicopter with a given input power or permit the same range or capacity with a lower power requirement. A study was therefore undertaken to examine the possible improvements for a transmission design with drive train arrangements based on a split-torque principle over a conventional planetary design. With a split-torque design input power and torque are divided between two parallel paths and then recombined at the output shaft.

Transmission Research, Inc., under contract to Lewis, studied the split-torque design configurations based on either three, four, or five final drive pinions for a twin-input, 3600-hp transmission with an output rotor speed of 258 rpm and an overall speed reduction of 81:1. The four-pinion design resulted in the lowest overall weight with comparable totals of gears and bearings. The study showed that as compared with a current planetary transmission the split-torque design can result in a weight reduction of 15 percent, improved reliability because of redundant power paths, a power loss reduction of 9 percent, and a reduction of 38 percent in the number of noise meshes. This study is complete. There are no plans to build or test prototypes. However, any future helicopter transmission design program should consider the split-torque arrangement as a viable alternative to the conventional planetary design.



Gear train arrangement for the four-pinion split-torque transmission

Bibliography

White, G.: A 3600 HP Split-Torque Helicopter Transmission. NASA CR–174932, 1985.

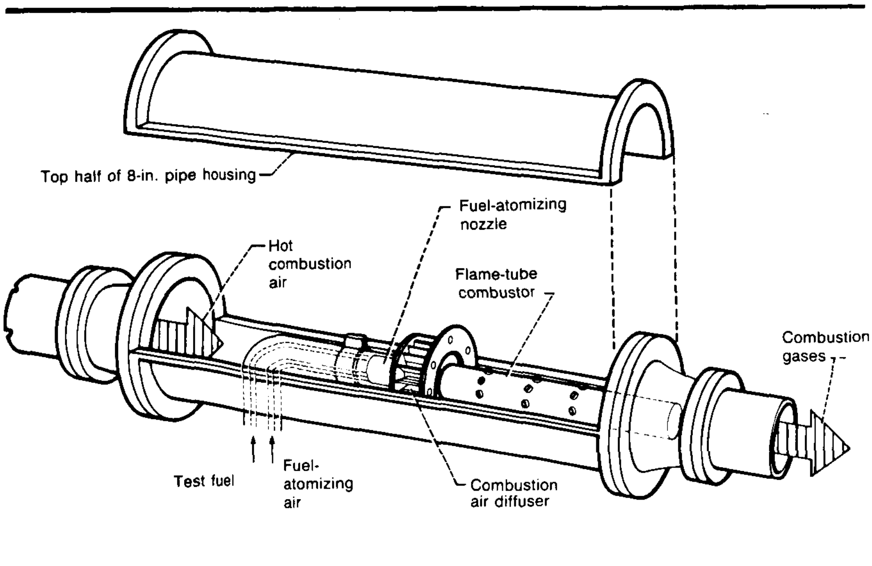
Lewis contact, Harold H. Coe
(216) 433–3971)
Headquarters program office, OAST

Combustion Characteristics of Alternative Gas Turbine Fuels

Advanced automotive gas turbine engine technology is being evolved to provide alternatives to conventional internal combustion engines. Turbine engines have the potential of using a wide variety of fuels in their operation. To assess this potential, Lewis conducted a joint NASA/Department of Energy experimental program in-house to determine the combustion characteristics of commercial diesel fuel number 2, automotive-grade gasoline, methanol, diesel fuel obtained from tar sands, a coal-derived diesel fuel made by an Exxon process (EDS), a hydrogenated EDS fuel, a blend of 50 percent EDS and 50 percent diesel fuel, and a blend of 77 percent EDS and 23 percent diesel fuel.

The test rig incorporated a flame-tube combustor and a single fuel-spray injection nozzle. Operating variables were airflow rate (1/4 to 1 lb/sec), air pressure (1 to 10 atm), inlet air temperature (800 to 1600 °F), and steady-state fuel-air ratio (0.008 to 0.030). Test results were obtained in terms of fuel performance (i.e., combustion gas temperature, pattern factors, thermal conversion efficiency, and residence time requirements) and exhaust gas emission levels of unburnt hydrocarbons, carbon monoxide, carbon dioxide, nitrogen oxides, and soot.

Test results demonstrate that for the range of conditions investigated high combustion efficiencies, over 99 percent, are attainable for all of the fuels. The EDS fuels, however, produced oxides of nitrogen concentrations at least 20 percent above gasoline levels. In addition, the EDS fuels because of their poorer thermal stability tended to pyrolize during operation; soot buildup near the injector sometimes blocked fuel nozzle passages. Experiments are being extended to higher inlet air temperatures.



Rig for testing alternative fuels

Bibliography

Cohen, J.D.: Analytical Fuel Property Effects—Small Combustors (Phase 1). (R82AEB078, General Electric Co.; NASA Contract NAS3-22829). NASA CR-168138, 1983

Lewis contact, R. James Rollbuhler ((216) 433-3391)
Headquarters program office, OAST

Design Codes for Ceramic Mixed-Flow Turbines

The specific fuel consumption (sfc) of small gas turbine engines can be significantly reduced by simultaneously raising the turbine inlet temperature (with no loss in turbine aerodynamic performance) and eliminating the turbine coolant flows. A ceramic (no coolant) mixed-flow turbine offers the potential of meeting these conflicting requirements.

Much work has been done to develop better ceramic material properties and structural design methods. At present, however, a conventional radial turbine designed to ceramic material stress limits must operate at less than optimum blade speed. In theory the resulting performance reduction can be avoided by backsweeping the rotor blades, but this increases the blade bending stresses and shortens turbine life. A backswept blade for a mixed-flow turbine can be designed without the increased blade bending stresses, but little technology and few design procedures exist for this type of turbine.

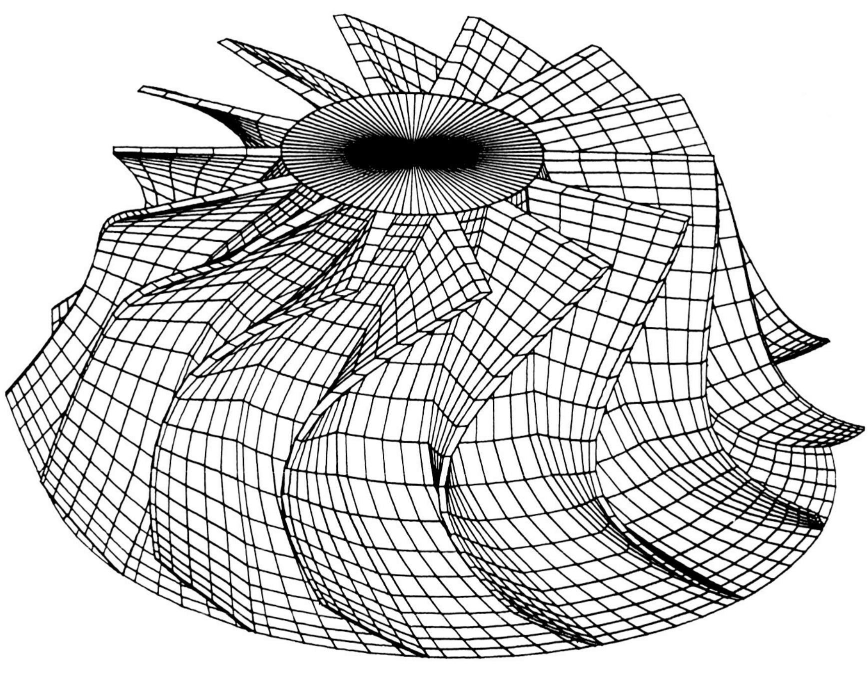
Lewis has developed a new aerodynamic design procedure applicable to mixed-flow machines in-house, completed a design study, and selected an optimum aerodynamic design. An advanced structural analysis code for predicting the probability of fast fracture failure in monolithic ceramic components was developed concurrently by the Analex Corporation under the guidance of Lewis engineers. The code combines finite-element structural analysis (NASTRAN) with Weibull statistical and failure criteria from fracture mechanics. The new code was applied for the first time to a mixed-flow rotor, giving Lewis the in-house capability of analyzing and designing ceramic components. We have completed the aerodynamic and structural analyses of the mixed-flow turbine. The results indicate high efficiency and a 0.994 probability of survival for the latest rotor design. Future work will focus on verifying the design results.

Bibliography

Civinskas, K.C.: Aerodynamic Design Analysis of a Mixed-Flow, High Specific Work Turbine. AIAA Paper 85-1275, July 1985.

Gyekenyesi, J.P.: SCARE: A Postprocessor Program to MSC/NASTRAN for Reliability Analysis of Structural Ceramic Components. J. Eng. Gas Turbines Power, vol. 108, no. 3, July 1986, pp. 540-546.

Lewis contact, Richard J. Roelke ((216) 433-3403)
Headquarters program office, OAST



Structural analysis of mixed-flow rotor

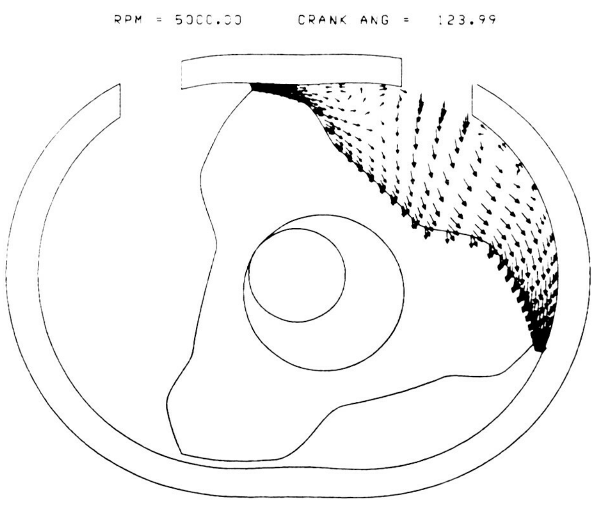
Rotary Combustion Engines

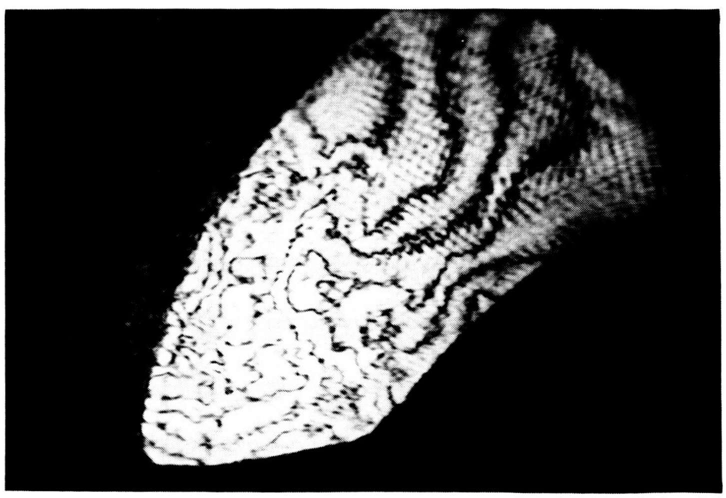
Previous studies and preliminary experiments have shown that the rotary combustion engine is a viable and highly attractive candidate for a light aircraft propulsion system. To obtain high specific power and good fuel economy, Lewis is working to understand the detailed physics occurring in the combustion chamber of this engine. Two efforts in particular have as their objective a description of the in-chamber fluid motion.

We have completed a numerical simulation of the fluid flow in a motored two-dimensional Wankel engine geometry. The governing equations were the density-weighted, ensemble-averaged conservation equations of mass, species, *x*-momentum, *y*-momentum, and total energy that are valid for unsteady, compressible flow of a viscous and conducting ideal-gas mixture. A closed solution of these equations was obtained by employing a variation of the k–ϵ model of turbulence. This turbulence model can account for some of the effects of compressibility, streamline curvature, low Reynolds number, and preferential stress dissipation.

Concurrently we used holographic interferometry to examine the flow structure in a motored rotary engine test assembly. Examination of large- and small-scale flow structures was made possible by viewing refraction-induced fringe activity. Further analysis of the flow field using laser velocimetry as well is now under way.

Lewis contact, Dr. Harold J. Schock, Jr. ((216) 433-6382)
Headquarters program office, OAST





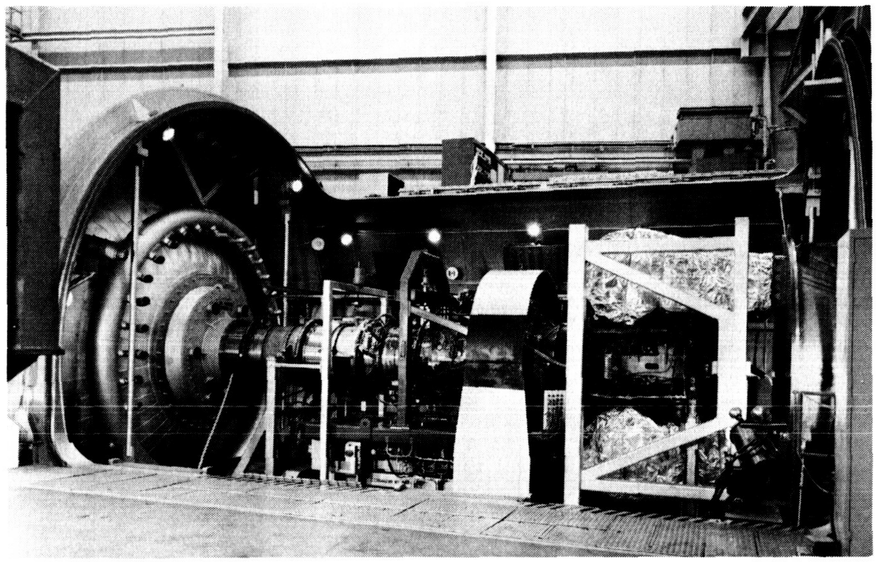
Numerical simulation of fluid flow in Wankel engine

Interferogram of motored rotary engine test assembly

Aeropropulsion Facilities and Experiments

Thrust-Reverser Tests in an Altitude Facility

The requirements for greater operational capability of the next generation of military aircraft will dictate the use of advanced multifunction engine exhaust nozzle systems. Two-dimensional exhaust nozzles with thrust-vectoring and thrust-reversing capability integrated with the engine and aircraft control systems will enhance aircraft performance by improving maneuverability during tactical operations.



Advanced nozzle with exhaust-gas collection system

To measure nozzle performance, to demonstrate nozzle operability, and to determine the feasibility of altitude testing an advanced exhaust nozzle system capable of thrust vectoring and reversing, a two-dimensional, convergent-divergent exhaust nozzle designed by Pratt & Whitney Aircraft was installed on a PW1128 turbofan engine in the Lewis Propulsion Systems Laboratory. A facility exhaust-gas collection system designed at Lewis specifically for thrust-reverser operation in an altitude facility performed successfully during the tests. Tests were conducted at several flight conditions including various altitudes over a range of flight Mach numbers. At each condition thrust vectoring and thrust reversing were demonstrated at several engine power settings ranging from idle to maximum nonafterburning power. Thrust vector angles ranged from 0° to 20°, and reverse thrust was varied from 0 to 100 percent. In addition, thrust vectoring was demonstrated during reverser operation, as was transient nozzle operation between full-forward and full-reverse thrust. The success of these tests has demonstrated the feasibility of testing full-scale advanced exhaust nozzle concepts that feature thrust reversing and vectoring in altitude test facilities.

Lewis contact, Charles M. Mehalic ((216) 433-5704)
Headquarters program office, OAST

Acoustically treated section of 9- by 15-Foot Low-Speed Wind Tunnel

Wind Tunnel Acoustical Treatment for Propeller Noise Testing

Future commercial air transports will be designed to have good fuel economy along with low overall operational costs. But it is also necessary to meet specified noise requirements both internal and external to the aircraft. Although final noise levels must be determined with the aircraft, certain measurements can be made during wind tunnel testing to predict the noise levels for the actual hardware. For propellers to be acoustically tested in the wind tunnel the tunnel walls must have no or minimal sound reflections.

Through a Lewis experimental program a new wall treatment was designed for acoustically testing propellers. The treatment consists of metal boxes 13.5 inches deep filled with layers of Kevlar sheets. The Kevlar layers act as an acoustic high-pass filter in absorbing sound. The acoustic impedance was designed to have a low-frequency rolloff of 250 Hz. For this design the resistance was close to 1.0 and the reactance was nearly zero. These values are equivalent to those of air. With this treatment sound is absorbed almost uniformly with frequency down to the low-frequency rolloff.

Bibliography

Dahl, M.S.; and Rice, E.J.: Measured Acoustic Properties of Variable and Low Density Bulk Absorbers. NASA TM-87065, 1985.

Lewis contact, George H. Neiner
((216) 433-5661)
Headquarters program office, OAST

Aerospace Technology

Materials

IR–100
PS200—A New Wide-Temperature-Spectrum Solid Lubricant Coating

Advanced designs of adiabatic diesel, Stirling, and gas turbine engines all require high-temperature lubricants. In many cases the temperature and chemical reactivity of the atmosphere are too extreme for oils or greases to be used, and solid lubricants must be considered. Conventional solid lubricants such as molybdenum disulfide and graphite are useful to 350 to 500 °C. For higher temperatures novel solid lubricants must be used. In a Lewis research program to develop high-temperature lubricants a plasma-sprayed composite coating called PS200 was developed. PS200 is lubricative in chemically reactive atmospheres such as air or hydrogen from room temperature to 900 °C. The coating composition consists of hard, wear-resistant chromium carbide with additions of barium fluoride–calcium fluoride eutectic and silver. The additives act synergistically to reduce the friction and abrasivity of the carbide while retaining its excellent wear resistance.

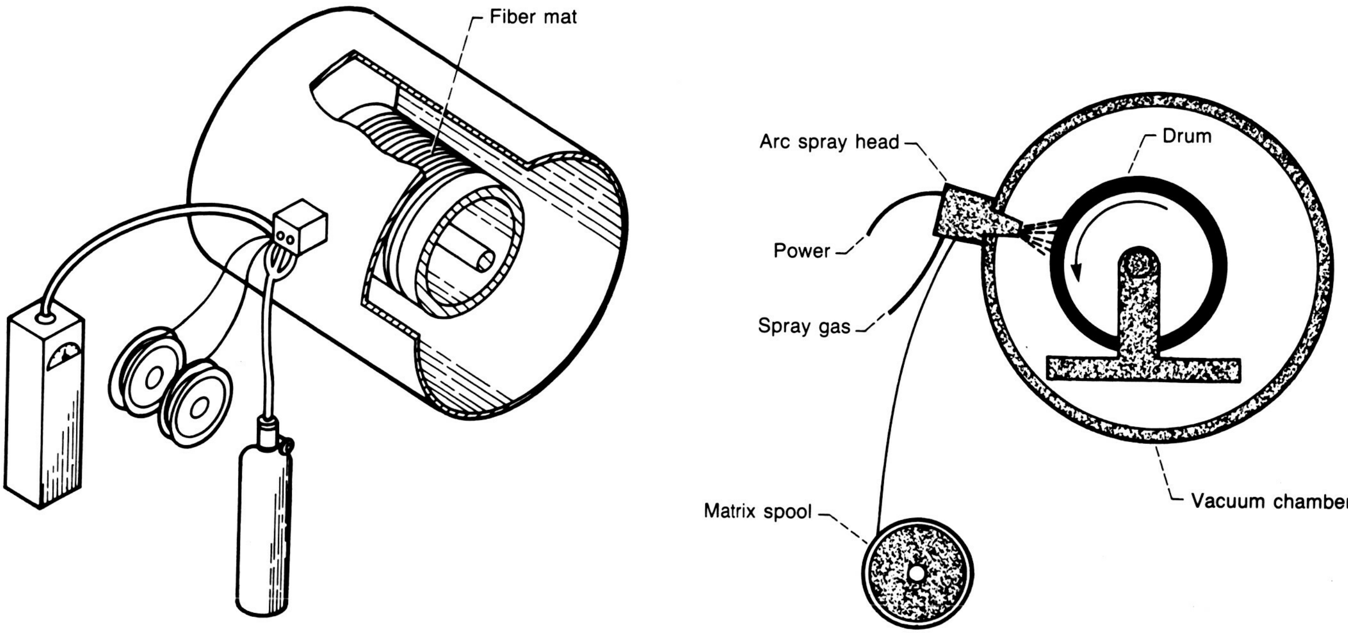
Research & Development magazine has selected the PS200 lubricant for an IR–100 award as one of the 100 most significant technical developments of 1986.

Lewis contact, Harold E. Sliney
((216) 433–6055)
Headquarters program office, OAST

Gas bearing journal coated with PS200 and finished by diamond grinding

IR–100
Processing of Metal-Matrix Composite Monotapes

A critical barrier to the acceptance of metal-matrix composites for commercial application has been lack of a reliable, cost-effective method for preparing monotapes for later consolidation into composite components. A method invented at Lewis, called the arc spray mono-



Overall view

Schematic of operation

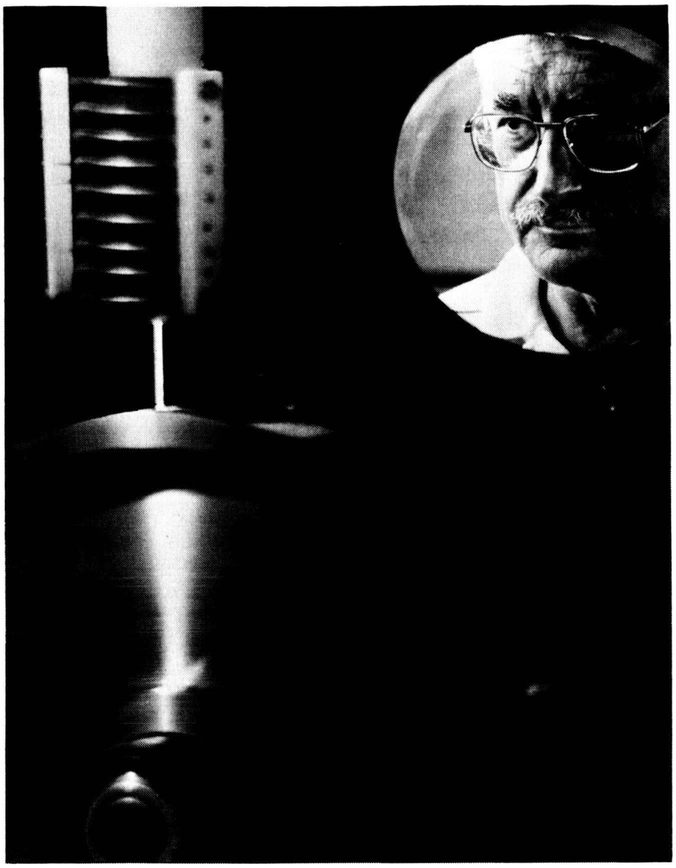
Arc spray monotape fabrication apparatus

tape technique, allows processing of high-purity, low-cost monotapes that can be consolidated by hot pressing or by hot isostatic pressing into sheet and tube forms for final component fabrication.

In the arc spray monotape technique the desired reinforcing fibers are wound on a drum. The wound drum is then placed in an evacuated chamber. Two spools of wire of the desired matrix composition are fed into an arc spray gun mounted on the vacuum chamber. As an electric arc is struck between the two wires, melting the matrix material, high-pressure argon fed into the gun sprays the molten metal onto the fibers, where it solidifies. The monotape thus produced is separated from the drum and cut into desired shapes for component fabrication. Monotapes have been produced that were 1½ ft wide and 4 ft long, but the limiting size is that of the drum and vacuum chamber. Both metallic and ceramic fibers have been used in this process to strengthen matrices of copper, stainless steels, superalloys, and refractory metals.

The arc spray monotape technique has been transferred to industry, with two companies having the technique in operation. This invention (U.S. Patent 4,518,625) was selected as the Lewis 1985 Invention of the Year. The inventor received a 1986 Federal Laboratory Consortium Special Award for Excellence in Technology Transfer. Research & Development magazine has selected the arc spray technique for an IR-100 award as one of the 100 most significant technical developments of 1986.

Lewis contact, Leonard J. Westfall
((216) 433–5526)
Headquarters program office, OAST



Rapid solidification processing: a molten stream becomes a ribbon of metal

Rapid Solidification Processing

Rapid solidification processing in various forms has been of interest for a number of years. A unique facility that uses the melt-spinning rapid solidification process is now operational at Lewis. Although this facility was designed and built to conduct in-house research, cooperative, publishable investigations with researchers in academia, industry, and other Government agencies will be considered to maximize the value of this investment.

A major feature of the melt-spinning process is the rapid quenching of alloys or intermetallic compounds from the liquid to the solid state at cooling rates on the order of 1 million (10^6) deg C/sec. Such rapid solidification radically affects the physical and metallurgical nature of materials: grain size is greatly reduced, segregation of alloying elements or impurities is minimized, and homogeneity is greatly improved as compared with conventional casting. These microstructural changes can result in physical and mechanical properties much different from those normally found in alloys quenched at more conventional rates.

Preliminary research has resulted in copper alloys with fivefold increases in the solid-solution alloying content of chromium and resultant fourfold increases in room-temperature strength. Such alloys demonstrate great potential for long-life, high-conductivity applications in rockets, shuttles, and orbital transfer vehicles.

Bibliography

Jech, R.W., et al.: Rapid Solidification via Melt Spinning: Equipment and Techniques. J. Metals, vol. 36, no. 4, Apr. 1984, pp. 41–45.

Lewis contact, Thomas K. Glasgow
((216) 433-5011)
Headquarters program office, OAST

Tungsten-Fiber-Reinforced Niobium Composites

Current space power system designs specify niobium-base alloys for heat pipes and power conversion system components, but these alloys have limited strength for more advanced, higher operating temperature systems. Materials with greater strength and better creep resistance are needed for long-term (7 to 10 yr) service. Metal-matrix composites have the potential to meet these needs.

Tungsten-fiber-reinforced niobium monotapes were prepared at Lewis by the arc spray technique and hot pressed into sheets. Tensile tests on specimens machined from the sheet material showed the tungsten-niobium composites to be 5 to 11 times stronger than unreinforced niobium at temperatures up to 2200 °F. Since weight saving is a key factor for space power systems, the strength-weight ratio of a material is an important consideration. Tests showed the strength-weight ratios of these composites to be 3 to 8 times higher than those of unreinforced niobium and 2 to 3.5 times higher than that of Nb–1Zr, the niobium alloy selected for initial space power systems.

Research is continuing to optimize processing conditions and matrix composition, to determine long-term (10 000 hr) creep properties, and to measure fiber-matrix interaction rates.

Bibliography

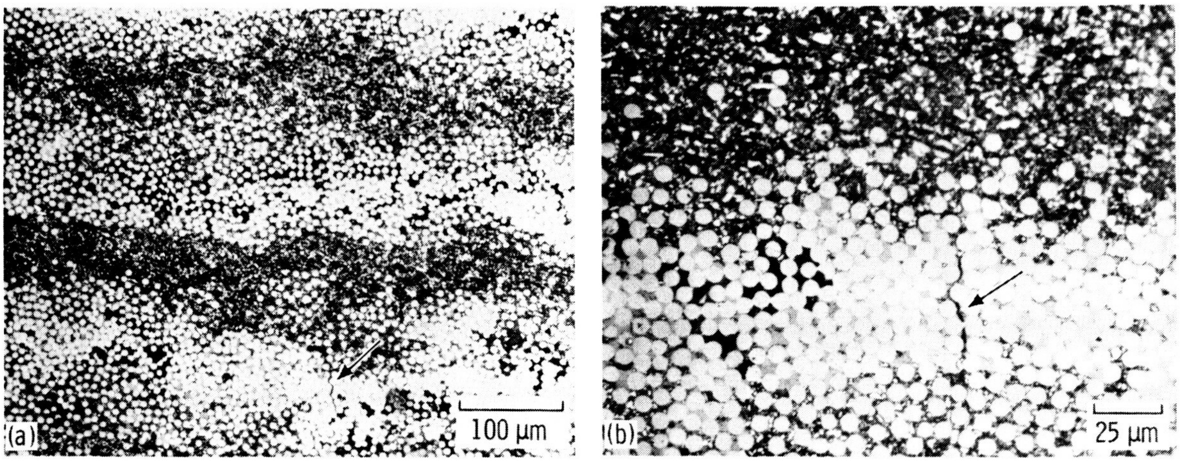
Westfall, L.J., et al.: Preliminary Feasibility Studies of Tungsten/Niobium Composites for Advanced Space Power Systems Applications. NASA TM–87248, 1986.

Lewis contact, Donald W. Petrasek ((216) 433–5528)
Headquarters program office, OAST

High-Temperature Ceramic Composites from Polymer Precursors

Fiber reinforcement of a ceramic matrix offers the potential for a high-temperature material with decreased flaw sensitivity and hence greater reliability than generally is observed for monolithic ceramics. But fabrication of a reinforced ceramic requires low temperatures so that the fiber and the fiber-matrix interface are not degraded during processing.

Using polymeric precursors to a ceramic matrix allows low-temperature processing and



High-temperature graphite–poly(arylacetylene)–silicon carbide composite. (a) Layering of fiber- and particulate-rich regions. (b) Some penetration of particles into fiber tows. Arrows indicate single matrix crack.

control of rheology in the infiltration of fiber tows or preforms. The composite can be formed by methods analogous to those used in fabricating resin-matrix composites and then pyrolyzed to yield a ceramic char. Polymers containing silicon, carbon, and nitrogen can be converted to ceramics stable to 1200 to 1300 °C. To eliminate the need for repeated impregnation and pyrolysis cycles, the polymer must exhibit a high char yield, minimal dimensional shrinkage or cracking on pyrolysis, and a low melt viscosity for ease of fiber infiltration. Ceramic powders can be incorporated to minimize shrinkage and to control thermal expansion.

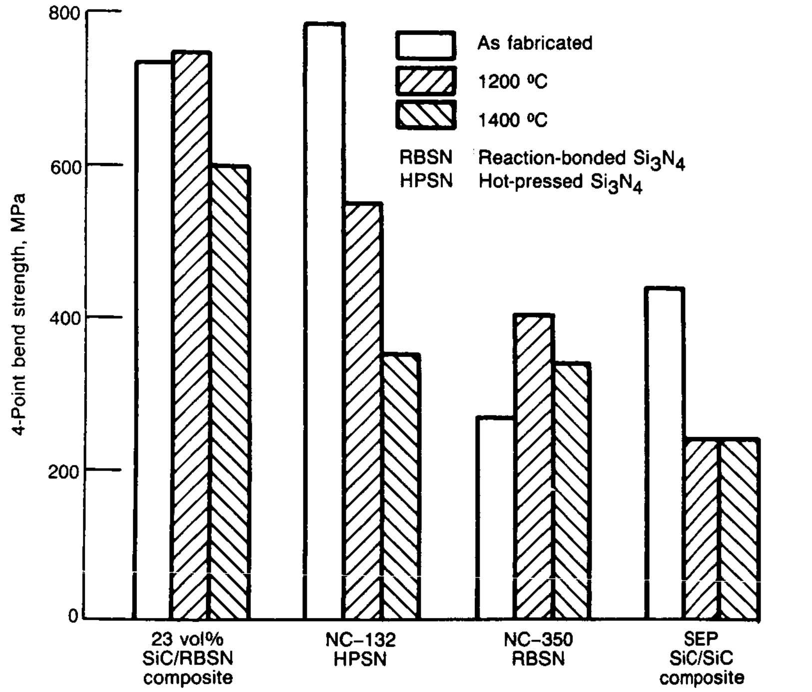
Composites fabricated at Lewis from aromatic ethynyls, continuous carbon fibers, and silicon carbide powder had char yields greater than 94 percent to 850 °C and less than 3 percent linear shrinkage on pyrolysis. Matrix pores were smaller than 1 μm. Matrix cracking in unidirectional layups was minimal, and thus only a single impregnation cycle was required. After pyrolysis at 600 °C the composites were thermally stable to 1450 °C in nitrogen.

Unidirectional composites exhibited brittle fracture when tested in tension, failing at stresses of nominally 30 ksi and strains of 0.18 percent. Fracture occurred primarily at the fiber-matrix interface. Incorporating a particulate filler made it difficult to obtain a uniform distribution of fibers and particles within the composite. This difficulty was obviated by the use of shorter tows and submicrometer particles and by the incorporation of fibers with noncircular cross sections to diminish close packing.

Bibliography

Hurwitz, F.I.: A Ceramic Matrix Composite Based on Polymerization and Pyrolysis of Ethynylated Aromatics. Advancing Technology in Materials and Processes, SAMPE, 1985, pp. 1375–1386.

Lewis contact, Frances I. Hurwitz
((216) 433-5503)
Headquarters program office, OAST



Elevated-temperature bend strength for silicon carbide composites

Stability of Fiber-Reinforced Ceramic Composites at 1400 °C

In its pursuit of structurally reliable ceramics Lewis has developed a fiber-reinforced ceramic composite that is not only stronger and tougher than the unreinforced monolithic ceramic but also capable of maintaining these properties to temperatures as high as 1400 °C.

The composite, SiC/RBSN, consists of a reaction-bonded silicon nitride matrix reinforced by thermally and mechanically stable silicon carbide fibers produced by chemical vapor deposition at AVCO Specialty Materials. These fibers have high strength, high modulus, high creep resistance, and a surface coating suitable for imparting toughness to the SiC/RBSN composite. After 100 hours in air at 1400 °C the composite showed no significant loss in strength from the as-fabricated condition, always displaying metal-like noncatastrophic failure. In air at 1200 and 1400 °C the SiC/RBSN composite displayed better bend strengths than commercially available RBSN, hot-pressed silicon nitride, and a silicon carbide composite fabricated at Societé Europiène de Propulsion (SEP) in France. The improved toughness coupled with excellent thermal stability and high-temperature strength makes the SiC/RBSN composite a potential material for advanced aerospace applications.

Bibliography

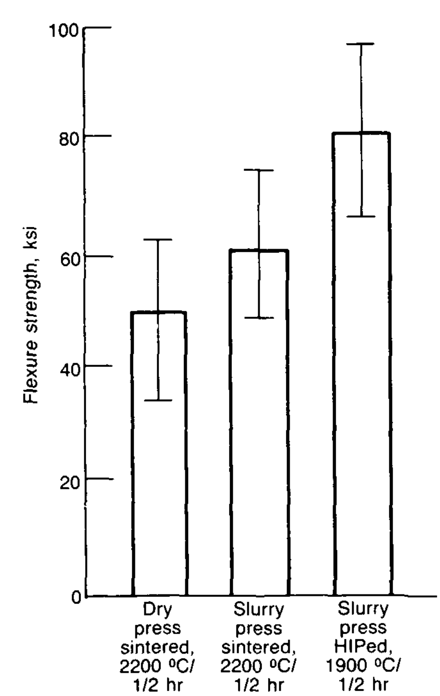
Bhatt, R.T.: Mechanical Properties of SiC Fiber-Reinforced Reaction-Bonded Si_3N_4 Composites. NASA TM-87085, 1985.

Lewis contact, Ramakrishna T. Bhatt ((216) 433-5513)
Headquarters program office, OAST

High-Strength and Ultra-Fine-Grained Silicon Carbide for Advanced Heat Engines

Silicon carbide is of great interest for structural use in heat and automobile engines. This ceramic offers outstanding high-temperature creep resistance and strength because it can be sintered at high temperature without liquid-phase sintering additives. However, large grains produced at these temperatures can act as strength-limiting flaws. Lewis has developed a processing method for hot isostatic pressing of silicon carbide to produce high-density, ultra-fine-grained, high-strength monolithic bodies. A silicon carbide preform is wrapped with a graphite foil (Grafoil) coated with boron nitride, encapsulated in tantalum, and hot isostatically pressed. Using this technique, we achieved a final density greater than 96 percent of theoretical at 1900 °C, much lower than the 2150 to 2200 °C required for pressureless sintering.

The resulting material exhibited an ultra-fine-grained microstructure, with grain size varying from 0.2 to 3 μm, as compared with 1 to 30 μm for the sintered material. It also had significantly higher flexure strength (four-point bending), 86 to 95 ksi as compared with 50 to 60 ksi for the sintered material. Strengths as high as 108 ksi have been achieved for this material. Its improved strength combined with its superior oxidation and creep resistance offers an excellent potential for high-temperature structural applications.



Room-temperature flexure strength of sintered silicon carbide

Bibliography

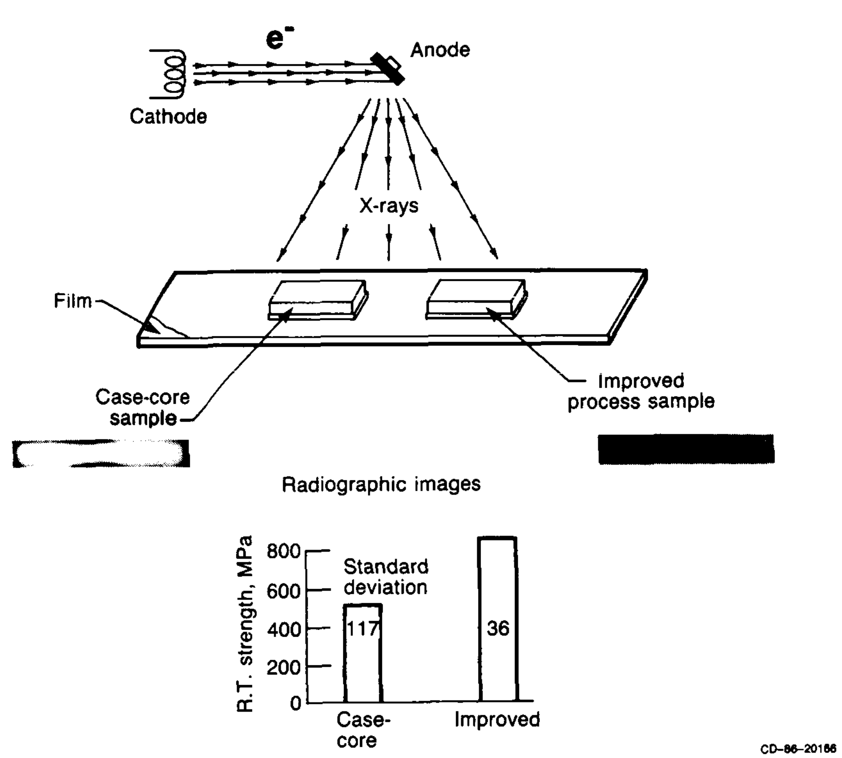
Dutta, S.: Strength Optimization of α-SiC by Improving Processing. Structural Ceramics Workshop, NASA CP-2427, 1986, pp. 89-98.

Lewis contact, Dr. Sunil Dutta
((216) 433-3282)
Headquarters program office, OAST

Radiographically Guided Optimization of Silicon Nitride Processing

Silicon nitride is a prime candidate for heat engine applications because of its resistance to oxidation and thermal shock and its room- and elevated-temperature strength. However, scatter in its mechanical properties is a great drawback from a design and reliability standpoint. This scatter is attributed to defects and inhomogeneities occurring during processing of Si_3N_4 powder compositions or during fabrication of silicon nitride parts. Lewis recently identified density gradients in sintered silicon nitride, characterized by x-radiography. These gradients appeared to depend strongly on powder processing and sintering conditions. On the basis of this preliminary work Lewis then systematically investigated how processing affects the relation between density gradient and flexural strength.

Conventional x-radiography was used to characterize structural uniformity as affected by systematic changes in powder processing and high-pressure nitrogen sintering parameters. A sintered Si_3N_4 composition containing approximately 6 wt% each of Y_2O_3 and SiO_2, designated NASA 6Y, was improved over baseline material of the same composition. Radiographically revealed dense-case, less-dense-core structure was eliminated by a combination of using wet sieving powders, extending powder grinding and sintering times, minimizing boron nitride setter contact, and adjusting the sintering height in the furnace.



Improvement in silicon nitride by radiographically guided processing

The resulting material had four-point flexural strengths of 857, 544, and 462 MPa at room temperature, 1200 °C, and 1370 °C, respectively—improvements of 56, 38, and 21 percent over baseline NASA 6Y properties. Improved material uniformity and reliability were demonstrated by a threefold reduction in the standard deviation and a fourfold increase in the Weibull modulus at room temperature. Accompanying the improvement in strength was a change in the type of flaw causing failure to a less strength-limiting columnar β-Si_3N_4 grain.

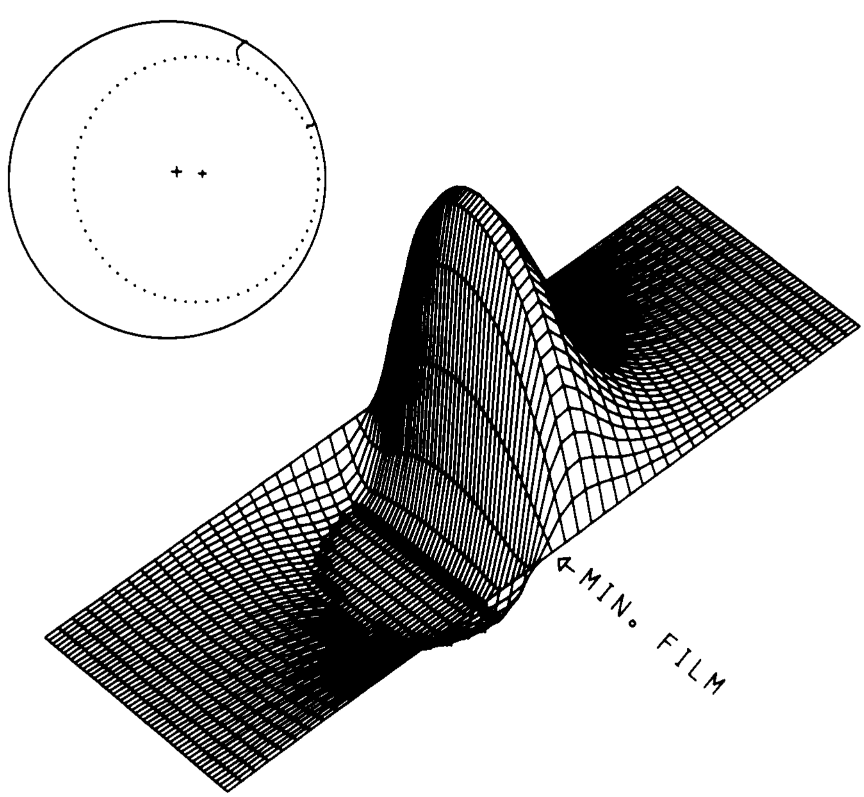
Bibliography

Sanders, W.A.; and Baaklini, G.Y.: Correlation of Processing and Sintering Variables with Strength and Radiography of Silicon Nitride. NASA TM-87251, 1986.

Lewis contacts, William A. Sanders ((216) 433-3297) and George Y. Baaklini ((216) 433-6016)
Headquarters program office, OAST

Theoretical Modeling of Cavitation in Dynamically Loaded Journal Bearings

The trend toward higher speed, higher power density rotating machinery has mandated steady advances in both rolling-element and fluid-film bearing technology. Higher operating speeds have aggravated problems associated with vibrations due to critical speeds, unbalance, and stability. A critical element in the design and selection of antiwhirl bearings for high-speed systems is the ability to predict the instability threshold speed, or the onset of potentially dangerous subsynchronous vibration frequencies. To predict this speed, one needs to determine the hydrodynamic force components coupled to the dynamical equations of motion. Calculation of the hydrodynamic force components depends on the film model used and how cavitation is handled for the fluid-film bearing or damper. Many of the film models used to generate stability maps involve overly restrictive theories and treat cavitation superficially. Unforeseen vibration problems may thus occur. Lewis sought to provide a transient code that would account for cavitation more realistically under dynamic loading and help preclude serious vibration problems in high-speed rotating machinery.



Pressure distribution and bearing configuration at beginning of separation

A vastly improved numerical approach to handling the boundary conditions at the liquid-vapor interface (cavitation boundary) has been demonstrated under dynamic conditions. This unique approach should greatly improve the predictability of the hydrodynamic force components necessary to determining the instability threshold speed.

This work also introduces a new numerical technique for implementing Cauchy (mixed) boundary conditions on a moving boundary. This technique has never been demonstrated in a moving boundary problem, but it should have a wide-ranging applicability to problems involving moving interfaces such as those encountered in phase changes (melting, solidification, and vaporization) or sudden density changes (shock waves).

Computer graphics was used to summarize the results of the dynamic behavior in the form of a color graphic motion picture. This method of presentation allows the viewer to see the actual motion of the shaft within the bearing housing while simultaneously observing the effect of this motion on the pressures and resulting cavitation within the fluid film.

This ongoing in-house program is being continually upgraded. Thermal effects on the fluid and deformation effects on the bearing housing are being included in the code. Closely controlled experiments are being run to compare with predictions made by the numerical analysis.

Bibliography

Brewe, D.E.: Theoretical Modeling of Vapor Cavitation in Dynamically Loaded Journal Bearings, ASME Paper 85-TRIB-51, Oct. 1985.

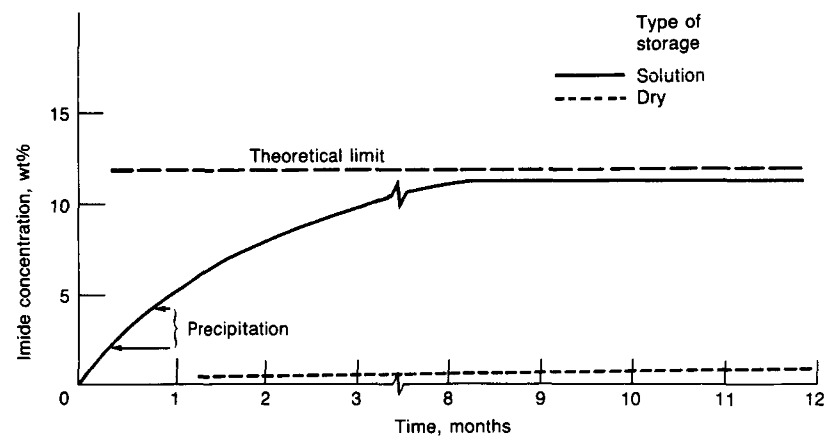
Brewe, D.E.; Hamrock, B.J.; and Jacobson, B.O.: Theoretical and Experimental Comparison of Vapor Cavitation in Dynamically Loaded Journal Bearings. NASA TM-87121, 1986.

Lewis contact, David E. Brewe
((216) 433-6067)
Headquarters program office, OAST

Dry Solids for Longer Shelf Life of PMR-15 Resins

Lewis developed PMR-15 polyimides in response to the need for processable, high-temperature-resistant matrix resins for fiber-reinforced advanced composites. PMR-15 resins are commercially available from a number of suppliers and are used in a variety of aerospace, aeronautical, and commercial applications.

In manufacturing PMR-15 resins resin solutions are prepared by dissolving monomer reactants in a low-boiling-point alcoholic solvent. The monomer solutions are then applied to a reinforcement, and the bulk of the solvent is removed to form "prepreg" materials, which are then cured at elevated temperature and pressure in an autoclave or press to form composite parts. Before curing,



Formation of insoluble imides during storage of PMR-15 resin at room temperature

the composition of the resin is continuously changing due to monomer reactions that occur during storage. The degree and type of these reactions depend on the storage conditions and the solvent content of the resin. Resin compositional changes include the formation of soluble higher esters, which severely affect composite processability and properties, and insoluble imides, which precipitate from solution. Although prepreg materials containing low solvent levels (3 to 5 wt %) may be stored at low temperature (0 to 40 °F) for extended periods (6 months or longer) before resin compositional changes affect composite processing and quality, the shelf life of solutions stored at room temperature (75 °F) is limited to 20 days before reacted materials precipitate.

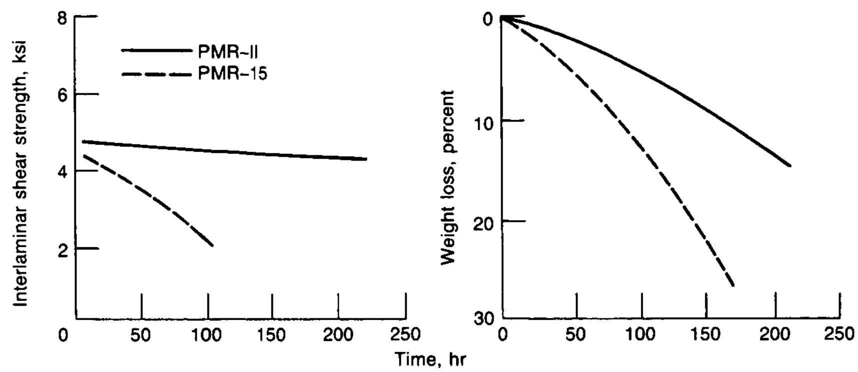
Lewis recently developed a simple procedure for significantly extending the room-temperature shelf life of PMR-15 polyimide resin material. Monomer reactions are quenched by vacuum drying PMR-15 resin solutions at 70 to 90 °F immediately after they have been prepared. The absence of solvent eliminates the formation of higher esters and reduces imide formation to a negligible level. The fully formulated dry PMR-15 resin powder material can be readily dissolved in the solvent at room temperature just before use. Graphite-reinforced PMR-15 composites prepared from dried resin reactant compositions stored at room temperature for 4 and 11 months had processing and mechanical properties identical to those of composites prepared from fresh PMR-15 solutions.

This innovation will result in less waste and added savings for manufacturers of PMR products. It eliminates the need for refrigerated handling during shipping and storage and the need to handle and store volatile solutions for long times. Current in-house studies will establish the effect of storage time on the long-term thermomechanical properties of composites prepared from stored dry reactants.

Bibliography

Roberts, G.D., and Vannucci, R.D.: Effect of Solution Concentration and Aging Conditions on PMR-15 Resin. SAMPE J., vol. 22, no. 2, Mar.-Apr. 1986, pp. 24–28, 213.

Lewis contact, Raymond D. Vannucci ((216) 433-202)
Headquarters program office, OAST



Properties of graphite fiber–PMR resin composites after exposure to air at 700 °F and 60 psia

PMR Polyimides for Improved Performance at 700 °F

Engine studies have shown that advanced designs will require higher thrust-weight ratios. These can be achieved by improving engine performance through the use of high-strength lightweight composite materials. Existing metallic materials do not offer the lightweight characteristics required.

PMR-15 polyimides, developed at Lewis, are used in a number of composite engine components, but their use is limited to those sections of the engine that operate at 500 to 550 °F. Although these applications have resulted in significant cost and weight benefits, further benefits can be realized by applying composites to the hotter sections of turbine engines. Thus Lewis is developing matrix resins for use to 700 °F.

A recently identified PMR-II polyimide composition performed significantly better than the current PMR-15 composition at 700 °F.

Using PMR methodology we prepared unreinforced resins from various monomer reactants and screened them for thermo-oxidative stability at 700 °F under both ambient and 60-psia air pressure. The resin system exhibiting the best overall balance of processability and 700 °F properties was then used to prepare graphite-fiber-reinforced composites. PMR-II composites exhibited significantly less weight loss and negligible drop in shear strength beyond 200 hours of 700 °F exposure, as compared with the rapid drop in weight and shear strength of the PMR-15 composite after shorter exposures.

The improved PMR-II resin may meet the requirements for short-term composite applications in hotter engine sections. Lewis is working to develop 700 °F resin systems for long-term use.

Lewis contact, Raymond D. Vannucci ((216) 433-3202)
Headquarters program office, OAST

PMR–T Matrix for Tougher Composites

Under Navy and NASA sponsorship the General Electric Co. recently completed the development of a graphite–PMR polyimide air bypass duct to replace the titanium duct currently used on the F-404 engine, which powers the Navy's F-18 fighter. Other components currently under consideration for composite applications are engine inlet guide vanes, first- and second-stage stators, and anti-icing leading-edge wing panels.

A major concern in these applications is the material's resistance to low-velocity impact damage. Low-velocity impact can result in hidden internal damage in composite structures. Although the damage may not at first degrade the structural integrity of the component, load reversals from vibrations induced during flight may cause the damage to grow until structural failure occurs. This type of damage (which can result from dropped tools, runway debris, etc.) can occur in both the air-frame structures and the engine. With the broadening interest in improving engine performance with composites, the need for a tougher, more damage-tolerant PMR polyimide material is obvious.

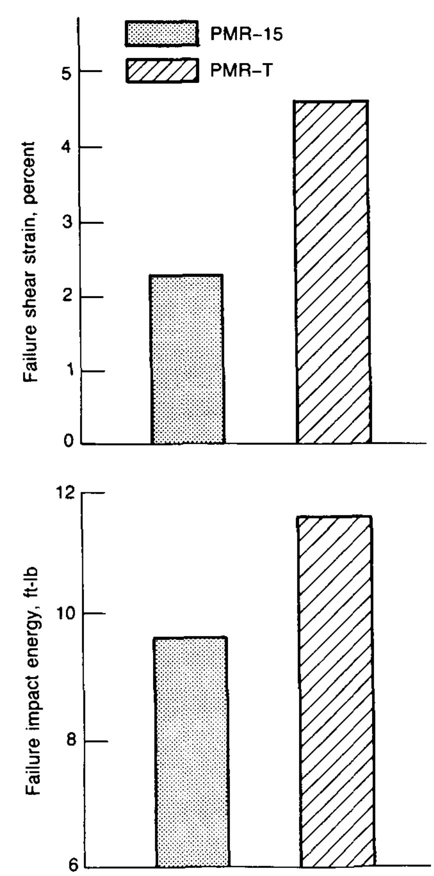
Lewis has identified PMR resins, called PMR-T, with significantly better composite shear strain and low-velocity impact properties. The best overall balance of composite toughness, retention of mechanical properties at 600 °F, and processability was obtained by replacing 20 mole % of the diamine used in PMR-15 resins with a diamine containing twice the number of flexible phenyl connecting groups. The PMR-T composites had 85 percent higher shear strain to failure and absorbed 25 percent more energy during low-velocity impact than PMR-15 composites. Although the PMR-T composite's glass transition temperature was approximately 50 deg F lower, only a minimal difference in 600 °F flexural strength was observed after 1500-hour exposure to air at 600 °F.

The improved ductility offered by PMR-T resins provides composite materials with better low-velocity impact resistance without sacrificing PMR processability or long-term 600 °F mechanical properties. Lewis is working to develop composite systems that improve toughness without lowering the composite's glass transition temperature.

Bibliography

Vannucci, R.D.; and Bowles, K.J.: Graphite/PMR Polyimide Composites with Improved Toughness. SAMPE Q. vol. 17, no. 2, Jan. 1986, pp. 12–18.

Lewis contact, Raymond D. Vannucci ((216) 433-3202)
Headquarters program office, OAST



Composite properties affecting toughness

Intercalated Graphite Fiber-Epoxy Composites

Graphite fiber–epoxy composites are being considered for use in large space structures because of their light weight, high strength, and high moduli. The usefulness of these composites can be expanded by intercalating graphite fibers to make them electrically conductive. Intercalation, the insertion of guest atoms or molecules between the graphite planes, improves the electrical conductivity of certain high-modulus graphite fibers. For example, the electrical conductivity of Union Carbide pitch-based P-100 graphite fibers is improved by a factor of 5 after treatment with bromine. The intercalated P-100 fibers have a conductivity comparable to that of stainless steel.

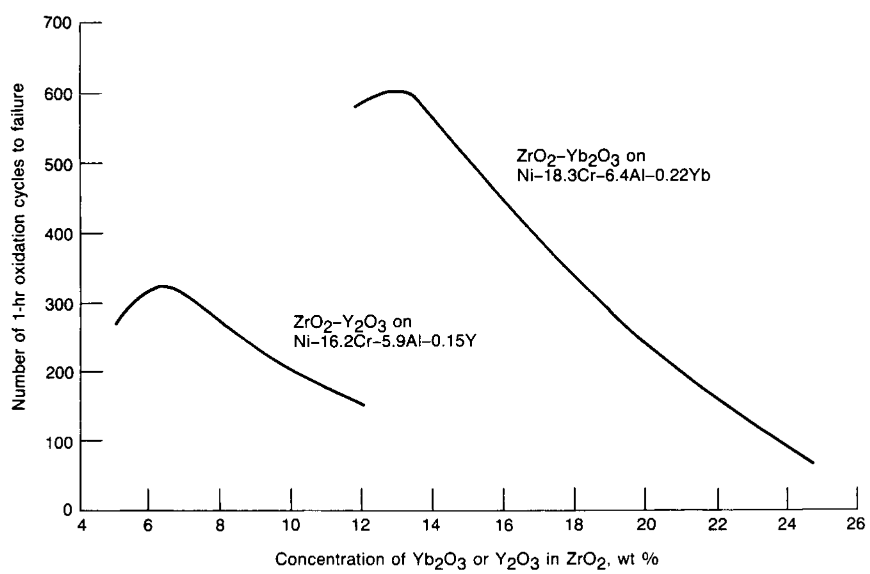
Bromine-intercalated graphite fibers have been studied thoroughly at Lewis, and their improved electrical conductivity has been remarkably stable under a number of environmental conditions, such as vacuum, 100-percent humidity at 60 °C, and temperatures to 200 °C. Furthermore bromine-intercalated graphite fiber–epoxy composites have tensile strengths and tensile moduli that are similar to those of pristine composites and interlaminar shear strength that is 18 percent greater. Hence electrical conductivity can be improved without compromising the mechanical properties of the composite material.

Several applications of intercalated graphite fibers are being explored. Cofunctional composite space structures, where the fibers serve as both a structural reinforcement and an electrical ground, may be made from intercalated graphite fibers. Composite aircraft surfaces may be protected from lightning strikes by adding a layer of conductive fibers. Chopped fibers added to thermoplastic matrices may yield injection-molded equipment with electromagnetic interference shielding. The conductivity of these fibers may also be tailored to provide aircraft deicing.

Lewis contact, Bruce A. Banks
((216) 433-2308)
Headquarters program office, OAST

IR-100 Improved Performance of Thermal Barrier Coatings

Thermal barrier coating (TBC) systems provide a means of insulating heat engine components from hot working gases. The insulation effect of current TBC's typically results in an equilibrium temperature difference across the coating of 100 to 300 deg F. The coating system consists of a ceramic coat on top of a metallic bond coat applied to the metallic component to be protected. The failure of TBC's is governed primarily by bond-coat oxidation, the capability of the ceramic coat to accommodate thermal strains, and the degree to which in-service conditions alter strain tolerance. Understanding these life-limiting factors and the phenomena that control them has led to the development of improved TBC's. New ceramic and bond-coat compositions developed in an on-going, in-house program at Lewis have longer lives than state-of-the-art compositions. Bill-of-materiel TBC systems are presently based on coating compositions containing yttrium. When ytterbium is substituted for the yttrium in these coatings, as much as an 80 percent improvement in life is realized for optimum compositions. Understanding the role played by such rare earth oxide additions is the subject of ongoing investigation at Lewis.



Performance of ytterbium and yttrium thermal barrier coatings at 1120 °C

Research & Development magazine has selected the improved TBC to receive an IR-100 award as one of the 100 most significant technical developments of 1986. Two patents have been awarded for the ytterbium compositions of the bond and ceramic coats.

Bibliography

Stecura, S.: Advanced Thermal Barrier System Bond Coatings for Use on Ni-, Co-, and Fe-Base Alloy Substrates. NASA TM-87062, 1985.

Lewis contact, Dr. Stephan Stecura
((216) 433-3263)

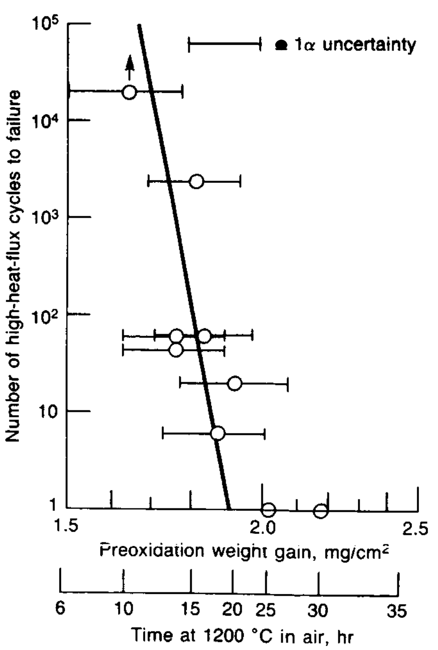
Headquarters program office, OAST

Response of Thermal Barrier Coatings to High Heat Flux

As part of an on-going in-house program at Lewis directed at elucidating the failure mechanisms of thermal barrier coatings, a series of experiments to examine the high-heat-flux behavior of a state-of-the-art thermal barrier coating were recently completed. The test specimens consisted of a 0.13-mm-thick NiCoCrAlY bond coat that had been low-pressure plasma sprayed on a superalloy substrate. The bond coat was then overlayed with an air-plasma-sprayed ceramic, 0.25-mm-thick $ZrO_2-7\%Y_2O_3$. Before high-heat-flux exposure the 1.3-cm-diameter specimens were preoxidized for various times isothermally at 1200 °C. The high-heat-flux test consisted of repeated 0.5-sec exposures to a 4000 °C plasma flame. This exposure produced a very large calculated temperature gradient of 800 deg C across the ceramic layer.

The relation between weight gain and preoxidation time was determined in independent measurements. For weight gains above about 2.0 mg/cm^2, or 25 hours of preoxidation at 1200 °C, the preoxidation was sufficient to fail the coating. For weight gains below about 1.6 mg/cm^2, or 10 hours of preoxidation at 1200 °C, no failures were observed even after as many as 20 000 high-heat-flux cyclic exposures.

This study has shown that state-of-the-art thermal barrier coatings are resistant to high heat flux. Furthermore the results confirm the existence of a critical oxidation weight gain above which the coating will fail in a single high-heat-flux cycle. The effects of time at temperature, especially bond-coat oxidation, are thus established as a major mode of coating degradation.



Effect of preoxidation time at temperature and specific weight gain on cycles to failure of a thermal barrier coating in a high-heat-flux plasma

Bibliography

Miller, R.A.: Oxidation-Based Model for Thermal Barrier Coating Life. J. Am. Ceram. Soc., vol. 67, no. 8, Aug. 1984, pp. 517–521.

Miller, R.A.; and Berndt, C.C.: Performance of Thermal Barrier Coatings in High Heat Flux Environments. Thin Solid Films, vol. 119, 1984, pp. 195–202.

Lewis contact, Robert A. Miller
((216) 433-3298)
Headquarters program office, OAST

Hot Corrosion of Ceramics

In high-temperature applications such as gas turbine engines and heat exchangers sodium and sulfur impurities can deposit as molten salts and create serious high-temperature corrosion problems. These problems have been well documented for metal components. Recent Lewis work, however, has demonstrated that silicon carbide and silicon nitride ceramics are also quite susceptible to this type of corrosion. Both ceramics corrode by dissolution of the oxide scale in the molten salt. For silicon carbide this leads to severe pitting of the substrate and severe strength degradation. Current work focuses on understanding this pitting phenomenon, which appears to correlate with the release of gas bubbles by the corrosion reactions.

Because most types of silicon nitride contain refractory oxides, the role of these additives in the corrosion process has been explored in detail. Corrosion of yttria-containing silicon nitride depletes yttrium near the surface. For most types of silicon nitride corrosive attack of the substrate occurs in the form of deep grain boundary attack. The effects of these microstructural changes on strength are being assessed. The insights gained from these fundamental studies are leading to some possible strategies for controlling hot corrosion of ceramics.

Bibliography

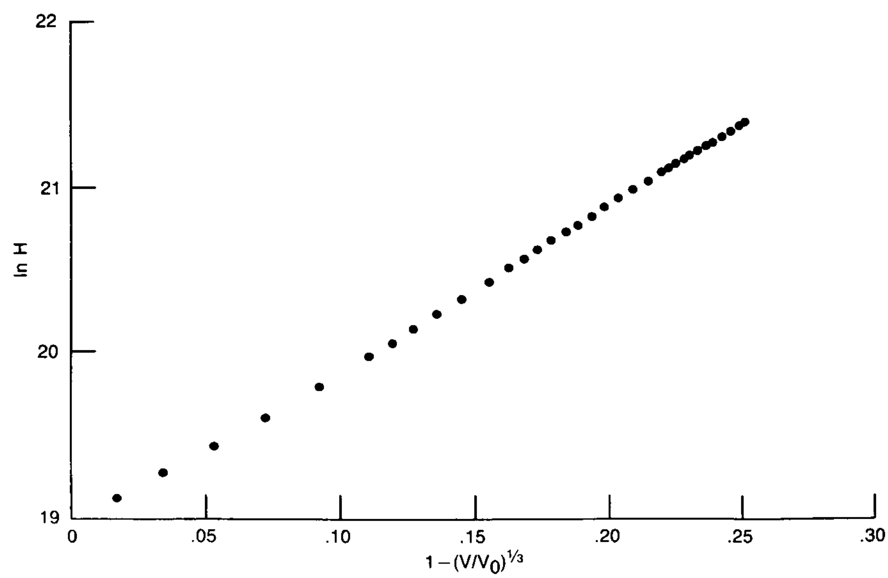
Jacobson, N.S.; and Smialek, J.L.: Hot Corrosion of Sintered α-SiC at 1000 °C. J. Am. Ceram. Soc., vol. 68, no. 8, Aug. 1985, pp. 432–439.

Jacobson, N.S.; Stearns, C.A.; and Smialek, J.L.: Burner Rig Corrosion of SiC at 1000 °C. Adv. Ceram. Mater., vol. 1, no. 2, Apr. 1986, pp. 154–161.

Lewis contacts, Dr. Nathan S. Jacobson ((216) 433-5498) and Dr. James L. Smialek ((216) 433-5500)
Headquarters program office, OAST

Fundamental Properties of Solids and Interfaces

Current theoretical research involves the extension of universality in binding energy relations, the equation of state of solids, and the energetics and electronic properties of defects in solids (e.g., grain boundaries). Progress has been made in discovering a universal



Experimental values of $H(X,T) \equiv \ln [PX^2/3\,(1-X)]$ versus $1-X$ for hydrogen, where P is compressive pressure, $X \equiv (V/V_0)^{1/3}$, V is volume, and V_0 is equilibrium volume per atom. The theory predicts that the data plotted in this form should be linear.

equation of state for Van der Waals, ionic, covalent, and metallically bonded solids. These results have been applied to predict isothermal temperature dependence of the bulk modulus and its derivatives and thermal expansion for all classes of solids. Some preliminary work is being performed in examining phase changes. The grain boundary studies have involved the first quantitive evaluation of volume-dependent terms for metals and a simplified method for determining such terms. A new simplified method for evaluating the energetics of such systems based on universality is under study along with preparations for model calculations.

In examining the reaction kinetics of silicon carbide fiber surfaces experimental techniques have been developed and demonstrated to heat SiC fibers in ultrahigh vacuum, expose them to gases, look at evolved gases, and examine the fiber surfaces.

Lewis contact, Dr. John Ferrante ((216) 433-5835)
Headquarters program office, OAST

Microgravity Materials Science Laboratory

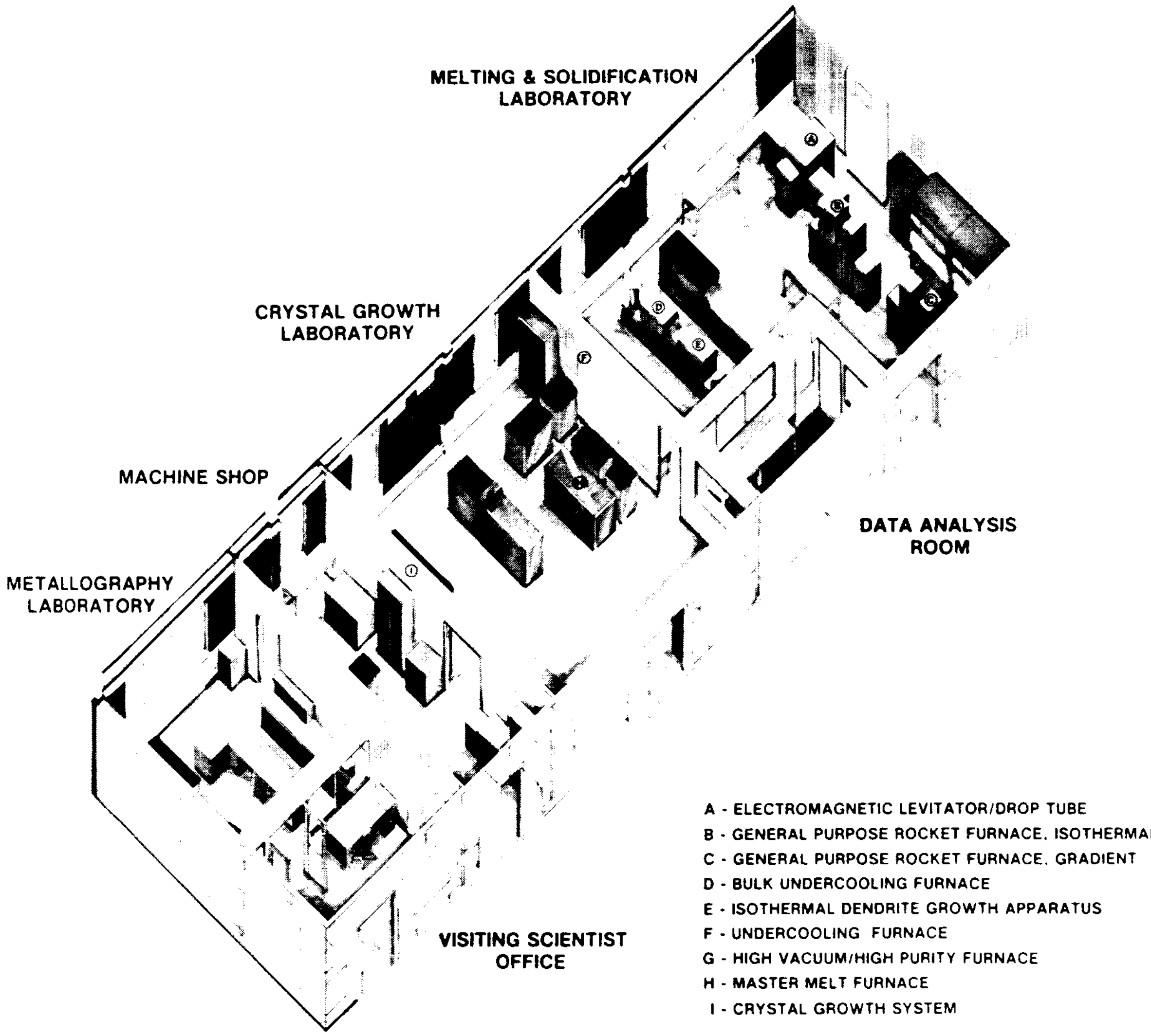
The Lewis Microgravity Materials Science Laboratory (MMSL) offers to industry, university, and Government materials researchers wishing to conduct preflight experiments assistance and easy access to shuttle-like equipment. Experiments are performed by MMSL personnel alone or in cooperation with guest investigators. NASA funds work if it is to be published in a timely manner. If a company requires that the work remain confidential, NASA is reimbursed. The MMSL is appropriate for exploring microgravity science concepts related to materials preparation or processing. Ideas for potential shuttle flights or eventual space station involvement are examined.

Although the MMSL was officially opened in September 1985, only a few materials processing furnaces were then available. More recently equipment for isothermal dendritic growth, solidification in a traveling thermal gradient, electromagnetic levitation, physical vapor transport, and bulk undercooling has become operational. There has been a corresponding growth of interest in using the laboratory. The equipment is used to characterize gravity-driven convection effects and to compare in-crucible versus containerless processing.

There are now 19 users of the laboratory—10 with experiments under way. Two of the current experiments include industrial partners Westinghouse and 3M. The most highly developed experiments are the isothermal dendritic growth and the micro- and macrosegregation efforts, both of which have received approval as flight experiments.

Work continues to ready a magnetically damped high-temperature directional solidification apparatus, an acoustic levitator, and laboratories for ceramics/glass and polymers processing. The laboratory and procedures for its use are described in a Lewis brochure entitled "Microgravity Materials Science Laboratory."

Lewis contact, Leslie Greenbauer-Seng ((216) 433-5013)
Headquarters program offices, OSSA and OCP



Microgravity Materials Science Laboratory

Structures

Unique Micromechanics Equations for High-Temperature Metal-Matrix Composites

The mechanical performance and structural integrity of fiber-reinforced metal-matrix composites are, in general, functions of the behavior of the constituent materials at the micromechanistic level. It is not uncommon for the individual constituent materials to exhibit significantly different behaviors. Moreover, constituent behavior is dynamic, particularly in high-temperature applications. The materials are continuously changing character because of the nonlinearities associated with large local stress excursions, temperature-dependent material properties, time-dependent effects, and constituent chemical reactions.

Available methods for describing and tracking this dynamic constituent behavior at the micromechanistic level are limited. Lewis is thus conducting a comprehensive program to develop novel computational mechanics methodologies for advanced-composite propulsion structures. As one approach we used composite micromechanics theory to derive simplified expressions relating the anisotropic behavior of the basic composite unit (e.g., a unidirectional ply) to the behavior of the individual constituents. We derived a unique set of micromechanics equations for high-temperature metal-matrix composites by using a mechanics-of-materials formulation that assumes a square-array unit cell model with a single fiber, a matrix material, and an interphase. Concurrent with the derivation we performed a preliminary validation study using three-dimensional finite-element analysis to assess the general applicability fo the formulation and to evaluate the accuracy of the equations for a specific composite system. Results of the study demonstrate excellent agreement between micromechanics-predicted equivalent properties and those simulated in the finite-element analysis.

The equations have been implemented as part of an integrated computational capability for the nonlinear analysis of high-temperature multilayered fiber-composite blade structures.

Lewis contact, Dale A. Hopkins ((216) 433-3260)
Headquarters program office, OAST

ICAN: A Versatile Code for Predicting Composite Properties

ICAN (Integrated Composites ANalyzer), a stand-alone computer code developed at Lewis, incorporates micromechanics equations and laminate theory for analyzing and designing multilayered fiber composite structures. In a recent study we established further confidence in the predictive capabilities of ICAN. ICAN predictions and experimental data were compared for composite systems subject to severe thermal environments, for woven composites, and for select new composite systems including those made from high-strain-to-fracture fibers. The comparisons demonstrate the versatility of ICAN as a reliable method for determining composite properties suitable for preliminary design.

The complete documentation of ICAN with a compiled listing, users instructions, a programmers manual, and sample cases for each option will soon be available through the Computer Software Management and Information Center (COSMIC), Suite 112, Barrow Hall, Athens, Georgia 30602.

Lewis contact, Carol A. Ginty
((216) 433-3335)
Headquarters program office, OAST

Predicting Thermomechanical Deformation

Many high-temperature aircraft and rocket engine components experience thermomechanical deformation. Such deformation is often the ultimate cause of structural failure in these components. This problem can be alleviated through improved designs based on better predictions of thermomechanical material behavior. Lewis is working to determine how thermo-mechanical deformation affects material behavior. We then evaluate and incorporate these effects into constitutive models for better prediction capabilities.

A series of "stepwise" nonisothermal tests have been completed on a representative combustor liner material, Hastelloy-X. All indications from these tests suggest that deformation models based exclusively on isothermal data cannot accurately predict thermomechanical material behavior. Presently we are using a computer-controlled test system for in-phase and out-of-phase thermomechanical tests on Hastelloy-X. The results from these tests reveal nonisothermal characteristics and strongly reinforce the inadequacy of isothermal data being used to describe thermomechanical behavior.

Current experimental results are being analyzed in search of trends in material behavior that will lead to improved thermomechanical model predictions. Some trends have been identified, but more experimentation is needed to further define them. Using the data and observations from the program, we are incorporating these trends into models and thus improving their thermomechanical prediction capability.

Lewis contact, Paul A. Bartolotta
((216) 433-3338)
Headquarters program office, OAST

Simplified Inelastic Structural Analysis

To assess the durability of hot-gas-path components in aircraft gas turbine engines and space power propulsion systems, we must be able to accurately calculate the stress-strain response at the critical location for crack initiation. Nonlinear finite-element computer codes are generally too costly in computing time and resources to use in the early design stages of hot-gas-path components. To perform nonlinear analyses more economically, Lewis is developing a simplified inelastic procedure and computer code. This procedure is based on the assumptions that the inelastic region is local and that the total strain history can be defined by a few elastic finite-element analyses. Therefore a very rapid inelastic analysis can be performed by operating only on the critical location rather than on the complete structure. Classical incremental plasticity methods involving the von Mises yield criterion and a bilinear kinematic hardening rule are used to characterize the material cyclic behavior. Creep computations are performed for increments involving dwell times by using a power-law model and a time-hardening rule.

The simplified procedure and more sophisticated finite-element methods were exercised in structural analyses of an air-cooled turbine blade airfoil for a transatlantic flight mission. These analyses were conducted on a Cray X-MP computer using the MARC finite-element computer code. The nonlinear finite-element analyses were performed with the unified constitutive models of Bodner and Walker and with classical creep-plasticity models. The structural analysis methods were compared in terms of calculated total strain ranges, mean stresses, and predicted fatigue lives at the critical location, as well as the computing times for two analytical cycles. The simplified method gave a predicted life comparable to that of the classical inelastic finite-element analysis and much more conservative than the life predictions based on the unified models.

The computing time for the simplified analysis included 81 seconds to perform elastic finite-element analyses for the startup, maximum takeoff, and shutdown conditions and 1 second for the actual simplified procedure. The nonlinear finite-element analyses required over 1 hour of computing time.

Lewis contact, Albert Kaufman
((216) 433-3316)
Headquarters program office, OAST

Computational Simulation of Progressive Fracture in Fiber Composites

Predicting the progressive fracture of composite laminates is fundamental to developing the methodology for quantifying the durability and reliability of composite structures. Lewis is conducting fundamental theoretical and experimental research to develop formal methods and procedures for determining progressive composite fracture. In theoretical research we are developing composite mechanics, combined-stress failure criteria, criteria for identifying predominant fracture modes and associated fracture surfaces, and integrated computer codes for simulating progressive fracture in fiber composites. These studies have led to the development of computational methods for assessing composite structural behavior (integrity, durability, and damage tolerance). In experimental research we are developing methods for real-time ultrasonic C-scan of laminates under load to detect fracture initiation, damage growth, and fracture progression as these events occur as well as methods for postfailure examination of fracture surfaces to identify and catalog unique characteristics of the dominant fracture modes.

Lewis contact, Christos C. Chamis
((216) 433-3252)
Headquarters program office, OAST

Three-Dimensional Inelastic Analysis of Hot-Section Components

Hot-section durability problems appear in a variety of forms, ranging from oxidation and corrosion to erosion and distortion (creep deformations) to fatigue cracking. Even modest changes in shape, from erosion or distortion of airfoils, for example, can lead to measurable performance deterioration that must be accurately predicted during propulsion system design to ensure that long-term efficiency guarantees can be met. Larger distortions introduce serious problems such as hot spots and profile shifts resulting from diversion of cooling air, high vibratory stresses associated with loose turbine blade shrouds, and difficult disassembly or reassembly of mating parts at overhaul. These problems must be considered and efforts made to eliminate them during engine design and development. Initiation and propagation of fatigue cracks represent a direct threat to component structural integrity and must be thoroughly understood and accurately predicted to ensure continued safe and efficient engine operation.

Pratt & Whitney Aircraft, in partnership with United Technologies Research Center, MARC Analysis Corporation, and the State University of New York at Buffalo, under contract to Lewis, is conducting a program to develop three-dimensional inelastic analysis methods. Under this program a series of new computer codes embodying a progression of mathematical models (mechanics of materials, special finite element, and boundary element) were developed for the streamlined analysis of combustor liners, turbine blades, and turbine vanes. These models address the effects of high temperatures and thermal and mechanical loadings on the local (stress, strain) and global (dynamics, buckling) structural behavior of these components. These codes are based on polynomial theory in the sense that stresses, strains, and temperatures in generic modeling regions are polynomial functions of the spatial coordinates and that solution increments for load, temperature, and time are extrapolated linearly from previous information. These codes are referred to as MOMM (Mechanics Of Materials Model), MHOST (MARC-HOST), and BEST (Boundary Element Stress Technology).

Lewis contact, Christos C. Chamis ((216) 433-3252)
Headquarters program office, OAST

Designing for Fiber Composite Structural Durability in Hygrothermomechanical Environments

A major concern in the use of fiber composites has been predicting the structural durability of composite structures in service applications: mechanical load (static, cyclic, and impact), thermal, moisture, and combinations of hygrothermomechanical (HTM) environments. The general procedure for designing fiber composites for HTM environments is to use empirical data to select laminate configurations for the component and to validate them through the preliminary design phase. A variety of tests are conducted in the specified HTM environment. The results of these tests are used to reconfigure the laminates to meet the design requirements. This procedure, though successful, is costly and time consuming and must be repeated for each new design. It can be largely circumvented by a methodology for predicting the structural durability and service life of fiber composites in HTM environments.

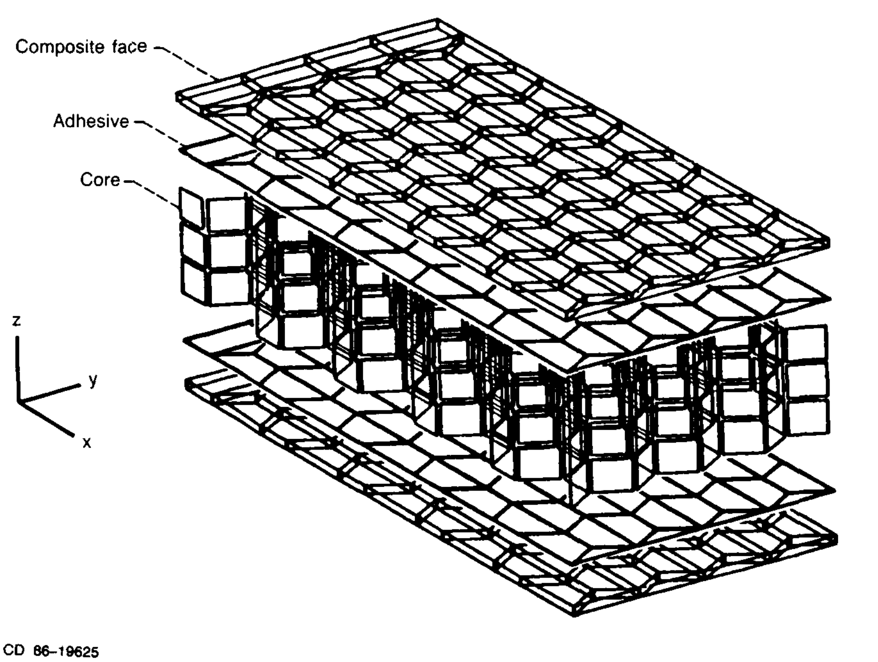
A predictively correct methodology for the HTM effects of stiffness and strength that can be used to design durable structural components was developed at Lewis over the past 7 years. It began with the development of an integrated theory for predicting hygrothermal effects on fiber composites and has culminated in three major computer programs: CODSTRAN (COmposite Durability STRuctural ANalysis), INHYD (INtraply HYbrid composite Design), and ICAN (Integrated Composite ANalyzer). These programs collectively provide the analyses required to design for structural durability.

Lewis contact, Christos C. Chamis ((216) 433-3252)
Headquarters program office, OAST

Computational Simulation of Fiber Composite Sandwich Thermostructural Behavior

Fiber composites are increasingly used in space applications in a variety of configurations. Sandwich structural configurations are an effective application of fiber composites. The faces of the sandwich resist loads by membrane action, the most structurally efficient use of thin fiber composite laminates. In addition, composite sandwich structures can be designed to meet very close thermal distortion tolerances, such as those required for the antennas and reflectors of communications satellites.

Designs to meet close thermal distortion tolerances are developed from detailed thermal properties of the composite sandwich as well as from the effects of temperature and moisture on these properties. Recent analytical studies at Lewis focused on developing computational methods for simulating the thermomechanical behavior of composite sandwich structures. These methods use analyses with several levels of progressive sophistication and simplification in conjunction with composite hygrothermomechanical theory.



Finite-element model of composite sandwich with honeycomb core

The several levels of sophistication include (1) three-dimensional modeling of the honeycomb, the adhesive, and the composite faces; (2) three-dimensional finite-element modeling of the honeycomb (assumed to be an equivalent continuous, homogeneous medium), the adhesive, and the composite faces; (3) laminate theory simulation where the honeycomb (metal or composite) is assumed to consist of plies with equivalent properties; (4) derivations of approximate, simplified equations for thermal and mechanical properties by simulating the honeycomb as an equivalent continuous, homogeneous medium; (5) equations for hygrothermal effects from cryogenic temperatures to 250 °F, with and without moisture present. *All* the honeycomb thermal and mechanical properties must be used to properly simulate the thermomechanical response of the composite sandwich.

Lewis contact, Christos C. Chamis ((216) 433-3252)
Headquarters program office, OAST

Progressive Damage, Fracture Predictions, and Postfailure Correlations for Fiber Composites

Lewis is developing computational mechanics methods for predicting the structural behavior and response of composite structures. In related experimental programs, including postfailure examination, we have studied various factors affecting composite fracture, such as laminate thickness effects, ply configuration, and notch sensitivity.

We use an integrated approach for characterizing the fracture of graphite-epoxy composites. The progressive damage of a stressed composite laminate is observed with the real-time ultrasonic C-scan (RUSCAN) unit. The ultrasonic images of the damage are then compared with the finite-element meshes of the CODSTRAN (COmposite Durability STRuctural ANalysis) code, which predicts the composite damage. In addition, the fractured composite surface is microscopically examined to determine the mode of fracture. These results are also compared with the fracture modes predicted by CODSTRAN.

The successful outcome of this integrated approach has led to an enhancement of the RUSCAN facility, including a dedicated microcomputer, newly designed hardware, specifically tailored software, and color graphics processing. These enhancements significantly advanced the research into the physics of progressive damage in composites. Simultaneously we are modifying the CODSTRAN program to accommodate color graphics software packages for direct comparison of experimental and theoretical results.

Lewis contact, Carol A. Ginty ((216) 433-3335)
Headquarters program office, OAST

Optimization of SSME Turbine Blade Dampers

Before 1975 turbine blade damper designs were based on experience and very simple mathematical models. Failure of the dampers to perform as expected showed the need to gain a better understanding of the physical mechanism of friction dampers. Over the last 10 years friction damper research for propulsion systems has produced methods for optimizing damper designs.

Some first-stage turbine blades on the high-pressure oxygen turbopump of the space shuttle main engine (SSME) have cracked from excessive vibration. One solution is to improve the ability of friction dampers to attenuate the blade vibration amplitudes. In a cooperative effort Lewis and Carnegie-Mellon University applied recently developed friction damper technology to the SSME oxygen turbopump.

Lewis tested four variations of a damper design known as the two-piece damper at a wide range of normal loads and excitation levels. A magnetic excitation system was extremely successful.

Carnegie-Mellon researchers fit mathematical models to the experimental data. They found constant-normal-load models to be inadequate because the geometry of the contacting surfaces results in a normal load that varies during the vibratory cycle. A variable-normal-load model was generated and tested. The final damper performance curves were based on the experimental data and the variable-normal-load model.

Two other damper designs were considered; the x-damper and the tip damper.

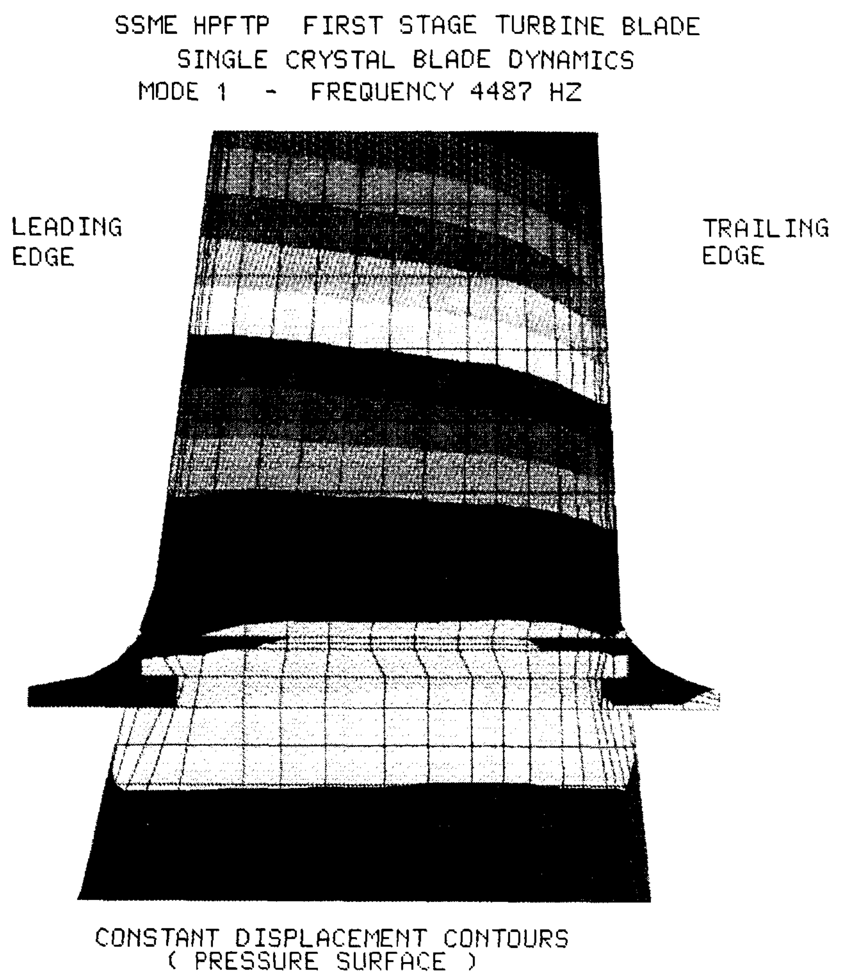
The conclusions of this study are (1) the two-piece damper design performs best with a 0.047-inch thickness, (2) damper performance can be considerably improved by eliminating the variable-normal-load effect, (3) the x-damper is a poor design, (4) the tip damper is an excellent design.

In a follow-on effort we are investigating the variable-normal-load effect, developing an improved two-blade test fixture, and correlating the bench test results with the contractor's rotating tests.

Lewis contact, Robert E. Kielb
((216) 433-6049)
Headquarters program office, OSF

Dynamics of Single-Crystal SSME Turbine Blades

Lewis has developed a casting process that may improve the turbine blades of the space shuttle main engine (SSME). The current casting process, known as directional solidification, results in a blade with a small number of radially oriented crystals. The new process results in a blade composed of a single crystal. Lewis is studying the sensitivity of the blade's structural dynamic characteristics to crystal axis orientation and comparing the predicted responses of the single-crystal blade and the original directionally solidified design.



Dynamic response of single-crystal SSME turbine blade

This in-house research project consisted of both analysis and experiments. A finite-element method was used to build a mathematical model of the single-crystal blade. Five blades of different crystal axis orientations were tested under nonrotating, room-temperature conditions. The dynamic properties were relatively insensitive to crystal axis orientation. Thus material specifications with tight restrictions on crystal axis orientation are not necessary.

The dynamic response of the single-crystal blade was comparable or preferable to that of the directionally solidified blade for all cases studied. The single-crystal blade is predicted to be a valuable replacement for the current SSME turbine blades.

Lewis contact, Larry A. Moss ((216) 433-6033)
Headquarters program office, OSF

Plane Strain Fracture Toughness of a Beryllium-Copper Alloy

The fracture control analysis of the shuttle-Centaur cryogenic valves required knowledge of the fracture toughness of beryllium-copper alloy in liquid hydrogen. Since no published data were available, the plane strain fracture toughness K_{IC} of the beryllium-copper alloy C172 was examined in liquid hydrogen at a Lewis facility renovated for this purpose. The alloy was tested in two forms and conditions: a 1.5-inch-thick plate that was solution annealed and age hardened to the maximum strength (AT condition), and a 2.25-inch round bar that was solution annealed, cold worked, and age hardened also to the maximum strength (HT condition). Both showed considerable increases in tensile properties in liquid hydrogen over room-temperature properties. The K_{IC} values also increased at the liquid-hydrogen temperature (−423 °F). The plate specimens showed larger increases in fracture toughness. The 1.5-inch-thick plate has a reported K_{IC} of approximately 33 ksi $\sqrt{\text{in.}}$ at room temperature, and 37.3 ksi $\sqrt{\text{in.}}$ in liquid hydrogen. The 2.25-inch round bar exhibited K_{IC} values of 33.4 ksi $\sqrt{\text{in.}}$ in the longitudinal direction and 24.3 ksi $\sqrt{\text{in.}}$ in the radial direction in liquid hydrogen.

The tested fracture toughness at -423 °F was used to replace the assumed K_{IC} value in the fracture analysis of the shuttle-Centaur cryogenic valves. Since the specimens taken from the radial direction in the bar sample closely simulate the orientation of the worse-case flaws (cracks), the lower K_{IC} value from the test was used instead of the assumed 30 ksi $\sqrt{\text{in.}}$

Lewis contact, Timothy D. Best
((216) 433-2359)
Headquarters program office, OSF

Correlation of Finite-Element and Experimental Vibration Data

The dynamic characteristics of structural systems are often predicted by finite-element analysis and then verified experimentally with dynamic analysis testing techniques. Greater demands for reliability, minimal vibrations, optimum performance, and low-cost design, among other criteria, require more sophisticated techniques. An important problem is identifying and quantifying the differences between results predicted by a finite-element analysis and results obtained from an experiment. There is considerable uncertainty in the finite-element modeling of boundary conditions, joint flexibilities, and damping. The results are not exact since the input data are approximated, and experimental error cannot be completely eliminated.

Lewis is working to develop and evaluate procedures for correlating finite-element and modal test data. Using simulated data from damped structures, we have identified differences in mass, damping, and stiffness parameters between finite-element analysis and experimental vibration data for viscously damped structures. Since the differences were identified in terms of physical parameters, direct correlations could be made to regions in the finite-element model. The number of measured modes required for producing accurate results was also determined. In 1987 modal synthesis techniques will be combined with identification algorithms so that the properties of structural connections can be determined and the required number of measured modes can be reduced.

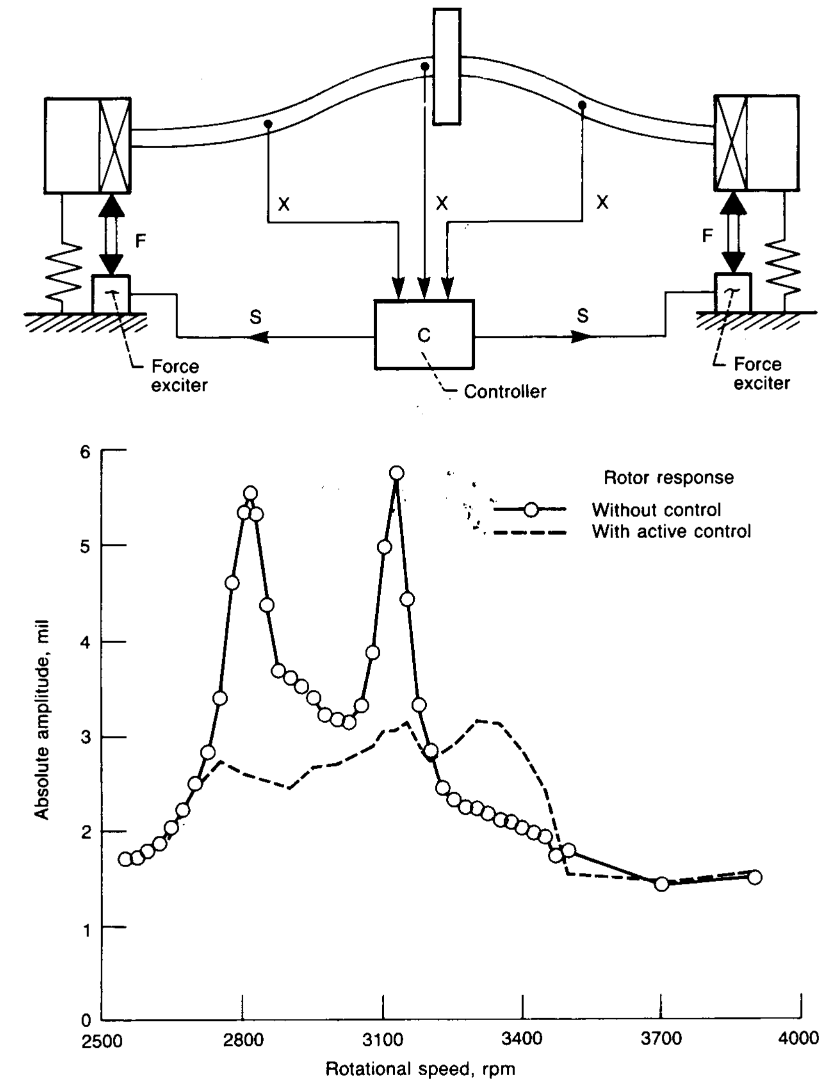
Lewis contact, Charles Lawrence
((216) 433-6048)
Headquarters program office, OAST

Active Rotor Control

Active rotor control is a method for limiting vibrations of flexibly supported rotors by an electronic feedback control system. The feedback control system senses the vibration level of a rotor system and damps the vibrations to within acceptable limits. The rotor can thus operate through and above its critical speeds, the bearings last longer, the rotating shafting can be smaller and lighter, and the rotor generally operates more smoothly.

Although there has been considerable research in active vibration control, relatively little attention has been given to its application to rotating machinery. This unique experimental effort uses the Lewis rotating systems dynamic rig. The significant features of the active rotor control system are the electronic controller and the force exciters. Lateral rotor vibration is sensed at a number of locations and input to the electronic controller. The controller processes the vibration signals and commands the force exciters to provide the desired forces to the rotor supports.

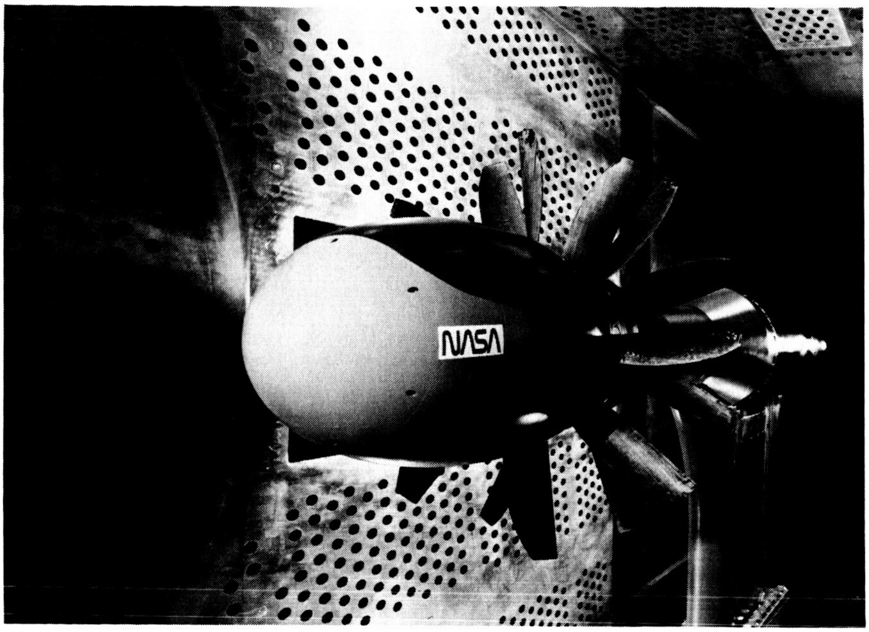
The electronic controller is programmed by entering "feedback coefficients" to provide any desired percentage of damping. The feedback coefficients are calculated by a computer program and are based on a modal analysis of the rotor system.



Active rotor balance system and steady-state unbalance response data

Preliminary experiments at Lewis with the active rotor control system have demonstrated that a high degree of damping is achievable with this system. Future research will involve improvements to the experimental setup and the feedback system.

Lewis contact, Eliseo DiRusso ((216) 433-6027)
Headquarters program office, OAST



Advanced propfan in wind tunnel

Aeromechanical Model Tests of Propfan

The aeromechanical analysis for the design of high-speed propellers, or propfans, is more complex than that for conventional propellers because of the propfan's different blade characteristics and aerodynamic operating conditions. Propfans have six or more swept, thin, low-aspect-ratio blades that operate in subsonic, transonic, and possibly supersonic flows. Therefore Lewis is conducting an experimental research program on the flutter and forced-response characteristics of advanced propfans. This program involves both in-house and contract work with industry. During 1986 flutter and forced-response data were obtained from 2-ft-diameter counterrotation models in NASA and industry wind tunnels. Blade strains and blade deflections were measured during steady-state and vibratory operating conditions. Blade deflection data were obtained with photographic, video, and laser techniques. This research program will be continued with both single- and counterrotation advanced propfan models. The large-scale demonstrator propfans that will be flight tested during 1986 and 1987 were designed by using analyses developed and verified with data from this program.

Lewis contact, Oral Mehmed ((216) 433-6036)
Headquarters program office, OAST

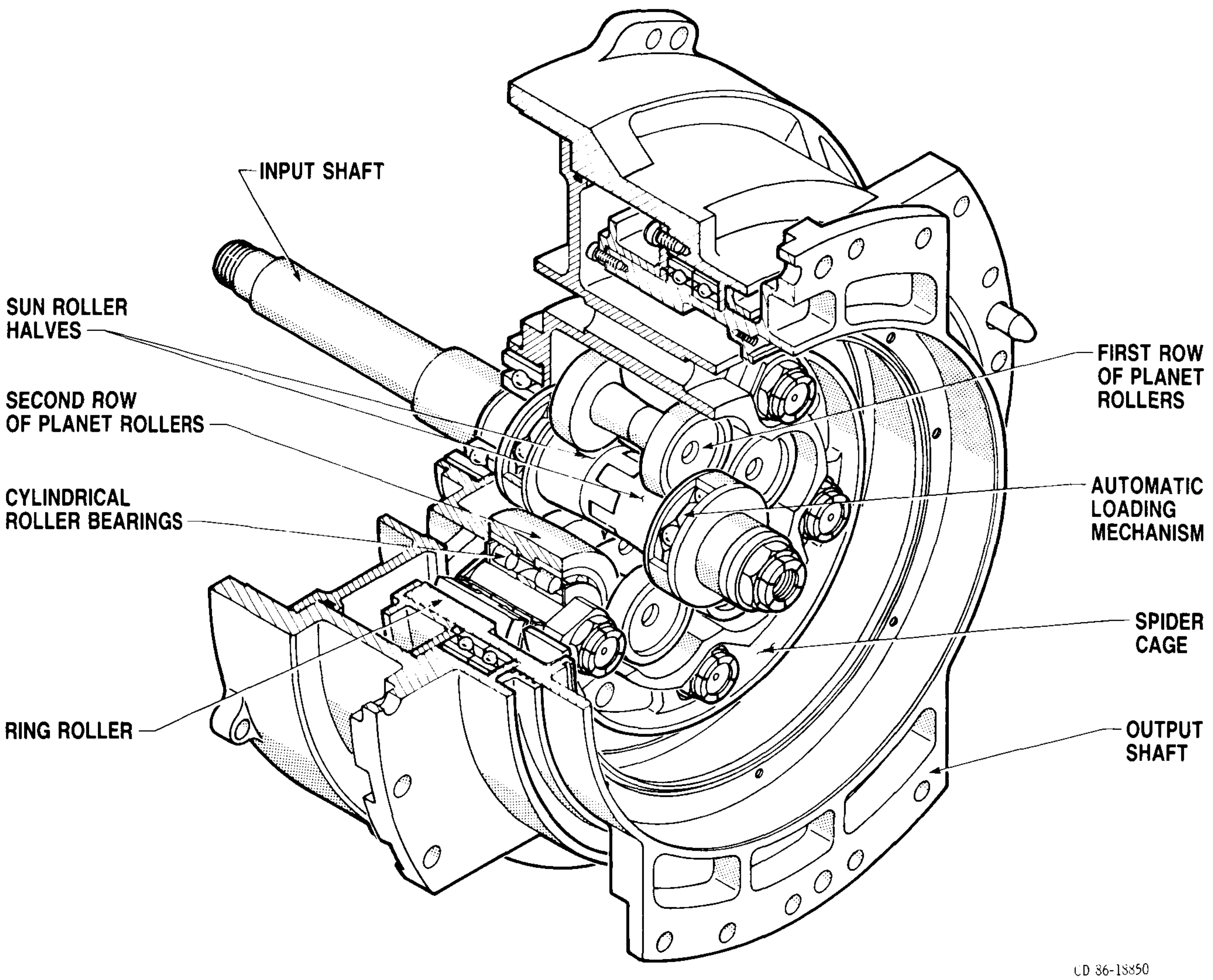
High-Torque Roller Drive Actuator for Satellite Attitude Control

Satellite pointing systems must operate with high accuracy, low vibration, and quick response. These systems generally rely on a gimbaled gyroscope for attitude control about one, two, or three axes. Motion about each axis is typically provided by a high-resolution servomotor driving through a speed reduction unit, accurately positioning the satellite relative to the spinning gyroscope. Lewis decided to investigate the advantages of using a traction roller drive as the speed reduction unit by measuring the roller actuator's zero mechanical backlash, low-torque ripple, and high-torque holding ability.

A series of in-house tests and analyses were conducted with an advanced Nasvytis planetary (16:1 ratio) roller drive. In operation an electronically controlled servomotor drives the actuator's input shaft in either a clockwise or counter-clockwise direction based on attitude control commands from the satellite controller. Torque flows from the input shaft–sun roller combination through two sets of planet rollers and finally to the actuator output shaft, which in turn places the satellite in the desired orientation. Test results confirmed that the drive operates with no mechanical backlash (critical for accurately positioning satellites about a desired setpoint) because the rollers operate in continuous rolling contact (unlike competitive gear drives, where the load transfers from tooth to tooth while passing through the mesh).

Because of the rollers' low sliding nature the drive was designed to operate dry, lubricated only with a thin ion-gold plating on the roller surfaces. This simple lubrication scheme improves the drive's reliability in the vacuum space environment. The drive operated smoothly with minimal torque ripple and actually provided some Coulombic attenuation of input torque oscillations. For high system response rates high system torsional stiffness is important. Analyses and component stiffness measurements showed that rollers can be two to five times stiffer than comparable gear components, although this drive's structural support stiffness must be improved to achieve an overall higher system stiffness.

These and other tests have shown roller actuator technology to be suitable for satellite attitude control systems. The results of this study will also be incorporated into developing a rotary joint for a space-based robot. Manipulator systems envisioned for space experiment laboratories must also operate smoothly so as not to disturb samples being tested in the microgravitational (10^{-6} g) space environment.

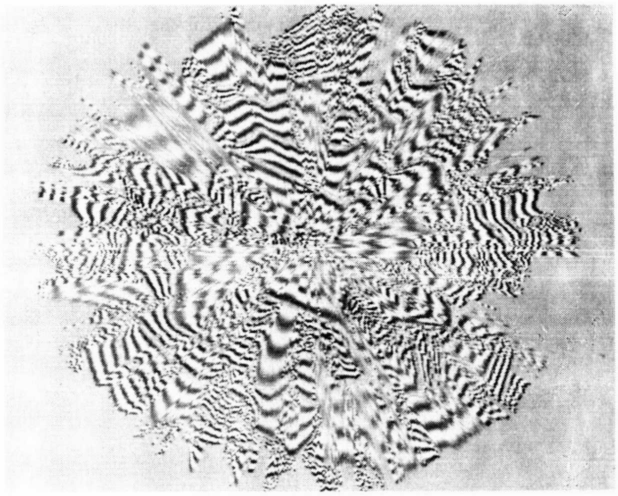


High-torque, backlash-free roller drive actuator for satellite attitude control

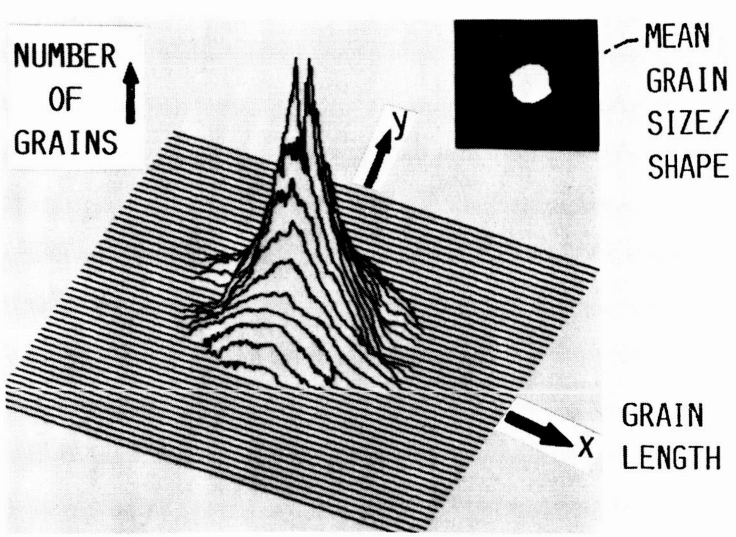
Bibliography

Steinetz, B.M.; Rohn, D.A.; and Anderson, W.J.: Evaluation of a High-Torque Backlash-Free Roller Actuator. NASA CP-2423, 1986, pp. 215-240.

Lewis contact, Bruce M. Steinetz
((216) 433-3302)
Headquarters program office, OAST



Tone-pulse-encoded microstructural image



Grain size distribution

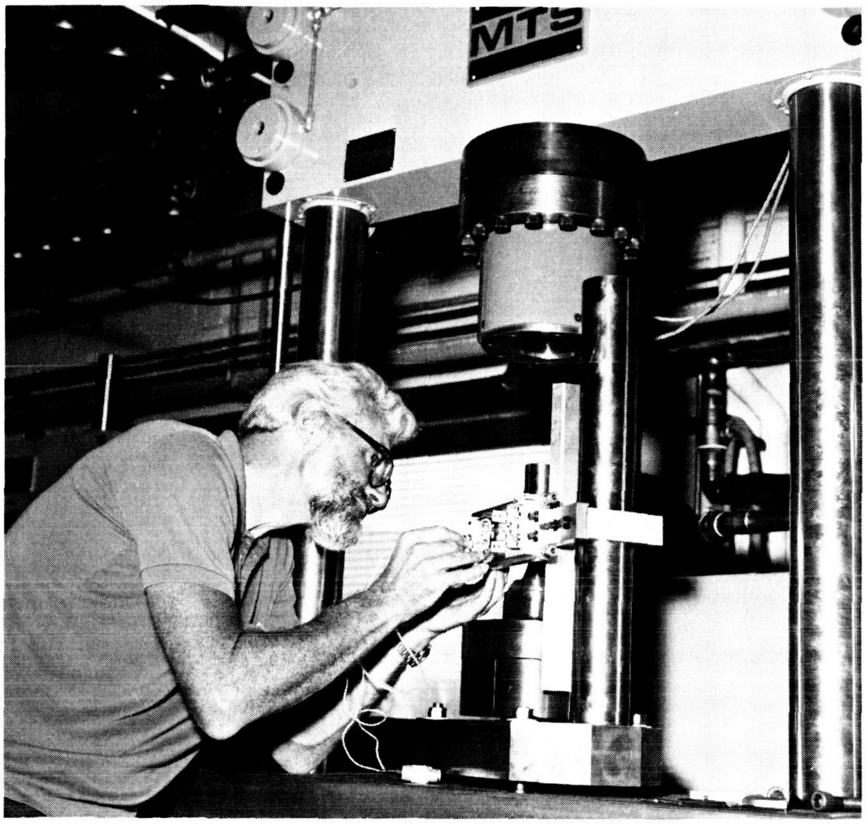
Determination of Grain Size Distribution

Material properties such as tensile strength, hardness, yield stress, fracture stress, and impact resistance are known to be directly related to the grain size distribution. Thus analysis of these properties requires detailed knowledge of the grain size distribution.

Grain topologies are generally so complex that determinations of grain size distributions using current techniques are crude and imprecise. Researchers have resorted to estimating the mean or average grain diameter, which ideally should be determined from the grain size distribution. Recent research at Lewis has shown that the grain size distribution can be obtained by applying two-dimensional Fourier transform theory to tone-pulse-encoded microstructural images of photomicrographs.

These microstructural images are Fourier transformed to yield the density of the frequency components of the encoded image. A theory has been developed that relates the density of the frequency components to the density of the length components. The latter density corresponds directly to the grain size distribution function, from which the mean grain shape, size, and orientation can be obtained. Future work will examine porosity size distributions in ceramics and fiber spacing distributions in composites.

Lewis contact, Dr. Edward R. Generazio
((216) 433-6018)
Headquarters program office, OAST



Multiaxial fatigue testing machine

Multiaxial Fatigue Testing

Multiaxial fatigue testing capability has recently been added to Lewis' high-temperature fatigue and structures laboratory. Significant results have already come from Lewis' multiaxial fatigue research program. Understanding of multiaxial fatigue had not included any concepts for dealing with complex nonproportional multiaxial loading beyond applying simple equivalent stress parameters, which have been found to be inadequate. Recently, as the result of Lewis research, it was found that a wide range of structural materials fall into two broad categories of behavior with regard to crack initiation and growth under complex multiaxial loading. Furthermore these two categories of behavior can be modeled from a life prediction standpoint by using uniaxial fatigue life data as a data base, even for very nonproportional multiaxial fatigue loading. The first category, materials that demonstrate shear plane initiation and propagation, has the correlating parameter

$$\hat{\gamma} + \hat{\epsilon}_n + \frac{\sigma_{no}}{E}$$

where $\hat{\gamma}$ is the maximum shear strain associated with the multiaxial cycle, $\hat{\epsilon}_n$ is the maximum normal strain imposed across the plane during the cycle (zero under pure shear cycling), and σ_{no} is the maximum normal stress imposed across the plane of maximum shear (equal to the shear stress under pure shear). The second category, materials that crack on the maximum principal strain, has the correlating parameter

$$\left.\frac{\Delta\epsilon_1}{2}\sigma_1\right|_{max}$$

where $\Delta\epsilon_1$ is the cyclic principal strain and σ_1 is the associated principal stress.

It is now sufficient to run just a few simple tests on a material to identify its mode of behavior under multiaxial loading. Then its life prediction under very complex loading can be related back to already developed uniaxial data bases.

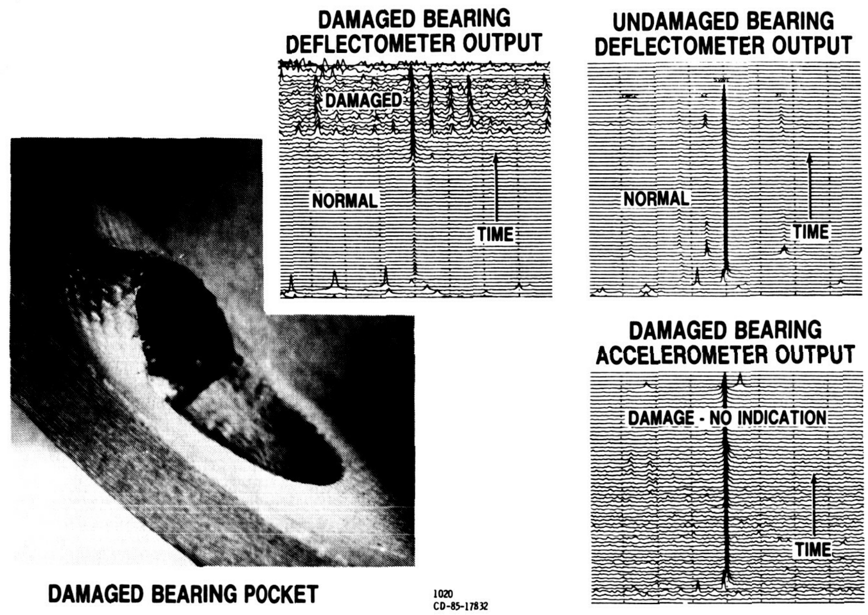
Lewis contact, Dr. Robert C. Bill
((216) 433-3209)
Headquarters program office, OAST

Space Propulsion Technology

Bearing Wear Detection

Presently the condition of turbopump bearings in a reusable rocket engine, such as the space shuttle main engine, is determined by a costly process of disassembly and inspection. Lewis is supporting research to develop monitoring instrumentation for determining the condition of rocket engine components during operation. This instrumentation is to be incorporated into a system that will also predict the remaining useful life of the components.

Lewis has contracted for the construction of a test fixture for evaluating turbopump bearing monitoring by a fiber-optic deflectometer. The key element of the deflectometer is a bundle of optical fibers with its end close to the outside surface of the outer bearing race. Light is transmitted onto the outer race from a fiber bundle, and the light reflected from the race is then transmitted through a fiber cable to a detector. The magnitude of the reflected photoelectric signal is a function of the distance between the race and the sensing element. A nominal bearing will generate a half-sine-wave output for each ball that deflects the race. As bearing condition degrades, each ball generates a complex waveform of harmonics and intermodulated frequencies. The bearing wear is monitored in real time by following the development of this complex waveform on a spectrum analyzer.



Bearing wear detection

During several bearing test runs the output of the deflectometer indicated anomalous bearing behavior. On the basis of this output the tests were stopped to prevent catastrophic bearing failure. Subsequent disassembly of the test fixture confirmed the indicated bearing damage. The standard instrumentation, an accompanying accelerometer monitoring the bearings, did not indicate bearing damage.

It is estimated that the deflectometer indicated a failure 20 minutes before the accelerometer would have done so, or for a space shuttle main engine almost three missions before the bearings would have been replaced.

Lewis contact, Robert M. Masters
((216) 433-2463)
Headquarters program office, OAST

Prediction of Cumulative Fatigue Damage in Materials

Lewis and the Case Western Reserve University are jointly developing a method for accurately predicting the behavior of materials and structures subjected to complex repetitive loadings. It has been recognized for some time that Miner's "classical" linear damage rule results in life predictions that are too optimistic for the material and structural behavior in reusable space propulsion systems.

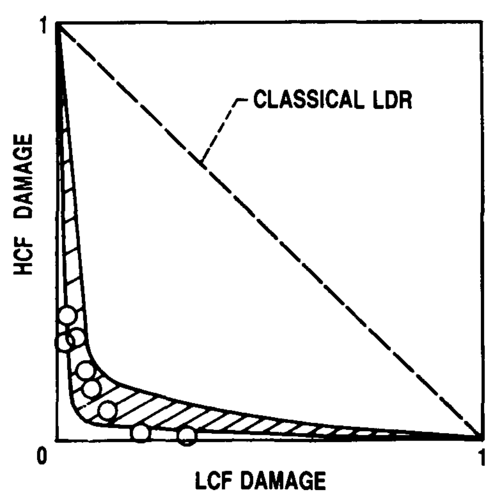
Over the years a number of alternative nonlinear methods have been proposed for more accurate predictions. However, most of these techniques required the evaluation of material constants from extensive cumulative fatigue damage tests. Notable exceptions are the so-called damage curve approach (DCA) and its bilinear equivalent, the double linear damage rule (DLDR), developed at Lewis and introduced in 1980.

The DCA and DLDR have now been reexamined and modified to improve their accuracy and applicability to engineering problems associated with reusable space propulsion systems. The advantageous features of each were incorporated into what is known as the double damage curve approach (DDCA). The newly developed DDCA utilizes the two universalized constants from the DCA and DLDR formulations. Thus no new information is required to perform a cumulative damage fatigue life prediction. However, if specific cumulative damage data are available, they can be incorporated by optimizing the two constants in the DDCA equation.

The curve based on universal constants in the DDCA equation has direct applicability to mission life prediction for the space shuttle main engines (SSME). The approach accurately predicts the observed severe degradation in fatigue resistance experienced by metals subjected to superimposed high-cycle fatigue (HCF) and low-cycle fatigue (LCF). Numerous SSME hot-gas-path components experience HCF/LCF loadings on each mission. Since existing SSME components were built before the development of workable nonlinear cumulative damage life prediction models, component lives were assessed on the basis of the only available model, Miner's unconservative classical linear damage rule (LDR). More accurate life assessments are now possible with the introduction of the nonlinear DDCA model.

The DDCA using specific material constants has been successfully applied to recently obtained interaction results at Lewis for the alloy Haynes 188 at 1400 °F. Haynes 188, a cobalt-base alloy, is the material used for the SSME liquid-oxygen posts in the main injector assembly. The HCF/LCF results were predicted much more accurately by the DDCA than by the unconservative LDR.

Lewis contact, Stanley J. Marsik
((216) 433-2460)
Headquarters program office, OAST



Application of double damage curve approach to Haynes 188

Materials Ignition Sensitivity in Oxygen Environment

Serious consideration is being given to a dual-expander turbine drive cycle for advanced high-pressure, high-performance rocket engines for orbit transfer vehicles. In this cycle both the hydrogen and oxygen propellants regeneratively cool the thrust chamber and are then used as turbine drive gases for their respective propellant turbopumps. This approach offers the advantage of higher chamber pressure operation (more turbine power) and thus higher performance than an expander cycle engine in which only the hydrogen propellant drives both propellant pumps. In any high-speed turbopump mechanical rubbing, as well as impact from debris, can result in metal ignition and burning if proper metals and design are not used.

Lewis is assessing the hazard of material ignition in an oxygen drive turbine. Several materials have been identified that exhibit superior resistance to ignition in an oxygen environment. Still left undetermined, however, were the characteristics of pairs of dissimilar metals rubbing together. We hypothesized that a high-conductivity material could significantly change the ignition sensitivity of a low-burn-resistant material by conducting heat away from the contact area.

A series of tests were conducted to simulate the ignition hazard associated with mechanical rubbing conditions that may be encountered in turbopumps from thermal growth, bearing failure, and rotor imbalance. The ignition sensitivity of a dissimilar pair of materials was about the same as that of the least-burn-resistant material rubbing on itself. Even a high-conductivity material such as copper, which generally could not be ignited when rubbing on itself did not significantly change the ignition sensitivity of the low-burn-resistant material.

Lewis contact, John M. Kazaroff ((216) 433-2473)
Headquarters program office, OAST

Transient Radiative Cooling of a Drop-Filled Layer

The liquid-droplet radiator is a proposed potentially lightweight device for dissipating waste heat in space applications. A moving layer of coolant, consisting of thousands of parallel directed streams of liquid drops, is passed through space to lose energy by transient radiative cooling. The streams of drops then flow into a collecting device so that the working fluid can be reused.

Several analytical studies have examined the radiative characteristics of a layer filled with a large number of drops that emit, absorb, and scatter radiation. The transient energy equation, coupled with the equation of radiative transfer, was solved numerically to yield the emittance of the layer. The transient cooling behavior indicated that, after an initial period, a similarity solution is achieved where the emittance becomes constant with time. This solution was then obtained analytically and was extended to a more general situation where there is a non-uniform velocity distribution across the drop-filled layer. The analytical and numerical work is now being extended to allow for freezing of the liquid drops so that both latent and sensible heat can be used for dissipating energy.

Lewis contact, Dr. Robert Siegel ((216) 433-5831)
Headquarters program office, OAST

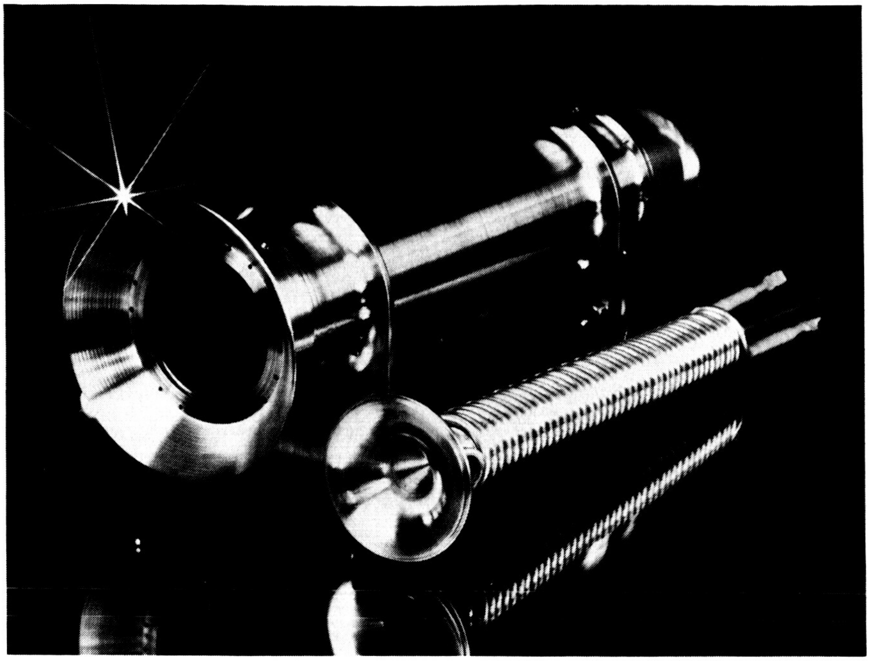
Enhanced Heat Transfer for Rocket Combustors

The thrust chamber of an advanced propulsion system for an orbit transfer vehicle (OTV) serves a dual function. It produces thrust, and it provides most of the energy required to power the propellant turbopumps used to produce the high chamber pressure. Lewis has contracted with Rocketdyne for the analysis, design, fabrication, and testing of an advanced combustion chamber that will increase enthalpy extraction from the combustor of an advanced OTV propulsion system.

A series of tasks were performed to evaluate the effectiveness of adding ribs to the hot-gas wall and fins in the coolant passages. Both hot-air heat transfer and cold-flow fluid boundary layer behavior were tested with the various rib designs. Cold-flow studies were also performed with a velocimeter on the coolant channel fins. The results indicated that the ribs should enhance the thermal pickup by 42 percent and that the fins should decrease the hot-gas-wall operating temperature by 40 deg F.

The most effective ribs and fins will now be designed into a calorimeter test piece that will be added to an actual rocket thrust chamber. This chamber will then be hot fired and the test results compared with the predicted results.

Lewis contact, Harold G. Price ((216) 433-2471)
Headquarters program office, OAST



Multipropellant resistojet

Verification of Multipropellant Resistojet Feasibility

Many detailed studies have shown that multipropellant resistojets offer great benefits for manned space systems such as the space station. A resistojet thruster can provide the key propulsion function of orbit maintenance at thrust levels that do not disturb low-gravity research and technology efforts. Additionally the use of gases from the environmental control and life support system, laboratory modules, attached payloads, and other sources provides major logistic and cost benefits as those wastes then do not have to be disposed of by very expensive means, such as return to Earth. Because no multipropellant resistojet had ever been demonstrated, Lewis began a program to first verify the feasibility of the concept and then develop a thruster.

Grain-stabilized platinum was chosen as the heat exchanger and nozzle material that would be most compatible with a wide variety of heated propellants and also provide strength and creep resistance in the heated mode. Extended tests at Lewis operating grain-stabilized heaters in steam, hydrogen, nitrogen, and carbon dioxide have provided mass loss data that indicate heater and heat exchanger lifetimes from 5 to over 90 years depending on the type of propellant. Life tests of laboratory model thrusters operated on carbon dioxide at Lewis further confirmed the validity of the multipropellant thruster concept.

A contract was awarded to Rocketdyne for the design and fabrication of multipropellant resistojets to be tested at Lewis. A low-risk design approach was undertaken so that the thruster materials processing and assembly procedures would be state-of-the-art methods. Pressure vessel and heater welds are located in lower temperature extremities in order to preserve the platinum grain stabilization in the hot zones. The first thruster has been successfully fabricated and will soon be tested to characterize performance, plumes, and lifetime.

Lewis contact, James S. Sovey
((216) 433-2420)
Headquarters program office, OSS

Low-Power Arcjet Technology

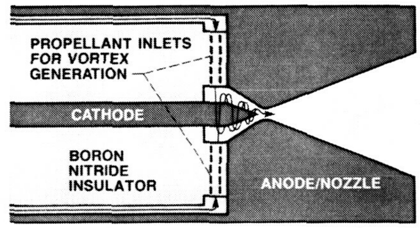
Lewis is investigating direct-current arcjet thruster systems for application to satellite auxiliary propulsion functions. Arcjets may provide more than 50 percent higher specific impulse than state-of-the-art auxiliary propulsion systems.

In an arcjet a gaseous propellant, such as decomposed hydrazine, is heated by an arc and expanded through a nozzle to produce thrust. The voltage and current characteristics of arcs are difficult to control, and the starting and steady-state characteristics are quite different. Thus the power processor and the thruster are both critical components, and their proper dynamic and steady-state integration is essential. Starting transients and transients due to arc instabilities were found to be quite damaging to the electrodes. Lewis research on arc and fluid stability and power management fundamentals has resulted in the ability to reliably and repeatably start the arcjet and make the transition to a stable steady-state operation without damage.

State-of-the-art hydrazine resistojets, currently used on a number of communications satellites, provide a specific impulse of 295 sec at 500 W. Initial applications of arcjets must be at this power level or slightly higher. However, research on arcjets in the past (1960's) was limited primarily to hydrogen, rather than storable propellants, and operation was stable only at 2 kW and higher. Therefore Lewis recently conducted fundamental studies on a water-cooled simulator to optimize the relative levels of tangential and axial inflow and to determine the optimum constrictor geometry. Stable operation was attained at power levels below 500 W with nitrogen.

Recent results for a laboratory thruster show that at power levels of interest, specific impulse can be increased 50 percent with gas mixtures simulating decomposed hydrazine. Even higher specific impulse can be attained with simulated ammonia, but using ammonia on satellites would require a new propellant management system.

Lewis contact, James R. Stone
((216) 433-2427)
Headquarters program office, OAST



Arcjet starting phenomena—gas dynamic arc stabilization

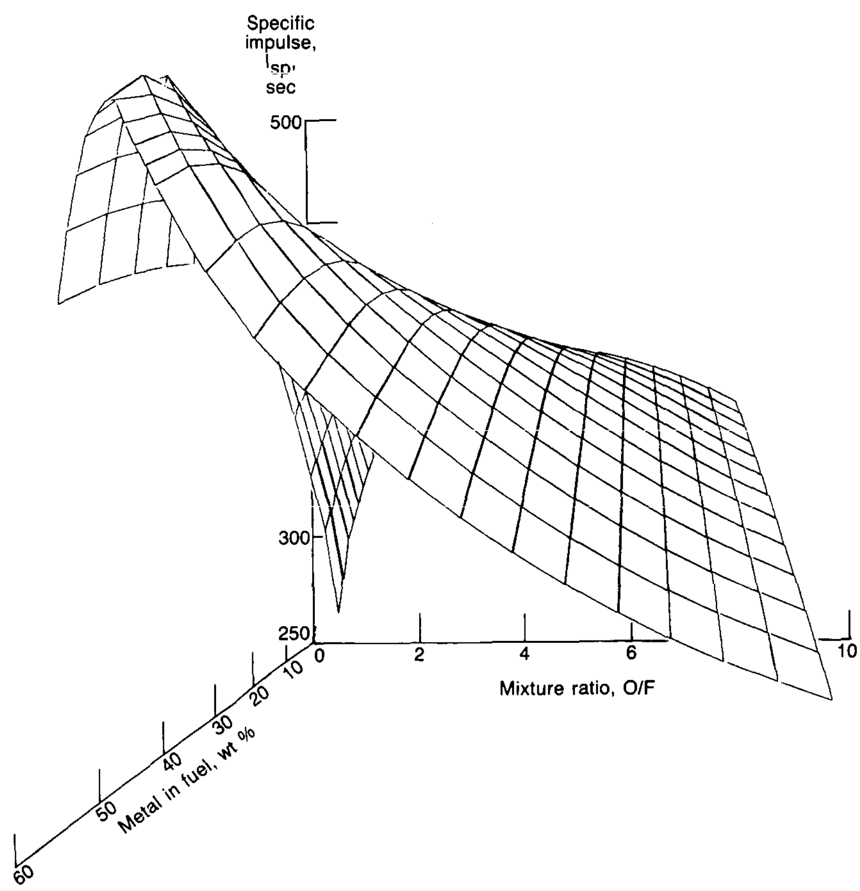
Evaluation of Metalized Tripropellants

The need for high-performance propulsion systems to transfer payloads into high-energy trajectories has renewed interest in adding metals to traditional liquid propellants. These tripropellants offer the opportunity to advance chemical rocket propulsion performance far beyond that of any bipropellant system. Tripropellants show promise for expanding the payload capacity of rocket-propelled vehicles by increasing both the specific impulse and the mass fraction. Lewis characterized the performance of selected tripropellant systems and reviewed technology issues pertinent to tripropellants to assess the potential of the tripropellant concept.

An analytical study was conducted in-house to determine the specific-impulse advantages of adding metals to conventional liquid bipropellant systems. The metals considered were beryllium, lithium, and aluminum. The bipropellant systems were H_2/O_2, N_2H_4/N_2O_4, RP-1/O_2, and H_2/F_2. Thermochemical calculations were made to determine the specific impulse of each tripropellant over a wide range of mixture ratios and propellant compositions. Specific impulse was fully characterized by using three-dimensional plots. The analysis indicated that tripropellants can theoretically increase the specific impulse and propellant density of conventional liquid bipropellant systems and can expand payload capacity.

We are conducting mission studies on the combined effect of both specific impulse and mass fraction on the payload capacity of various tripropellants. However, a review of pertinent technology issues indicated that key technology areas must be experimentally explored to realistically evaluate the potential of tripropellants.

Lewis contact, Robert L. Zurawski
((216) 433-2468)
Headquarters program office, OAST



Theoretical performance for Be/H_2/O_2

Performance of Ring-Cusp Thrusters with Xenon Propellant

Lewis is working to define an ion thruster propulsion subsystem for the proposed SP-100 nuclear power reference mission and for a 21st century manned mission to Mars. Input power levels to the propulsion subsystem would be over 270 kW and 3 MW, respectively. These and other studies suggest the need for larger, higher power xenon ion thrusters, beyond the 30-cm-diameter 10-kW level, to reduce the system complexity and the number of thrusters required to accomplish these missions. Developing these thrusters requires the demonstration of critical technologies, including a reduction in thruster discharge power requirements, which would benefit thermal designs. Reduced discharge power requirements had been demonstrated with a magnetic multipole ring-cusp ion thruster with inert gas propellants. But there were no subsequent studies to characterize the performance of the thrusters over a range of throttling conditions.

Lewis therefore began a program to compare the performance and life of the ring-cusp ion thruster and the baseline divergent-field J-series ion thruster.The ring-cusp thruster demonstrated lower discharge power requirements over a 2:1 range of flow rate. Overall the ring-cusp thruster performed better than the baseline and modified J-series thrusters, including higher thrust-power ratios over the range of specific impulse. The ring-cusp thrusters attained typical thruster efficiencies of 70 percent at a specific impulse of about 3500 sec. Mass spectrometry of the thruster ion beams indicated that the ring-cusp thruster had a lower species current ratio than the J-series thruster at fixed propellant efficiencies. Because of the ring-cusp thruster's lower values of multiply charged ions and lower operating discharge voltage, the screen grid of the ring-cusp thruster should last twice as long as the screen grid of the divergent-field J-series thruster.

Incorporating ring-cusp discharge chamber technology into the 50-cm-diameter ion thruster array proposed for the SP-100 reference mission would thus reduce the total dissipated power requirements by 6 kW and the cathode emission current levels by 18 A (25 percent) per thruster.

Bibliography

Byers, D.C.: Characteristics of Primary Electric Propulsion Systems. AIAA Paper 79-2041, Oct. 1979.

Patterson, M.J.: Performance Characteristics of Ring-Cusp Thrusters with Xenon Propellant. AIAA Paper 86-1392, June 1986.

Sovey, J.S.: Improved Ion Containment Using a Ring-Cusp Ion Thruster. J. Spacecr. Rockets, vol. 21, no. 5, Sept.-Oct. 1984, pp. 488-495.

Steinetz, B.M.; Rohn, D.A.; and Anderson, W.J.: Evaluation of a High-Torque Backlash-Free Roller Actuator. 20th Aerospace Mechanisms Symposium, NASA CP-2423, 1986, pp. 215-240.

Lewis contact, Michael J. Patterson ((216) 433-2405)
Headquarters program office, OAST

Development of a Gas Dynamic and Heat Transfer Analytical Code

SINDA is a popular finite-element model for solving complex conduction-heat-transfer problems in two and three dimensions. The SINFLO option is a finite-element fluid equivalent that solves the fluid flow portion of a problem, the related heat transfer into the surrounding structure, and the conduction within the structure. The conduction and flow options of the model can be used separately or in combination and under steady-state or transient conditions. Although the program was originally developed by Chrysler and modified by TRW, to our knowledge the flow option has not been operable in a general form anywhere in the country. The operating procedures were developed at Lewis under a National Research Council fellowship.

The SINFLO code was applied to a gaseous hydrogen resistojet, and the results were compared with a state-of-the-art industry analysis and a set of experimental tests run at Lewis, all at similar conditions. The SINDA/SINFLO analysis came within 5 percentage points of the experimental data in efficiency, considerably closer than the original industry prediction.

Lewis contact, Carl A. Aukerman ((216) 433-2441)
Headquarters program office, OAST

	Power, W	Flow, g/sec	Temperature, K	Specific impulse, sec	Efficiency, percent
Industry	1049	0.0326	[a]1957	696	72
SINDA/SINFLO	1049	.0326	[a]1654	640	61
Lewis[b]	1150	.0344	1800	606	56

[a]Calculated.
[b]Deduced from experimental data.

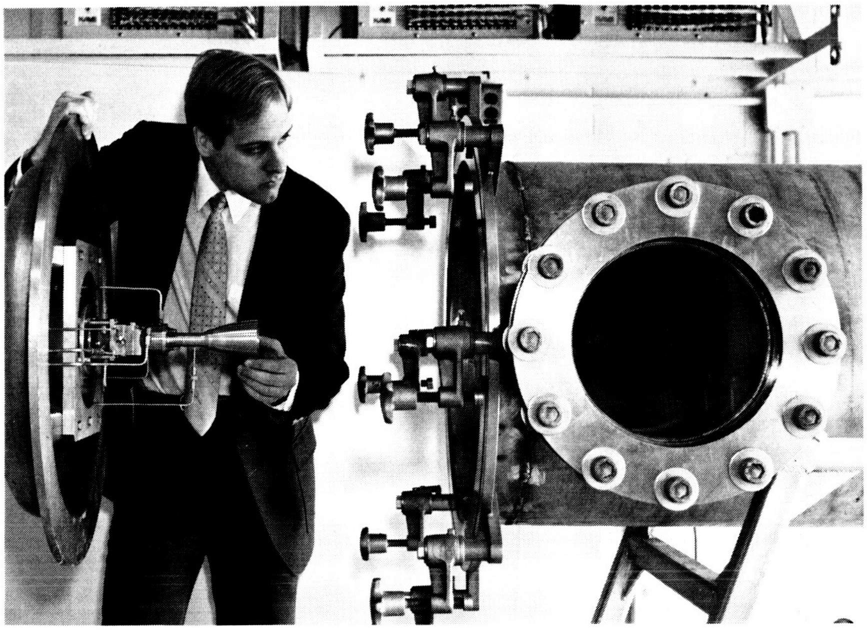
SINDA/SINFLO analysis

Testing of High-Area-Ratio Nozzles

Lewis is experimentally investigating the elements that contribute to the overall performance of a high-area-ratio rocket nozzle. The uncertainties in the existing codes at high area ratio result from a lack of knowledge of the core flow, boundary layer, heat transfer, and nozzle contour effects. Data are very limited because a unique and complex test facility is required to obtain such data.

A series of contoured nozzles with a 1-inch throat diameter are being fired in the Lewis rocket engine test facility using gaseous hydrogen and oxygen propellants. The nozzles have area ratios to 1000 and were designed by various industry techniques. We are measuring typical performance parameters as well as nozzle thermal and pressure profiles and are using the results to verify and modify existing analytical models.

Lewis contact, Carl A. Aukerman ((216) 433-2441)
Headquarters program office, OAST



Test capsule of ignition system test facility

Ignition System Test Facility

Future reusable space vehicle propulsion systems must have high performance, long life, and low cost while being reliable, safe, and maintainable. Each component of the propulsion system, including the ignition system, must satisfy these requirements. Conventional spark ignition systems are complicated and potentially unreliable additions to a rocket engine. This complexity is expensive and not conducive to the long life and high reliability required for reusable systems. Therefore alternative ignition system options need to be explored.

A test facility has been constructed at Lewis to experimentally evaluate hydrogen-oxygen ignition systems. The facility was designed for steady-state and transient testing of ignition systems at sea level or space-simulated altitudes. Altitude ignition characteristics are determined in a simulated space environment created with an air-driven ejector. A liquid-nitrogen heat exchanger chills propellants to simulate cryogenic boiloff temperatures. The facility also can test H_2/O_2 rockets to 25-lb thrust at sea level and to 5-lb thrust at space-simulated altitude.

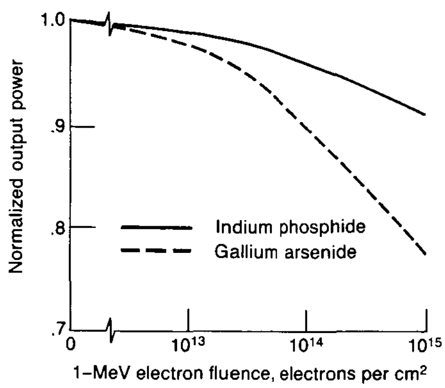
The facility will first be used to evaluate H_2/O_2 catalytic ignitors for advanced propulsion applications. Later its capabilities will be expanded to test ignitors for liquid oxygen/hydrocarbon propulsion systems.

Lewis contact, Robert L. Zurawski
((216) 433-2468)
Headquarters program office, OAST

Power Technology

Indium Phosphide Solar Cells

Because of their better radiation resistance and potentially high efficiency indium phosphide solar cells, when fully developed, have excellent potential for producing significantly more output power in the space radiation environment than either silicon or gallium arsenide cells. In the present very early stage in the development of indium phosphide cells efficiencies exceed 14 percent, and efficiencies of more than 20 percent are feasible. The radiation resistance of indium phosphide has proven superior to that of gallium arsenide, previously the most radiation-resistant space solar cell material, after 1-MeV electron irradiations performed in the dark. Similar results were obtained after 10-MeV proton irradiations. The indium phosphide cells have the unique additional advantage of even better performance, over that in the dark, when irradiated by electrons and simultaneously exposed to light. This property is not possessed by either gallium arsenide or silicon cells. In addition, damage due to the particulate radiation of space can be removed in indium phosphide by annealing at 100 °C, much lower than the annealing temperature of existing space solar cells. Thus, when used in a passively cooled concentrator operating at 100 °C, indium phosphide solar cells should show no degradation when operated in the space radiation environment.



Output power of radiation-damaged solar cells

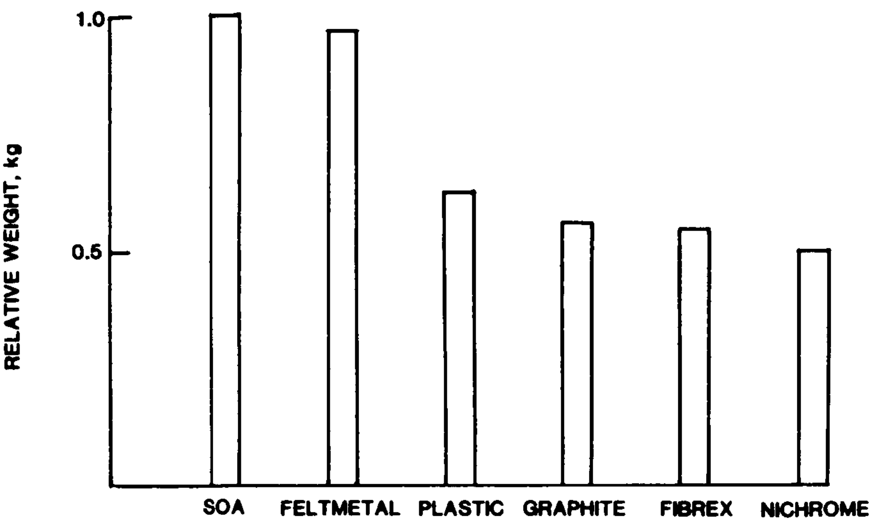
The indium phosphide cells whose performance was determined at Lewis were produced under a Lewis grant to Rensselaer Polytechnic Institute in a continuing program aimed at producing a highly efficient radiation-resistant cell.

Lewis contact, Dr. Irving Weinberg ((216) 433-2229)
Headquarters program office, OAST

Lightweight Nickel Electrodes

Increasing the energy density of the nickel-hydrogen battery system is one of the goals of technology development at Lewis. This goal can be achieved by developing a lightweight, longer life nickel electrode to replace the heavy, state-of-the-art sintered nickel electrode in current use.

Lewis is developing nickel electrodes that will be 30 to 50 percent lighter and have usable energy densities twice those of the sintered electrodes operated in a comparable cycling regime. A nickel-plated plastic plaque developed at Lewis and several commercially available materials (Feltmetal, nichrome webbing, nickel-plated graphite, and Fibrex fiber mat) have been studied.



Relative weights of experimental electrodes and a state-of-the-art sintered electrode

Experimental cells incorporating Feltmetal and Fibrex are being tested with encouraging results.

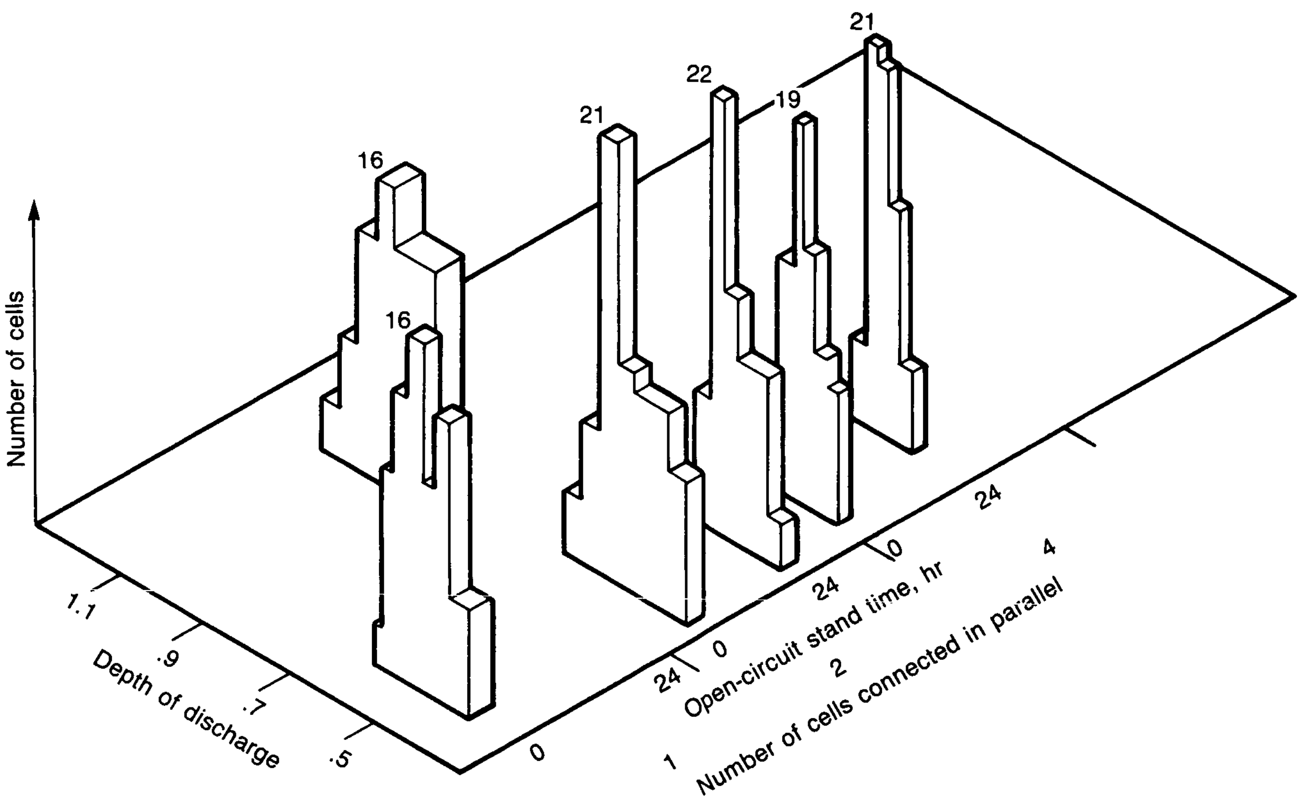
These lightweight electrodes are designed primarily for the bipolar nickel-hydrogen battery system that is being developed in-house and on contract at Ford Aerospace. Bipolar is a method of connecting cells in a battery in series by using a common conducting plate as the positive terminal of one cell and as the negative terminal of an adjoining cell. These designs are intended primarily for low-Earth-orbit applications.

Lewis contact, Doris L. Britton
((216) 433-5246)
Headquarters program office, OAST

Synthetic Battery Cycling

In evaluating the reliability of advanced battery technologies to meet the stringent requirements of large power systems for Earth orbit, attention must be focused on how cell performance affects battery performance. Lewis is conducting a program in which orbital cycling of a battery is numerically simulated to identify critical parameters that must be controlled at the cell level for longer battery life.

In multikilowatt battery systems the various cell arrangements possible for an equivalent battery must be evaluated so as to optimize cell performance and thus battery life. In the past batteries have been built with the accumulation of data obtained from single-cell experiments. One of the basic dilemmas of constructing batteries from single cells derives from the inescapable problem of cell variations affecting battery cycle life.



Synthetic battery-cycling profile

Electrochemical computational engineering principles were used to develop a simulation computer model for examining the effects of cell variations. The model also analyzes the effects of series and parallel configurations on the design of large battery systems. By using a mathematical representation for the charge and discharge of a cell as the basis for the model, we could examine the stochastic aspects of cell populations and cell configurations in a short time with a minimum of cost.

The network configuration of series and parallel interconnections of cells has an effect on how the battery functions. The life of a battery depends on the depth of discharge (DOD) of the individual cells in the battery. The optimum configuration, the one with the least spread in the DOD of the individual cells, was the configuration with the most cells (four) in parallel.

The synthetic battery-cycling technique has been applied to the sodium-sulfur battery, but any electrochemical system can be analyzed with this technique by making appropriate modifications to the basic equations.

Lewis contact, Harold F. Leibecki
((216) 433-6172)
Headquarters program office, OAST

Gigarad-Tolerant Deep-Impurity, Double-Injection Switches for SP–100

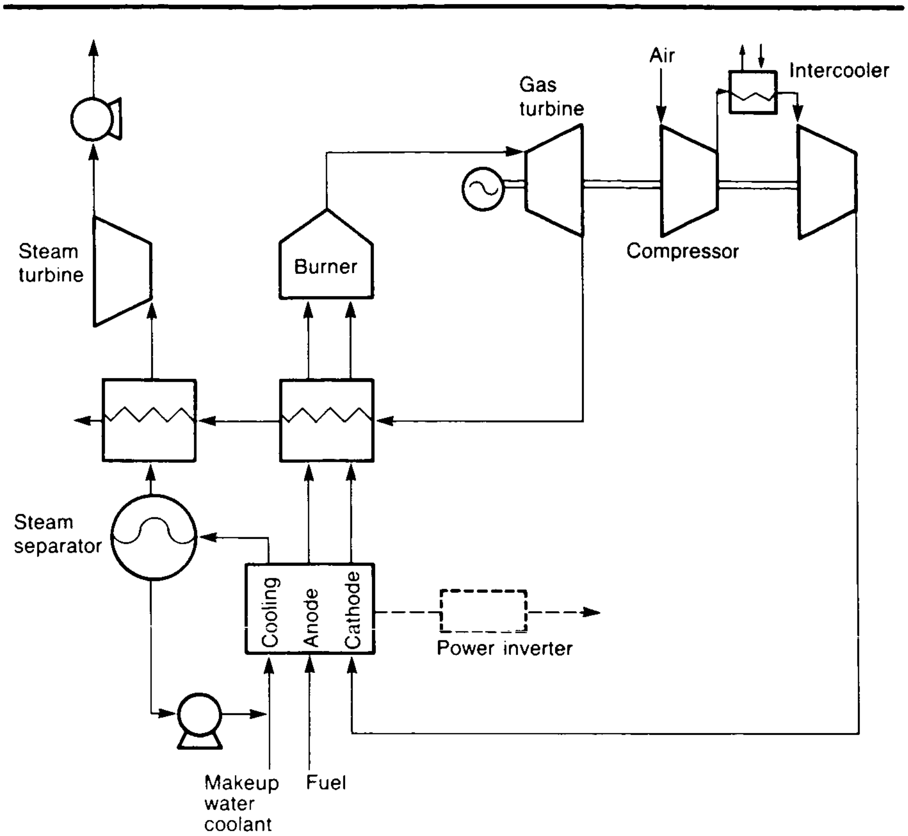
A newly developed family of semiconductor switches based on deep-impurity, double-injection (DI)^2 techniques in silicon have been studied for radiation hardness. Twelve pairs of switching devices in the form of unmounted, diced silicon chips were irradiated with gamma rays at the National Bureau of Standards Cobalt-60 Facility at radiation levels up to 1000 megarads (Si). The switching characteristics (on state, off state, and transitions between them) measured before and after the irradiation remained stable. Leakage currents actually decreased, and switching speed and the ratio of on- to off-state impedance remained unchanged. Devices have been switched in the 1000-V, 100-A region in the pulse mode and operated for more than 30 days at over 300 °C.

Several gating schemes provide better switching efficiencies, delay functions, and sensing applications than conventional semiconductors. Low-power, gated (DI)^2 switches have also been demonstrated with very low forward voltage drops and microwatt power dissipation for logic-level switching and memory applications. Thus gigarad-tolerant (DI)^2 switches designed for either high or low power levels and capable of high-temperature operation give promise of electronic control, sensing, and energy conversion at or near a nuclear reactor. This capability would dramatically reduce component and shielding weight and the heat rejection problems associated with multikilowatt and megawatt electric power generation, conversion, and distribution systems in space. Other uses for the new (DI)^2 semiconductors include the growth space station, lunar bases, the Strategic Defense Initiative, and spinoff applications now under development in medicine and life support and for industrial processes and equipment.

Lewis contact, Gale R. Sundberg ((216) 433–6152)
Headquarters program office, OAST

Design of Coal Gasifier/Fuel Cell Powerplants for Cogeneration

Under contract to Lewis a Cleveland State University research associate has designed seven coal gasifier (CG)/phosphoric acid fuel cell (PAFC) integrated cogeneration systems. A reference system using methane fuel has also been developed. The coal gasifiers integrated in these designs are, from the most commercially developed to the least, the Wellman-Galusha (W–G) air blown, the Koppers-Totzek oxygen blown, the Texaco oxygen blown, the high-temperature Winkler oxygen blown, the Westinghouse oxygen blown, the Kohlegas Nordrhein GmbH (KGN) air blown, and the TRW catalytic hydrogen process. An International Fuel Cell water-cooled PAFC is used in each system. Test results, arrived at using consistent assumptions and calculations, showed that the air-blown CG/PAFC systems have a higher efficiency (for KGN CG) and lower cost of electricity (COE) (for W–G or KGN CG) because of their low power consumption and low cost of air compression relative to the oxygen plants. The methane-fueled system yielded high efficiency and low capital cost but high COE because of the high cost of methane.



Generic PAFC/bottoming cycle system

Separate tradeoff studies were performed on optimal PAFC operating parameters (i.e., fuel utilization ratio, oxidant utilization ratio, and current density). A generic PAFC/bottoming cycle subsystem was developed to study the effects. The optimal fuel utilization ratios (energy ratios of consumed hydrogen to total input fuel) can be grouped into two categories: 0.69 for air-blown CG's, and 0.74 for oxygen-blown CG's. For a higher operating current density (300 A/ft^2 instead of the present design's 200 A/ft^2) the COE will be reduced by 4.5 percent. The effect of oxidant utilization ratio is small.

Lewis contacts, Dr. Marvin Warshay ((216) 433-6126) and Cheng-Yi Lu ((216) 433-6137)
Funding source, DOE

Organometallic Catalysts for Phosphoric Acid Fuel Cells

Lewis has an advanced research contract with the ECO Division of Tracer Technologies, Inc., to find substitutes for the strategic material platinum as an electrode catalyst in phosphoric acid fuel cells. ECO has investigated a class of organometallic cathode catalysts primarily represented by the cobalt tetraazaannulenes (CoTAA's). A broad spectrum of TAA analogs were synthesized and tested as cathode catalysts in a primary fuel cell. During this testing ECO observed that cathodes catalyzed with both CoTAA and platinum had higher performance than cathodes catalyzed with either CoTAA or platinum alone. A study of the mechanism of oxygen electroreduction at cathodes containing this mixed catalyst showed that the best combination of catalysts was one in which the CoTAA acted to catalyze oxygen reduction to hydrogen peroxide and the metal acted to catalyze oxygen reduction of hydrogen peroxide to water.

From the results of this study mixed catalysts that contain no noble metals were developed. Among the best was a mixed catalyst of CoTAA and manganese. Half-cell data showed that the performance of cathodes with this mixed catalyst at 100 mA/cm^2 was approximately 70 mV below that of cathodes with a mixed catalyst containing platinum and approximately 50 mV below that of platinum (at equal load) by itself. In a complete cell operating for 1000 hours with hydrogen and oxygen as reactants the CoTAA-manganese mixed catalyst was stable in the 200 °C phosphoric acid environment.

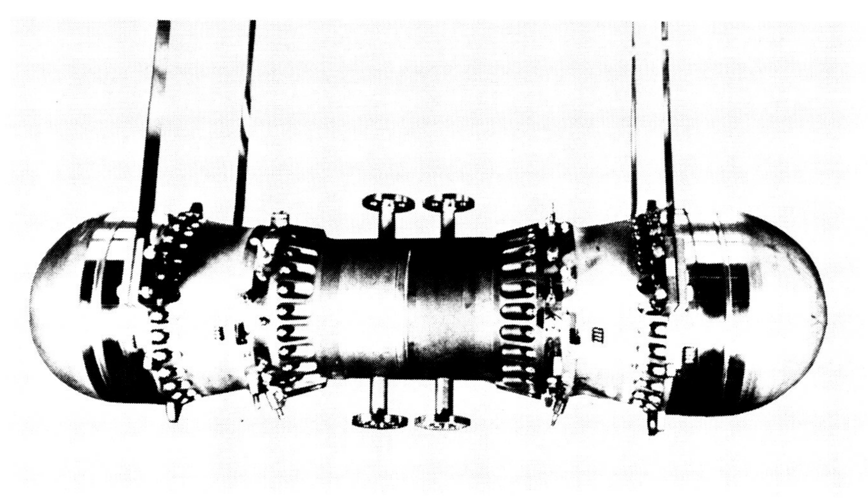
Lewis contacts, Robert B. King ((216) 433-6122) and Albert C. Antoine ((216) 433-6123)
Funding source, DOE

Free-Piston Stirling Engine

Lewis is evaluating the use of a free-piston Stirling engine for space power applications in support of the SP-100 Program. The Department of Defense, the Department of Energy, and NASA jointly fund the SP-100 Program to develop a 100-kW-class electrical space power module. The potential advantages of free-piston Stirling engines for space applications include high efficiency, extremely low vibration, simple components, and growth capability.

As part of the SP-100 Program, Mechanical Technology Incorporated has designed, fabricated, and successfully conducted initial low-power testing of a nominal 25-kW, two-opposed-piston Stirling space power demonstrator engine (SPDE) at an engine pressure of 75 bars—half of the design pressure. The 6 kW of electric power output achieved was within 10 percent of design predictions. These initial tests demonstrated the following design goals, which are important to the SP-100 effort:

(1) The opposed-piston engine provided excellent dynamic balance.



Stirling space power demonstrator engine

(2) Good engine performance was achieved at low temperature ratio (ratio of heater tube to cooler tube temperature of 2).

(3) Hydrostatic bearings with long-life potential were used successfully with the Stirling engine linear alternator system. Progress has been made toward the demonstration of design power at design pressure and frequency. Initial test results yielded a power output of about one-half of that predicted. A 60-percent improvement in power output resulted from design modifications to correct regenerator design deficiencies identified by inspection and diagnostic tests. The present engine configuration appears capable of delivering more than 20 kW of power to the linear alternator at an efficiency of better than 20 percent. However, the test cell's electric load system has proven inadequate for SPDE power levels above 14 kW. Some unplanned engine shutdowns have occurred because of an apparent mismatch between the engine and its load. The electric load is presently being carefully reviewed. As soon as this problem is corrected, full-design SPDE electric power output should be achieved. Mechanical operation of the engine during all testing has been nearly flawless.

Lewis contact, Jack G. Slaby ((216) 433-6136)
Headquarters program office, OAST

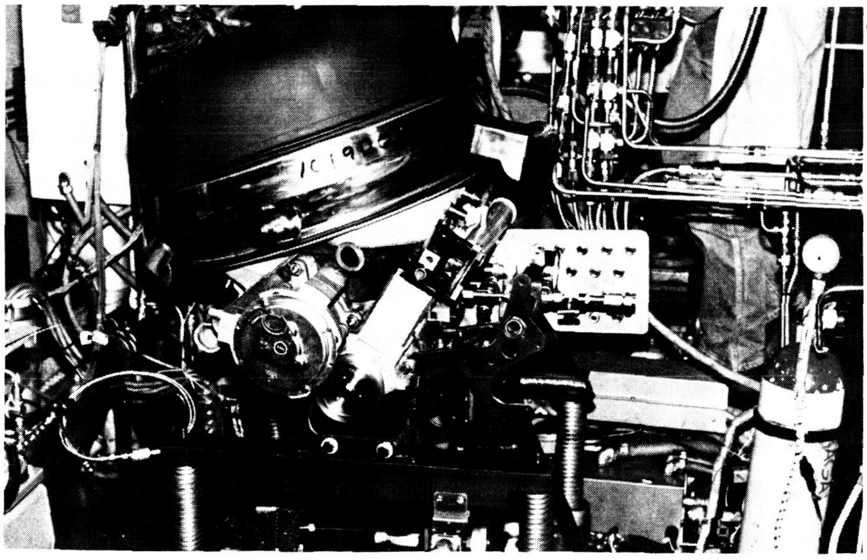
Automotive Stirling Engine

The Stirling engine is being developed under a U.S. Department of Energy (DOE) program to develop the technology for an alternative automotive powerplant. Lewis manages the Automotive Stirling Engine (ASE) Program for DOE under an interagency agreement. The prime contractor is Mechanical Technology Incorporated, and the major subcontractor is United Stirling AB of Sweden.

The first-generation (MOD I) engines in the ASE Program are near development. Seven MOD I engines have accumulated over 16,000 test hours. The technologies developed are now being incorporated in the second-generation (MOD II) engine. MOD I engines are also being applied in other areas. One has been incorporated in a generator set being tested by the Army at Fort Belvoir. Another has been installed in a van for testing by the Air Force at Langley Air Force Base.

Two MOD II engines have been fabricated and testing has begun. The MOD II engine is rated at 63 kW (84 hp) at 4000 rpm and operates at 820 °C. One MOD II engine will be installed in a General Motors Celebrity vehicle in 1987 to demonstrate the program objectives of fuel economy, exhaust emissions, and driveability. The MOD II Celebrity is projected to have a combined Environmental Protection Agency (EPA) urban/highway fuel economy of 41 mpg with unleaded gasoline and an acceleration time of less than 13 seconds (0 to 60 mph) and to meet all Federal emission standards. The MOD II Celebrity fuel economy is projected to be a 50-percent improvement over the 1985 U.S. fleet average for a 3125-lb inertia weight vehicle.

Lewis contact, Donald G. Beremand ((216) 433-6110)
Headquarters program office, OAST



Automotive Stirling engine

Variable-Speed, Constant-Frequency Generating System

One of the major problems in wind turbine design is mating the wind turbine to an electric power system. An important characteristic of any electric power system is that it maintain constant frequency. Otherwise motors do not run at the correct speed, and clocks do not keep correct time. A wind turbine rotor will run at variable speed since it is being driven by the continuously variable wind. When an electric generator is connected to a wind turbine, its speed (frequency) will also vary continuously unless some means is used to control it.

Wind turbine speed is traditionally controlled with variable-pitch blades. The pitch change mechanism consists of hydraulic actuators, control valves, and a pump. Experience has shown that these systems require a high degree of maintenance. In addition, the hydraulic system may not respond quickly enough to occasional wind gusts. Generator frequency and power will then fluctuate.

An alternative approach to variable-pitch speed control is a variable-speed, constant-frequency (VSCF) generator. Several years ago Lewis undertook to develop such a system since it has the potential for being more reliable and more responsive than its hydraulic counterpart.

The VSCF generating system consists of a generator with a wound rotor connected to a variable-frequency power supply. When the generator's speed changes, the frequency applied to the rotor is changed such that the stator frequency is constant. This approach to correcting for a speed change is more responsive because it requires much less time to change the rotor frequency than it does to move a hydraulic actuator. In addition, the VSCF generator provides for independent control of real and reactive powers.

Field tests of the VSCF generating system on the MOD-0 100-kW wind turbine at the Lewis Plum Brook Station have shown that the VSCF system does improve the wind turbine's performance.

Lewis contact, Frank J. Brady
((216) 433-3873)
Headquarters program office, OAST

Space Communications

Textured Carbon on Copper: A Novel Surface with Extremely Low Secondary Electron Emission Characteristics

Values of true secondary electron emission and relative values of reflected primary electron yield for a range of primary electron beam energies and beam impingement angles were determined for a series of novel textured carbon surfaces on oxygen-free, high-conductivity copper substrates. The purpose of this investigation was to provide information necessary to develop high-efficiency multistage depressed collectors (MDC's) for microwave amplifier traveling wave tubes (TWT's) to be used in communications satellites and aircraft. To attain the highest TWT signal quality and overall efficiency, the MDC electrode surfaces must have low secondary electron emission characteristics. Copper, the material most commonly used for MDC electrodes, exhibits relatively high levels of secondary electron emission unless its surface is treated for emission control. A textured carbon surface on a copper substrate is a particularly promising treatment. Samples of textured carbon surfaces on copper substrates typical of three levels of treatment were prepared and tested at primary electron beam energies of 200 to 2000 eV and at direct (0°) to near-grazing (85°) beam impingement angles.

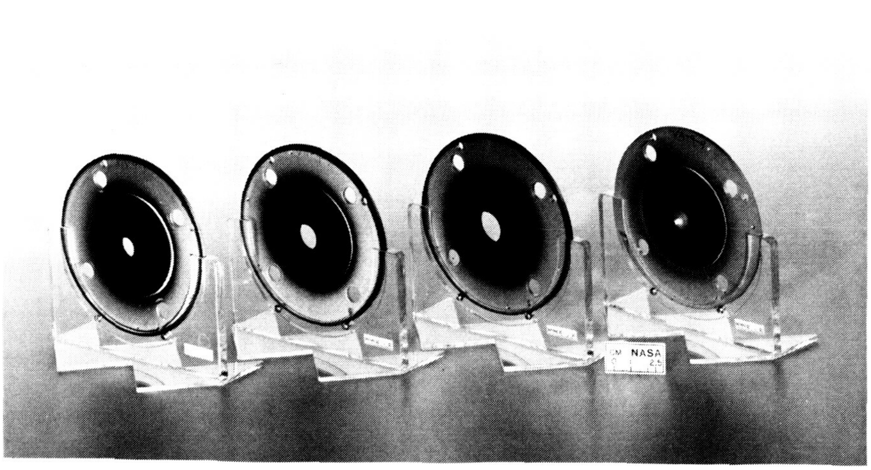
True secondary electron emission and relative reflected primary electron yield characteristics were compared for the three textured surfaces and with those of untreated copper. All of the textured carbon surfaces on copper substrates exhibited sharply lower secondary electron emission characteristics than did the untreated copper surface. One textured surface clearly yielded the lowest emission characteristics.

The paper that reported this work was written by Arthur N. Curren and Kenneth A. Jensen and was selected as the Lewis Distinguished Paper for 1986.

Lewis contacts, Arthur N. Curren ((216) 433-3519) and Kenneth A. Jensen ((216) 433-3610)
Headquarters program office, OAST

Treated Copper Multistage Depressed Collector Electrodes for High-Efficiency Traveling Wave Tubes

As described in the adjacent article Lewis has developed a process to deposit a highly textured carbon surface on copper. This process produces a surface that has extremely low secondary electron emission properties and is characterized by a dense, random array of microscopic carbon spires extending perpendicularly from the copper substrate. We have applied this textured carbon layer to copper electrodes in multistage depressed collectors (MDC's) for traveling wave tubes (TWT's) to evaluate the potential for overall efficiency enhancement. Copper is the most commonly used MDC electrode material, but its high secondary electron emission properties permit significant electron reflection and reemission, which adversely affect efficiency.



Textured-carbon-coated copper electrodes

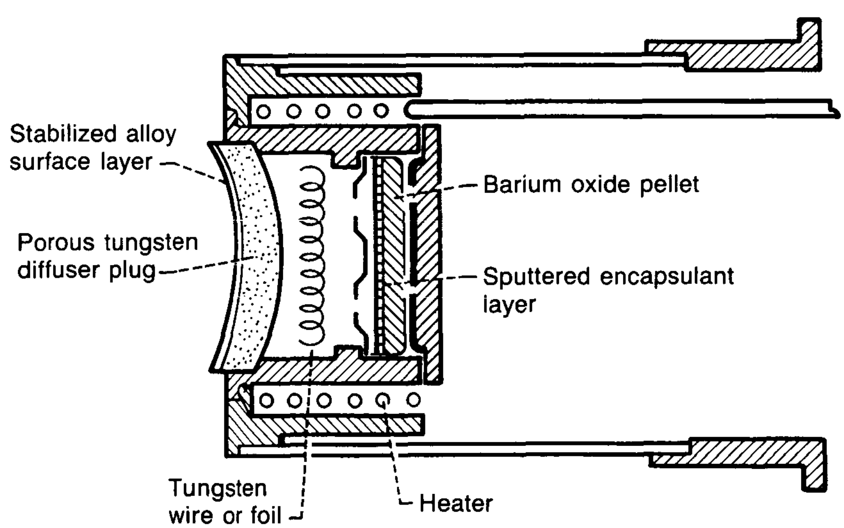
In a recent test sequence a Varian TWT with uncooled textured-carbon-coated MDC electrodes was operated at saturated radiofrequency output power of about 840 W from 2.5 to 5.5 GHz for 500 hours at 25-percent duty cycle and for an additional 100 hours at the direct-current beam, or zero-drive, condition. The operation was stable, and the MDC and overall TWT efficiency increases averaged about 13.5 percent relative to the same TWT with untreated copper MDC electrodes operated similarly.

In another, more severe, test with water-cooled textured-carbon-coated MDC electrodes a Teledyne MEC TWT was operated at saturated radiofrequency output power of about 510 W at 6.4 GHz for 1025 hours at continuous wave and for an additional 575 hours at the direct-current beam condition. Although efficiency comparisons were not made for this test, the very stable operation suggested no changes in internal conditions over the test period. Furthermore pre- and post-test examinations of the textured carbon surfaces with a scanning electron microscope revealed no damage or recognizable feature changes attributable to either test sequence. These tests provide confidence that the process is suitable for the MDC's of long-life TWT's for space communications applications.

Lewis contact, Arthur N. Curren ((216) 433-3519)
Headquarters program office, OAST

Long-Life Reservoir Cathode with High Emission Current Density

Barium dispenser thermionic cathodes are necessary for reliable long-life operation of high-frequency and high-power microwave tubes in space. Potentially a barium-oxide-reservoir dispenser cathode has a significantly longer operational life than the commonly used barium-impregnated type, especially at high emission current densities. Under a contract to Varian Associates a program has been implemented to develop a barium-oxide-reservoir cathode with high emission current density (up to 10 A/cm^2) and very long life (100,000 hours or more). An important feature of the program is the incorporation of recent developments in the use of tungsten alloys for enhancing electron emission from the cathode surface.



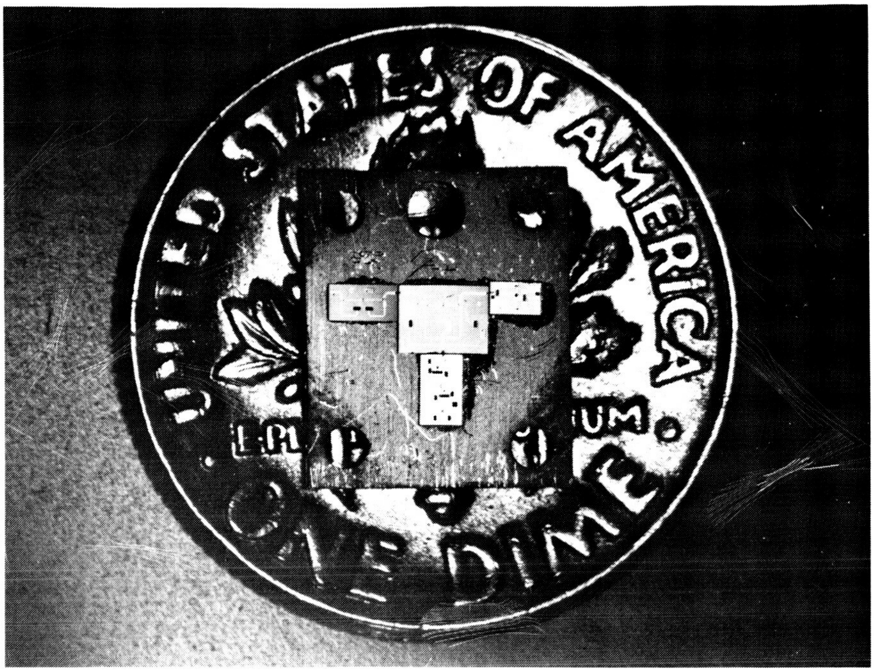
Barium-oxide-reservoir dispenser cathode

A number of major improvements in the technology have been made within the Lewis program, including the use of (1) a tungsten-osmium alloy for enhancing emission and lowering cathode operating temperatures, (2) a diffusion barrier for stabilizing the composition of the emitting surface, (3) segregated tungsten powder for controlling barium flow from the reservoir to the surface, and (4) a novel barium oxide encapsulation method for reducing the possibility of poisoning during cathode processing.

The result is a cathode offering long-life operation over a broad range of current densities, from 1 A/cm^2 to possibly as high as 50 A/cm^2. A prototype cathode has already demonstrated an emission current density of 16 A/cm^2. Plans include life testing at current densities to 10 A/cm^2 and further development work in cathode activation and long-term emission stability.

The improved reservoir cathode is very promising for applications in space communications for orbiting satellites, intersatellite links, deep space probes, and the space station and also for use in high-frequency backward-wave oscillators for submillimeter-wave spectroscopy in space.

Lewis contact, Edwin G. Wintucky
((216) 433-3510)
Headquarters program office, OAST



30-GHz monolithic low-noise receiver

30-GHz Monolithic Low-Noise Receiver for Satellite Communications

Many advanced scanning beam antenna concepts are based on complex feed arrays that require a receiver module for each of their elements. Such concepts are impractical unless the receivers can achieve the minimum size and weight that only a monolithic integrated circuit implementation affords.

Lewis is developing such a module under contract with Hughes Aircraft and Minneapolis-Honeywell. To date, each contractor has successfully developed a set of gallium arsenide submodules that perform the four functions required of the completed receiver: low-noise amplification, phase shifting, downconversion, and intermediate-frequency amplification with variable gain. Noise figures of approximately 6.5 dB have been achieved, with system gain of 17 dB, phase control from 0° to 360° in 32 steps, and 20 dB of gain control. Another design iteration will achieve further integration, consolidating several of these submodules in a single chip.

Lewis contact, Dr. Regis F. Leonard
((216) 433-3500)
Headquarters program office, OAST

60-GHz Traveling Wave Tube for Intersatellite Links

A coupled-cavity traveling wave tube has been developed by Hughes Electron Dynamics Division on contract to Lewis. The tube exhibits sufficient broadband capability to permit coverage with a single amplifier of the entire intersatellite communications band, from 59 to 64 GHz. The tube has been designed with a permanent-magnet focusing system and a four-stage depressed collector to achieve a weight of 6.8 kg and an efficiency of 35 percent. The coupled-cavity, slow-wave circuit permits operation at a radio-frequency power output of more than 100 W.

This device fills a need within NASA for a high-power, broadband amplifier at 60 GHz and has attracted interest throughout the communications satellite industry as well as from the Department of Defense. TRW is building and testing a vacuum-insulated power processor that operates with this tube.

Lewis contact, James A. Dayton, Jr.
((216) 433-3515)
Headquarters program office, OAST

SITE (Systems Integration, Test, and Evaluation)

The extension of commercial communications services into the 30/20-GHz frequency bands has necessitated the development of numerous new technologies at these higher frequencies. In particular, over the last 6 years NASA has sponsored the design of receivers, switches, solid-state amplifiers, and traveling wave tubes at 30 and 20 GHz. Evaluating how these components transmit high-rate (220 megabits/sec) digital data is important as guidance both in further development and in applications such as NASA's Advanced Communications Technology Satellite (ACTS).

A laboratory-based transponder consisting of a 30-GHz low-noise receiver, a C-band intermediate-frequency matrix switch, frequency upconversion to 20 GHz, and a 20-GHz high-power amplifier forms the core of the system. Serial minimum-shift keying (SMSK) modems, calibrated noise-insertion hardware, and in-house-designed digital ground terminal equipment complete the entire test system. Initial test results have indicated that the transponder is able to successfully transmit continuous pseudorandom digital data at 220 megabits/sec by using SMSK modulation. A typical signal degradation of 1.5 dB from theoretical was recorded for a bit error rate of 5×10^{-7}.

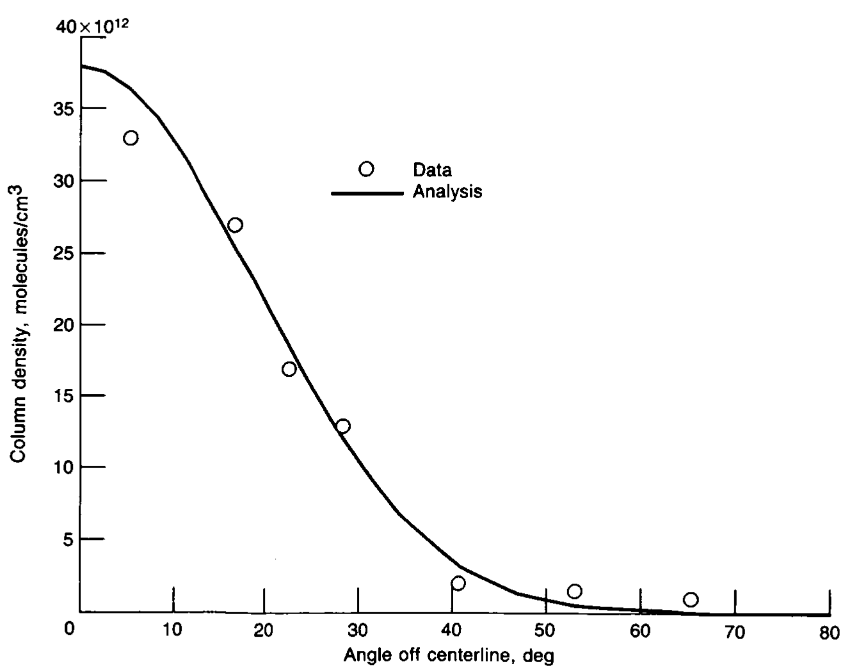
Features to be incorporated into SITE that will demonstrate critical time-division multiple access (TDMA) system concepts include burst-mode operation through a dynamic matrix switch, network control and system synchronization, power augmentation to compensate for rain fade, and range variation. A radiofrequency link experiment is being implemented to communicate between a prototype ACTS ground terminal and the SITE transponder.

Lewis contact, Godfrey Anzic
((216) 433-3570)
Headquarters program office, OSSA

SITE

Improved Modeling of Plume Profiles

Multipropellant resistojets for propulsion and waste-fluid disposal have been chosen for use on the space station. The multipropellant resistojet propulsion system benefits the space station by providing reboost capability and eliminating waste gases while saving the significant cost of delivering propellant to the space station. It does this by resistively heating waste gases from the space station's environmental control and life support system, materials technology laboratories, and attached payloads and expanding the hot gas through a nozzle. Lewis is analyzing the environment produced by the resistojet exhaust plume to predict whether the plume will contaminate sensitive space station surfaces and attached observational experiments.



Plume shape 36.4 cm from resistojet nozzle exit

The relevant contamination parameters are column density (the number of molecules per unit area), backflow (flow at angles greater than 90° from the nozzle centerline), return flux (contaminant molecules impinging on a surface because of intermolecular collisions with ambient molecules), and particle emission. To evaluate these parameters, the exhaust plume density field must be determined. Until recently not much work had been done in characterizing plumes for resistojet thrusters (0.1 to 0.01 lb). Therefore a source flow model for calculating far-field plume structure known as Simons' method, was modified to account for the highly viscous flow field in the resistojet nozzle. The model assumes that the flow originates from a point source at the nozzle exit plane and expands into the far field, where it is modeled by one of two equations, depending on where in the nozzle the fluid originated—the inviscid core or the boundary layer. Simons' method was improved by retaining a higher order term involving the ratio of boundary layer thickness to the nozzle exit radius in the equations for the plume density. Simons also, for some functions, carried out simplifying expansions that are not appropriate for resistojet nozzle flows. In applying the improved method a set of equations for the density in the far field is rapidly determined for use in evaluating contamination parameters. Column densities can thereby be calculated by integrating the plume density equations along a line of sight originating at a telescope location and looking out to the stars. Other contamination parameters can be determined once the plume is characterized.

This point source model was developed as a first approximation to a complex problem. It does not apply in the near field and breaks down in the backflow region. However, the far-field predictions compare well with data.

Plume modeling and potential contamination issues concerning the resistojet system for space station applications are the subjects of on-going work.

Lewis contact, David J. Hoffman
((216) 433-5282)
Headquarters program office, OSS

Demonstration of Low-Thrust Hydrogen/ Oxygen Thruster

The space station will require an auxiliary propulsion system capable of performing all required propulsive functions including attitude control during free-flying and docking maneuvers, orbit raising, and collision avoidance. Studies indicated the many potential benefits of gaseous hydrogen/oxygen thrusters of the 25-lb-thrust class for the space station. Lewis then began a program to design such thrusters and verify their life and reliability to ensure that the technology will be available for the initial space station.

Under contract to Lewis, Aerojet TechSystems and Bell Aerospace have designed, built, and tested small H_2/O_2 thrusters for durability and performance. Studies of the space station propellant supply and environmental control and life support systems indicated significant mission benefits from integrating the two systems and relying on the electrolysis of water to supply the gaseous hydrogen and oxygen propellants. This implied that the H_2/O_2 thrusters would be required to operate (1) over a wide range of oxidant-to-fuel ratios (mixture ratios) and (2) for long durations at mixture ratios at or near 8, which represents stoichiometric conditions. To verify thruster concepts, performance tests were conducted at mixture ratios from 2 to 8, and life tests were conducted at or close to a mixture ratio of 8. Aerojet and Bell accumulated total impulses of over 430,000 and 225,000 lb-sec, respectively, at mixture ratios of 7 and 8. No performance or physical deterioration of these thrusters was observed during the program. Lewis plans to continue the effort to provide a thruster fully optimized for a mixture ratio of 8 and to demonstrate the full lifetime required by the space station.

Lewis contact, Robert E. Jones
((216) 433-2450)
Headquarters program office, OSS

Hollow-Cathode Plasma Contactors for Electrodynamic Tether

Effective electrodynamic tether operation for drag makeup and orbital maneuvering propulsion and for power generation will require plasma contactors for low-impedance electrical contact with the ionosphere. Hollow cathodes are candidates for tether plasma contactors because of their high emission current capabilities and self-regulating current characteristics. There is experimental evidence for ampere-level electron current emission by hollow cathodes to the space plasma, both from ion thruster operation (Space Electric Rocket Test II) and from spacecraft charge control studies (ATS-6). However, the electron current collection capabilities of hollow cathode devices had not been studied. Lewis therefore undertook an experimental assessment.

A series of experiments were conducted in a large space simulation chamber to evaluate the electron current collection capabilities of several potential hollow-cathode plasma contactor geometries as a function of bias voltage (relative to a space plasma simulator), expellant type and flow rate, and contactor discharge power. A hollow cathode was used to generate a simulated space plasma, and both hollow cathodes and hollow-cathode-based geometries (derived from highly efficient plasma containment schemes developed for ion propulsion) were evaluated as potential plasma contactors.

Preliminary investigations determined that the ion production rate of hollow cathodes was insufficient to produce the high-density plasma region necessary for ampere-level electron current collection. Subsequent experiments with hollow-cathode-based geometries designed to increase the ion production rate demonstrated electron current collection levels greater than 10 A over a range of 12 m at low bias voltages. Furthermore under all test conditions ampere-level electron currents could be drawn to the hollow-cathode-based plasma contactors with bias voltage and neutral expellant flow only, independent of the discharge power to the contactor. The results indicate that ampere-level electron currents sufficient for electrodynamic tether operation can be collected from a space plasma with a minimum of plasma contactor design optimization.

Bibliography

Bekey, I.: Tethers Open New Space Options. Astronaut. Aeronaut., vol. 21, no. 4, Apr. 1983, pp. 32–40.

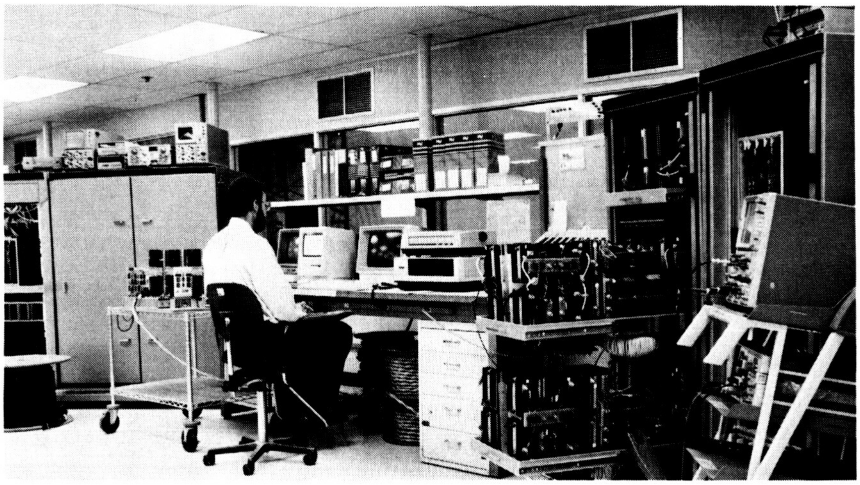
Bekey, I.: Applications of Space Tethers. IAF Paper-84-436, Oct. 1984.

Patterson, M.J.; and Wilbur, P.J.: Plasma Contactors for Electrodynamic Tether. Presented at Electrodynamics and Rotation Session of the NASA/AIAA/PSN International Conference on Tethers in Space, Sept. 17-19, 1986, Arlington, VA.

Lewis contact, Michael J. Patterson ((216) 433-2405)
Headquarters program office, OSS

20-kHz Power for Space Station

The space station represents the next major U.S. commitment in space. It must meet the needs of a broad spectrum of national and international users to fulfill its goals. The efficient delivery of power to multiple user loads is key to that success. Because of its many outstanding advantages and benefits to a wide range of users, a new 20-kHz power management and distribution (PMAD) system architecture developed by Lewis has been selected for the space station. Compared with other candidate power systems the high-frequency PMAD system provides much lighter weight, higher efficiency, lower cost, reduced electromagnetic interference effects, and improved crew safety. The 20-kHz PMAD system has exceptional flexibility, is inherently user friendly, and is compatible with all types of energy sources—photovoltaic, solar dynamic, rotating machine, or nuclear.



PMAD *system testbed for space station*

Lewis has recently completed under contract the development of a 25-kW, 20-kHz PMAD system testbed that demonstrates outstanding system flexibility, versatility, and transparency to user technology while maintaining high efficiency, low mass, and reduced volume. The PMAD system testbed is a single-phase, 440-V rms, 20-kHz system with a regulated sinusoidal waveform. A single-phase power system minimizes the wiring, sensing, and control complexities required in a multisource, redundantly distributed power system. The single phase, however, addresses only the distribution link, since multiphase lower frequency inputs are easily assimilated and multiphase variable-frequency outputs may be synthesized. A 20-kHz operating frequency was selected to be above the range of human hearing and minimize the weight of reactive components yet allow the construction of single power stages of 25 to 30 kW.

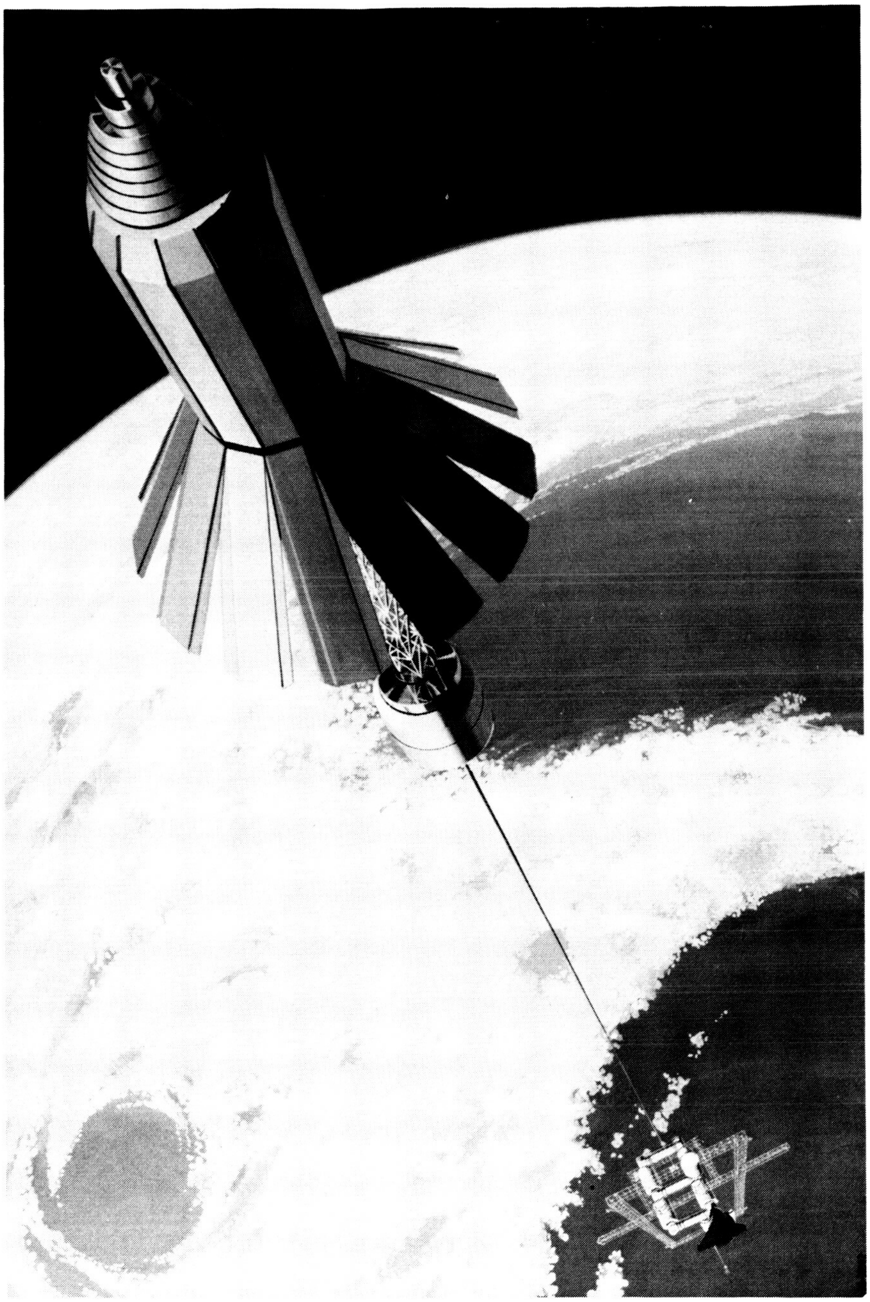
This technology promises significant benefits to the space station and platform and to other mass-limited missions such as the Strategic Defense Initiative and future aerospace craft such as the growth station, space shuttle II, and the national aerospace plane.

Lewis contact, Gale R. Sundberg
((216) 433-6152)
Headquarters program office, OAST

Assessment of Nuclear Reactor Power System Concepts for the NASA Growth Space Station

Lewis has completed a preliminary feasibility assessment of installation, operation, and end-of-life disposal options for three nuclear reactor power system concepts applied to a 300-kW growth version of the NASA space station. The assessment was focused primarily on the ramifications of nuclear safety and radiation contraints on space station operations. We also intended to recommend the most attractive reactor power system concept and to evaluate the merits of existing and near-term propulsion system concepts for the reactor end-of-life disposal to a wide range of ultimate destinations. The three concepts investigated were based on existing SP-100 program technology and used tether, single-boom, and dual-boom attachment to a projected dual-keel space station. A total radiation exposure dose of 20 rem was established for an astronaut's assumed 3-month occupation of the station. This dose consisted of approximately 75 percent natural background radiation and 25 percent reactor-attributed radiation. Human-rated shielding configurations were generated for each concept to provide radiation protection for a projected set of normal operating activities and locations including on-station activity (habitat and laboratory modules), normal and emergency extravehicular activity (EVA), and shuttle orbiter approach, docking, and departure. Allowable EVA time for end-of-life separation of a shutdown reactor power system was also considered.

Impulsive (chemical) energy requirements and propulsion vehicle system and propellant characteristics were identified for six potential final disposal destinations, ranging from a long-life, 1000-km Earth orbit to a solar system escape trajectory. A variety of existing and near-term expendable chemical upper-stage vehicles, both cryogenic and storable, were studied to identify their operational payloads and Δv capabilities. Also, a matrix of one-of-a-kind propulsion system components and reactor power system payload combinations was evaluated to identify potential attachment, integration, separation, and radiation safety issues as a function of time of attachment (i.e., from before reactor startup to after reactor shutdown).



Tether concept of nuclear reactor power system

C-2

The results of this assessment have generally confirmed the feasibility of installation, operation, and end-of-life disposal for the three concepts investigated. A number of open issues, however, remain with regard to definition of space station experiment requirements and their influence on reactor power system configuration and location.

All three attachment concepts were found to be compatible with boost to 1000-km Earth orbit at the end of life with any of the existing chemical propulsion, shuttle-compatible upper stages. For this disposal destination we recommend the payload-assist-module (PAM) upper stage be attached to and integrated with the nuclear power system after reactor shutdown. Should higher energy non-Earth-orbit disposal destinations be required, Earth-escape elliptical solar orbit is the preferred mode. Although the propulsive energy requirement is more than an order of magnitude greater than that for a 1000-km Earth orbit, it can be achieved by the lightweight tether mount concept with a Centaur G-prime-equivalent shuttle-compatible upper stage vehicle placed in low Earth orbit with a single launch. The heavier single- and dual-boom concepts can also be boosted to Earth escape but will require one-of-a-kind propulsion systems that are assembled in space following separate launches of the liquid propellant and the upper-stage hardware after reactor shutdown.

From the critical viewpoint of minimizing launch mass for installation and disposal the tethered reactor power system concept is clearly superior. This concept is a novel space application of terrestrial electric utility gas-filled transmission cable technology currently under study at Lewis. The tether concept achieves its low mass by trading shield mass for reactor-to-space-station separation distance. Also, the 2-km tether length minimizes radiation exposures for shuttle approach and departure.

We recommend that the electrolysis of water to produce gaseous oxygen and hydrogen propellant be investigated to assess potential launch mass savings. This propellant is attractive for boost to all reactor disposal locations, and the synergistic operational benefits associated with the use of water on the space station and volume-constrained shuttle launches may be significant.

Lewis contact, Harvey S. Bloomfield ((216) 433-6131)
Headquarters program office, OAST

Computational Technology Support

High-Performance Cray Stations

Cray X-MP/24

In January 1986 the first Lewis supercomputer, a Cray 1S, was replaced by the more powerful Cray X-MP/24. This machine is a vector computer operating at 9.5 nsec and has two central processors capable of functioning independently or in parallel, 4 million words of central memory, 64 million words of high-speed, solid-state memory extension, and 20 gigabytes of disk storage. Lewis user data were transferred from the old system to the new by using one of the capabilities of the unique Lewis Cray stations.

The Cray X-MP at Lewis is serviced by four high-speed channel-attached front-end interfaces (FEI's) that individually accommodate data transfer rates of 1.5 or 3.0 megabytes per second. Each FEI links the Cray to a front-end computer. The software that runs on each front-end computer, controlling data transfers and services to and from these FEI's, constitutes a "station." The speed of the FEI's, in conjunction with modifications and additions to Cray-supplied station software, enables each front-end system to closely couple its data processing and data base strengths with the Cray's computational power. This provides Lewis scientists and engineers with a most useful vector-processing capability.

The principal station to the Cray X-MP is an IBM-3033 running TSS, which is connected to two of the FEI's. The third FEI connects a VM/SP station on an Amdahl 5480, and the fourth FEI attaches a VAX-780 station. Because the TSS station is the oldest, having also serviced the Cray 1S, it has the most "customized" station software. Many of these customized features will be added to the VM station.

One station improvement added by Lewis is the ability to accept binary output files that have passed through an IBM converter routine on the Cray and to store them so that they can be read by IBM Fortran programs. The binary transfer is most useful in making motion pictures, where large volumes of data are transferred to the front end and processed by using the Lewis GRAPH2D and GRAPH3D graphics packages running on the IBM-3033.

Another station modification permits large Cray outputs to be stored on a temporary disk pool. The user is notified and—after freeing enough disk space or requesting more from his/her administrator—can retrieve the data set from the temporary pool. The user may also just ignore the message, and in a few days the data set will be automatically erased. This process has proved extremely beneficial in preventing the need for resubmitting very large jobs because of underestimates of the disk space needed for job output.

Since the Lewis Cray X-MP is fundamentally a "batch processor," job scheduling and station transfer rates are critical to good throughput. Although different daytime scheduling helps "debug runs" get through quickly, station features contribute to reducing the entire turnaround process. Editors residing on the front ends allow users to view part (or all) of a large Cray-generated data set, thus reducing the time required for checking output and making post-processing decisions.

Since the Cray peripherals and operating system are really not suited to data-base operations, another station duty at Lewis is to back up the Cray data base with a dedicated FEI and the peripherals of the IBM-3033. User access to tape is also provided through this system. This station will soon permit Cray users to move Cray data sets to the front end, where they will be stored on disk or tape and cataloged. User access will be by data set name. This will further free Cray disk storage for "active" data sets—those used within the last week or two.

Plans include a station feature that will accept "vector work," providing Cray services to IBM- or VAX-based applications. For instance, an IBM or VAX routine or group of routines, such as hidden-line generation, may also be available on the Cray in vectorized form. The station would honor the call for such a routine but send the job and the data to the Cray for high-priority execution. Because of the speed of the FEI's and the magnitudes of speed improvement resulting from vectorized code, this should be an extremely useful "value added" approach to Cray utilization, having the further benefit of keeping those applications not totally vector oriented on the more user-friendly operating systems.

Lewis contact, Dr. William F. Ford ((216) 433-5171)
Headquarters program office, OAST

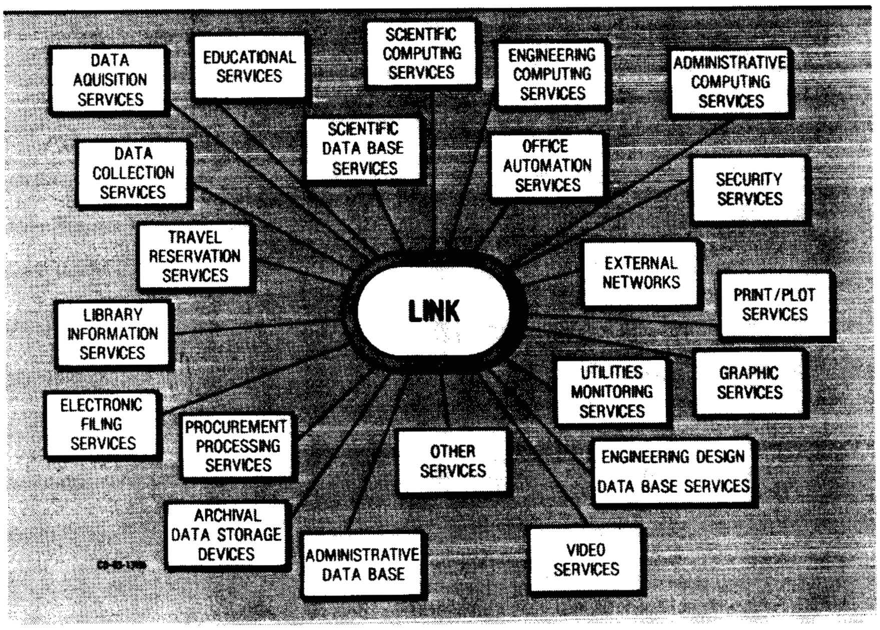
Lewis Information Network

The Lewis Information Network (LINK) is a dual-cable broadband local area network interconnecting all office and research test facilities at Lewis. The LINK system uses equipment and technology commonly available and found in cable television systems throughout the United States. However, Lewis uses this technology in much more diverse and specialized ways.

The LINK system simultaneously carries computer terminal data traffic, graphics data traffic, four channels of video, and real-time data from 50 research test facilities.

Probably the most visible manifestation of LINK is its capability to distribute video programming, both live and taped. Such programs include the Director's addresses, space shuttle coverage, and speeches by various visiting dignitaries.

One of the most significant improvements provided by the LINK system is in computer-terminal-to-mainframe communications. Before LINK, the most computer terminals that could be connected to Lewis computers was 256, through a simple electronic switch. Now, however, thanks to intelligent, frequency-agile modems transmitting across LINK frequencies, that number has increased to over 2000. Terminals and personal computers can now communicate directly with one another—something not possible with the old system.



Lewis Information Network (LINK)

The presence of the LINK system has given birth to distributed computer-aided designing (CAD). The Lewis version of CAD is called ICARE, for interactive computer-aided research and engineering. This system allows engineers and scientists to produce their ideas on remote computer workstations, in their own work areas, using graphical forms that allow for ease of redesign or alteration. This "real time" processing requires high-speed data transfer (over 1.5 million bits of information per second) that was not possible without the LINK system.

In addition to local computing capabilities Lewis computer users can communicate with computers throughout the world by means of the LINK gateway via telephone lines or Telenet (a commercial network). This also applies to inbound computer users for access of Lewis' large computer facilities such as the IBM-3033 and the Cray X-MP.

The ease of expanding the LINK system permits realistic but exciting goals. Short-term goals include video conferencing, electronic filing, travel reservations, educational services, utilities monitoring, security, and training. Long-term goals include continuous upgrading of components and expansion to utilize fiber-optic and digitized voice technology.

During 1986 the remainder of the major office buildings at Lewis have been cabled and are now fully operational. Educational video broadcasts such as NASA Update have become weekly occurrences.

With the LINK system in place, Lewis has become the first NASA site to have a totally integrated and operational communications network—a model for industry and other Government agencies.

Lewis contact, Dr. William F. Ford
((216) 433-5171)
Headquarters program office, OAST