NASA-TM-82949

NASA Technical Memorandum 82949

NASA-TM-82949 19830003820

Advanced Technologies for Turbomachinery Systems - An Overview

Melvin J. Hartmann
Lewis Research Center
Cleveland, Ohio

August 1982

NASA

ADVANCED TECHNOLOGIES FOR TURBOMACHINERY SYSTEMS - AN OVERVIEW*

Melvin J. Hartmann

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

Any performance gain in a turbomachinery system requires some advancements in a number of technology areas. The components (compressor, combustor, and turbine), materials, structural integrity, lubrication, bearings, sealing, and controls all must respond positively to a new and usually more demanding environment.

For more than 35 years a continuing fundamental and applied research program has been conducted at the NASA (formerly NACA) Lewis Research Center. Although about 10 years of this research program has been directed at advancements for aerospace propulsion and power generation systems, it provided considerable technology for a wide range of turbomachinery.

Currently a significant portion of this research is conducted in the Science and Technology (S&T) Directorate at Lewis. This paper presents a brief over-view of and status report on the research being conducted or sponsored by the S&T Directorate to further advance the technology for turbomachinery systems.

INTERNAL FLOW ANALYSIS CODES

Propulsion systems for advanced aircraft require lightweight, high-performance fans, compressors, cooled turbines, and propellers that are efficient over a wide range of operating conditions. The introduction into service of advanced turbomachinery components requires expensive accumulation of design and confidence-building experience. This experience is presently acquired through the costly and time-consuming procedure of experimental verification of empirically based incremental improvements in a given component, such as a fan, compressor, turbine, or propeller. The complex and interrelated nature of internal flow phenomena limits the performance of these propulsion components at many desired operating conditions. The attempt to understand and circumvent such problems through redesign and retesting has led to costly research and development cycles of new engines. The empirical step-by-step evaluation procedures formerly in use are prohibitively expensive both in dollars and time.

A reliable methodology for application of sophisticated numerical and analytical computer techniques could result in an impressive reduction in the cost and time required to perfect advanced turbomachinery components. However, much work needs to be done to develop practical analyses for three-dimensional, viscous, transonic, and unsteady flows, to verify these analyses, and to develop the methodology to interrelate them in a practical design-analysis system. Nevertheless, the payoff should be an impressive reduction in the cost and time of component development and a high level of confidence

*This is an extended version of the talk presented at the Eleventh Annual Turbomachinery Symposium sponsored by Texas A&M University, Houston, Texas, December 14-16, 1982.

in the resultant machinery. These components should be incorporated more readily and with improved results into advanced propulsion systems.

Turbomachinery Flows

A wide variety of flow characteristics is represented in the various types of turbomachinery. Figure 1 illustrates some of the many important flow features that a researcher would ideally like to compute. First, large axial, radial, and centrifugal pressure gradients occur within the flow passages because of fluid turning within the blade rows. Second, this turning of the fluid within the passages redistributes the incoming vorticity field and generates crossflows. At higher velocities strong shocks occur within the blade passages. These can be complex and interacting, and they in turn can generate their own additional vorticity fields. These shocks, of course, interact with the blade surfaces and end-wall boundary layers, often causing separation and additional blade loss.

A wide variety of viscous flow phenomena occur in the blade passages. Boundary layers exist on all blade and end-wall surfaces as well as on the surfaces of midspan dampers that may be present in the blade passages. Such boundary layers can have laminar, transitional, and turbulent regions. When pressure gradients are strong, of course, separation can also occur. Some separations may experience reattachment. There are also wakes downstream of all blade rows.

In addition to these common features, other more complex viscous flows redistribute the internal vorticity in the blade passages. For example, the horseshoe vortex, commonly encountered in turbines, is generated at the junction of the blunt leading edge and the end wall. Such vortices curl up, flow across the passage, and are shed downstream off the end wall or off the surface of the adjacent blade row. Another complex flow phenomenon is tip clearance flow, in which a vortex is induced by the leakage of fluid across the unshrouded tip of a rotating or stationary blade. In addition, the fact that half the blade rows operate in a rotating reference frame introduces the effects of centrifugal and Coriolis forces on both the mean flow and turbulence in these passages.

The resultant flow picture is an extremely complex one, particularly in the multistage environment of modern turbomachinery. No single analysis can hope to model all of these flow phenomena at the same time. In the analyses to be described, a number of approaches are used to divide this overall problem into problems of manageable size. First, the assumption is usually made to limit these analyses to a single blade row, either stationary or rotating. Next, within a given blade row, for a steady-state solution, the assumption is made that the flows in all blade passages are identical; thus only a single blade passage has to be analyzed. Within a blade passage the next decision to be made is whether a two or three-dimensional flow solution will be obtained. Obviously in a three-dimensional flow solution the entire passage is considered; however, many time assumptions are made to eliminate flows over the blade tips and/or the consideration of dampers that may exist in the blade passage. Beyond the decision concerning the dimensionality of the solution, a number of decisions can be made in the process of modeling the full flow equations down to a reasonable subset to be solved in the particular analysis being performed.

Flow Modeling

The ultimate equations a researcher would like to solve in any turbomachinery flow are the Navier-Stokes equations that govern general viscous fluid flows. However, solving these equations in their full form even on modern-day computers is quite time consuming. A great deal of information can be gained in most flows through solving a simplified form of the Navier-Stokes equations, in which all of the viscous terms have been neglected. These are the governing equations for inviscid flows, known as the Euler equations. Their irrotational limit reduces to the well-known potential flow equation.

A great deal of progress has been made in the last 10 years in the development of solutions to the full potential equation for internal turbomachinery applications. This equation admits the existence of discontinuities in the flow field. However, these shocks are isentropic and therefore will only have the proper strength and location if the Mach number of the flow approaching the shock is less than 1.3. Illustrative results obtained from a potential flow model [1] are shown in figures 2 and 3. Figure 2 shows Farrell's computation for a supercritical,"shock free," compressor stator tip section designed for NASA Lewis by Sanz using a hodograph technique [2]. The trailing edge of this blade ends in a cusp. The inlet Mach number is 0.71 and the inlet flow angle is 31.16^{o}. The results show that the rapid compression is captured very accurately by the potential method without any overreaction or steepening to form a shock.

Figure 3 indicates the importance of quasi-three-dimensional streamtube effects in the transonic flow regime. This figure shows a series of calculations performed on a thick compressor stator hub section, developed for NASA Lewis by Sanz. Farrell's approach was first used to calculate strict two-dimensional flow over the blade. This agrees very well with the Sanz hodograph solution, except at the trailing edge, where in Farrell's analysis the idealized blade of infinite length was replaced by a blade with constant trailing-edge radius. The remaining two curves on the figure show the effects of radius change and streamtube convergence. In the first of these curves, a streamtube convergence of approximately 14 percent (axial velocity density ratio, 1.15) was imposed, with no radius change in the streamsheet. The streamtube convergence strongly increases the Mach number on the suction surface of the blade, so that the presence of a reasonably strong shock is evident. In the final curve the opening up of the passage caused by a radius change of 5 percent entirely relieves the effect that was evident previously. The increasing radius has a strong decelerating effect on the flow since the blade-to-blade passage now diverges in the downstream direction. The differences evident in these three curves suggest very strongly the requirement to consider quasi-three-dimensional effects in transonic design situations.

Explicit solutions to the Euler equations have also been under development for a number of years, with applications for internal flow situations dating back to the 1950's. An explicit method is one in which all spatial derivatives are evaluated by using known conditions at a previous time step. Furthermore information at the new time level depends on information obtained from only a small number of points. The resultant methods are simple and easy to code. All such methods, however, are limited by the so-called Courant, Friedrichs, and Lewy (CFL) stability limit, which states that the domain of dependence of the numerical finite difference scheme must contain the complete domain of dependence of the original hyperbolic differential equations.

A major milestone in the development of explicit methods was the paper by MacCormack [3]. Under contract to NASA, Thompkins of M.I.T. has applied the

MacCormack algorithm to flow through a three-dimensional transonic compressor rotor [4]. This method can be applied to any general compressor blade shape, including those with part-span shrouds. Thompkins' code has been used [5] to calculate the three-dimensional flow field within a transonic axial compressor rotor at design speed and to compare those results to laser anemometer measurements at maximum-flow and near-stall operating points. Figure 4(a) shows Mach number contours for the measured laser anemometer results at a section 15 percent from the tip of the blade. These results can be compared with the calculated contours in figure 4(b) at the same location. These figures indicate a pronounced bow wave and passage shock system and show excellent agreement between the measured and calculated results.

A number of new Euler algorithms are under development at NASA Lewis. A procedure has been developed [6] for solving the first-order steady equations by embedding them in a system of second-order equations. Also developed [7] has been a technique for accelerating the convergence of explicit, two-step, Lax-Wendroff algorithms by introducing multiple-grid procedures. This work should result in the development of more efficient inviscid codes. Finally, a new class of algorithm has been developed [8] that uses fast, direct, Poisson solvers in the solution of three-dimensional, inviscid secondary flows. The method is expected to be applicable to the turning passages of turbomachinery blade rows.

A number of viscous flow codes for turbomachinery problems are also under development at NASA Lewis. The boundary conditions of the two-dimensional viscous cascade code [9] have been modified, and the code is being applied to several compressor and turbine cascades. This code is being extended to the quasi-three-dimensional blade-to-blade stream surface of a rotating blade row. Bodonyi, under a grant from NASA Lewis to Indiana-Purdue, has developed an inverse two-dimensional boundary layer code that analyzes a transitioning laminar separation bubble. This work awaits the acquisition of detailed experimental data for code verification and model improvement. Briley, of Scientific Research Associates, Inc., under contract to NASA Lewis has developed a viscous marching code for three-dimensional flows in turning ducts [10]. NASA Lewis is currently extending this code to cascades with flat end walls and constant spanwise blade sections. In addition, a three-dimensional viscous marching code for a rotating turbomachinery blade row is being developed.

Two codes have recently been developed under NASA Lewis sponsorship to design cascades that are shock free in supercritical flow. Sanz [11] has extensively modified the complex characteristic procedure of Bauer et al. [2] to permit the design of cascades with high turning and solidity. Under NASA grant, Beauchamp and Seebass incorporated the fictitious-gas approach of Sobieczky [12] into the potential code of [1]. This method provides a way to modify the supersonic portion of the contour of an existing blade to produce shock-free operation.

A substantial effort has been devoted to grid generation at Lewis. Conformal mapping techniques have been used [13] to develop body-fitted and C-type grids for turbomachinery blades. A different conformal mapping technique [13] has been used to generate C-type grids for viscous flows through turbomachinery blading. Both techniques can be used to generate three-dimensional grids by stacking.

Most turbomachinery codes in use today, both inviscid and viscous, are based on older long-running algorithms. Since solution of the Euler equations is now one of the most active areas of research in computational fluid mechanics and since a number of promising new methods are under development, this situation should soon be much improved.

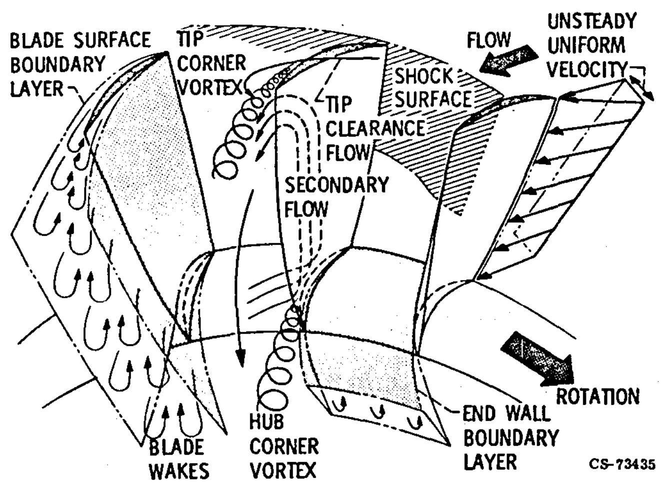


Figure 1. - Turbomachinery blade row flow features.

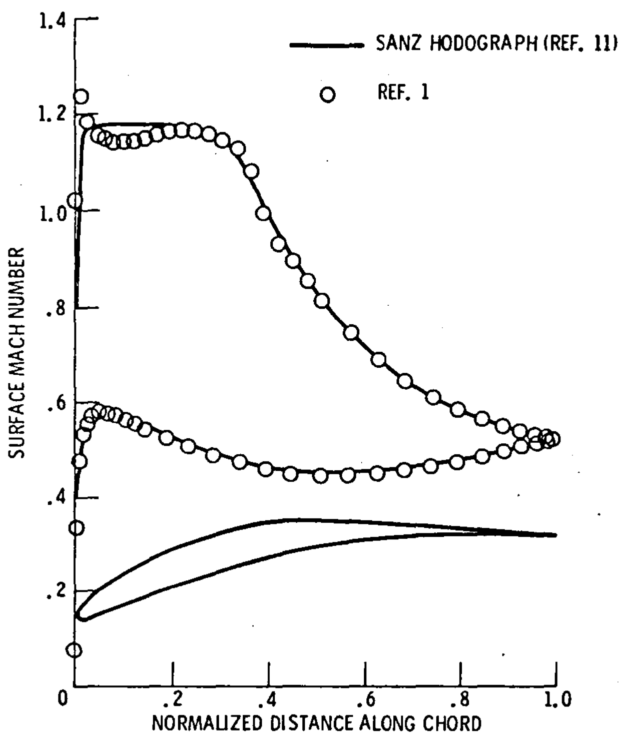


Figure 2. - Supercritical stator comparison.

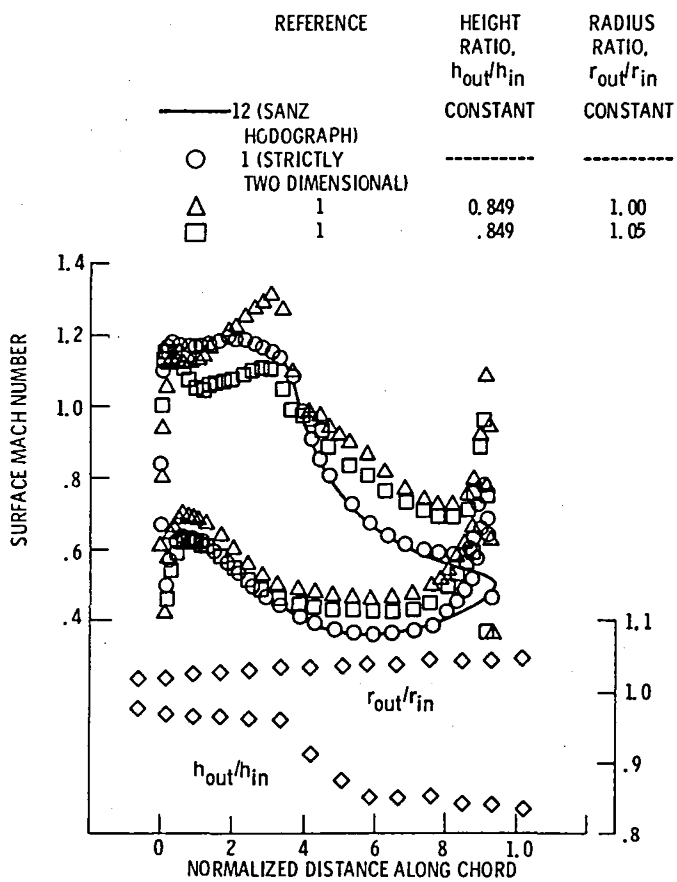


Figure 3. - Effect of streamtube thickness and radius change on flow about supercritical stator hub section.

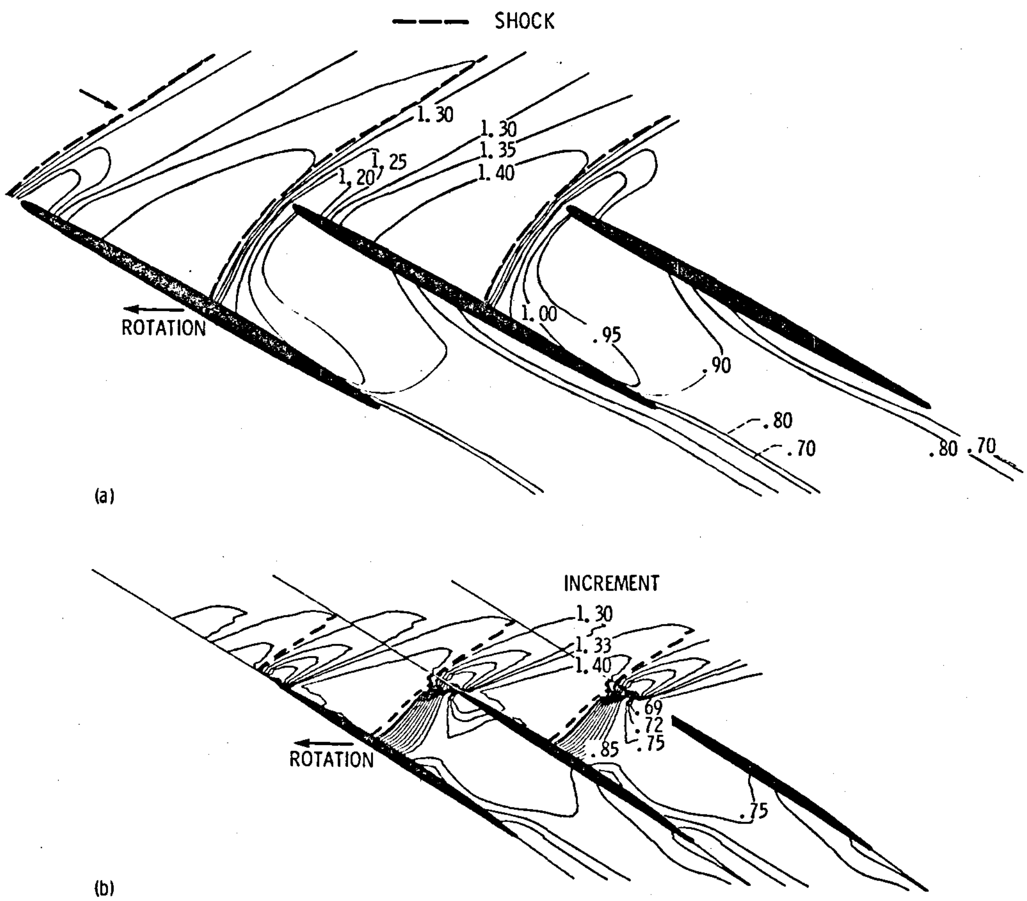


Figure 4. - Comparison of calculated and measured flows near tip of NASA transonic compressor rotor.
(a) Measured Mach number contours.
(b) Calculated Mach number contours - Thompkins method.

COMPRESSOR RESEARCH

Compressor research is directed toward (1) understanding and modeling the very complex internal flows and (2) providing advanced technology covering the different types of compressors (axial, centrifugal, and multistage), a broad range of compressor size (from 2- to 200-lb/sec flow), and a wide variety of fluid flows (e.g., subsonic, supersonic, unsteady, low Reynolds number, and distorted). Figure 5 reflects the scope of the compressor research activities, notes specific thrusts, and identifies needs and opportunities.

Currently most compressor design and analysis systems depend strongly on empirically based inputs (e.g., estimates of loss, fluid turning, blade loading parameters, and blade stall indicators). Design system improvements are directed toward moving from an empirical system to a "first principle" design system (i.e., a more direct inclusion of the flow physics). The two approaches to achieving this are to apply analytical codes to compute the internal flow through the entire flow passage and to develop improved experimental techniques that provide visualization and measurements of code verification data obtained in basic flow configurations as well as in the high-speed rotating blade passages. The goal of this effort is sharp improvement in both the accuracy and reliability of the design system. This would significantly reduce the time and costs required to incorporate new research concepts into production engines.

Advanced concepts deduced from analytical and experimental studies that indicate potential for improved performance are applied to new single and multistage designs. Analytical studies, for example, have suggested controlled-diffusion and supercritical, "shock free," blade shapes for improved flow over the blade surfaces. Experimental studies, for example, have suggested end bends and casing treatment configuration to improve flow in the end-wall regions. Novel concepts, which are usually high in risk but with high potential gains, are also studied. Examples of the latter are the supersonic through-flow and variable-flow compression concepts.

A research program to understand the flow and design problems in small compressors is being pursued at NASA Lewis. These compressors, which cover flow sizes from about 10 lb/sec down to 2 lb/sec, include those used in engines for helicopters, small business planes, cruise missiles, and auxiliary power units. This program addresses the size effects for both axial and centrifugal compressors. Of course, a strong effort will be made to formulate relevant scaling laws.

An unsteady component to compressor flow is introduced by wakes from upstream blade rows, wind gusts, aircraft maneuvers, and inlet flow distortions, as well as by time-unsteady flows. The interaction of the blades with the unsteady flows can lead to some performance degradation, noise generation, stability limitations, and severe blade vibrations. In the compressor program these unsteady flows are being studied as they influence the specific phenomena of blade flutter, forced vibrations, and stage stall inception and recovery.

Basic Flow Studies

A number of basic flow studies are being sponsored by NASA Lewis to provide experimental flow data to use in verifying new codes. These contractual studies, which are in progress but have not as yet published results, include studies of two and three-dimensional flows through ducts and cascades:

(1) At Nielsen Engineering, Inc., the three-dimensional flow through a large-scale, rectangular, curved duct with two divergent walls is being studied. Detailed flow measurements, particularly those on an entrance plane, will provide a consistent set of verification data to apply against three-dimensional computed results.

(2) At Penn State University, the two-dimensional boundary layer flow on the surface of a blade in cascade is being investigated. Laser-anemometer measurements of the laminar, transition, and turbulent portions of the boundary layer on a 9-inch-chord blade will be obtained.

(3) At United Technologies Research Center (UTRC), the two-dimensional turbulent boundary layer separation and reattachment on a long flat-plate surface are being studied by using laser-anemometer measurements.

(4) At Purdue University, under the direction of Dr. Sanford Fleeter, a 50-inch-diameter, low-speed annular cascade is now operational. The three-dimensional flow through typical inlet guide vanes and stator flow passages will be measured to provide verification data sets to apply against a variety of analytical codes.

Axial Compressors

At NASA Lewis advanced axial designs have been strongly influenced by three developments:

(1) Polynomial blade shape formulation by Mr. James E. Crouse of Lewis - This analytically defined shape is composed of two segments - the mean-camber-line angle and the thickness distributions of each segment specified by a fourth-order polynomial expression. The formulation provides increased control of the chordwise turning and area distribution. The shape is described in [14].

(2) Controlled diffusion concept - In this concept an optimized blade surface velocity distribution is specified and a blade shape designed to provide it. Basically the velocity distribution is a relaxing one that maintains the turbulent boundary layer close to a separation state. If a supersonic pocket occurs, the method of Sobieczky [15] is used to modify the shape for shock-free flow.

(3) Low-aspect-ratio blading - Experimental results have consistently shown that, at high blade loading levels, stall margin and efficiency were improved with low-aspect-ratio blade rows. Figure 6 demonstrates the effects of aspect ratio on the performance of a high-Mach-number stage.

Concepts to improve the efficiency of the end-wall flows were studied experimentally under contract by General Electric (GE) and Pratt & Whitney. These studies [16,17] were conducted in multistage configurations at subsonic speeds. Pratt & Whitney demonstrated that low-aspect-ratio blading had a larger stall margin but a slightly lower efficiency than the higher aspect-ratio blading. The P&WA performances are compared in figure 8. The General Electric studies demonstrated a small efficiency increase and a significant stall margin increase when the blade sections in the end-wall regions were twisted closed (end bends) to match the inlet blade angles with the airflow angles. These results are shown in figure 9.

Additional contractual experimental studies of end-wall flows are being conducted at Penn State University by Professor Lakshminarayana and his coworkers; and studies of secondary flows, at UTRC by Dr. R. Dring.

Efforts to improve measurement techniques are focused primarily on development and use of the laser-anemometer system [18]. This technique can be used to map the velocity field within rotating or stationary blade passages, including some velocities within the boundary layer. Figure 10 schematically shows a laser optical configuration and compares the measured and calculated Mach number contours within a transonic rotor passage. These preliminary results [19] are very encouraging.

At present a more complete mapping of the flow field through the rotor and stator of a transonic stage - designated stage 67 - is in progress. This low-aspect-ratio transonic stage has been selected to provide "benchmark-like" comparisons of measured and calculated flows in a NASA, university, and industry cooperative effort.

Multistage core compressors are being studied in three-stage configurations 20 inches in diameter with blade tip speeds from 1400 to 1500 ft/sec and a pressure ratio of approximately 4.5. All stationary vane rows can be reset remotely.

The overall performance of the three-stage compressor designated 74A-2 is shown in figure 11. Design values for pressure ratio and weight flow were 4.45 and 65.5 lb/sec, respectively. The performance data show the overflowing and relatively poor efficiency at design speed but reasonably good performance at the lower off-design speeds. The design parameters responsible for the operation were identified and an optimization test procedure was followed to determine a vane schedule that would maximize performance. Figure 12 shows the performance with a vane schedule that maximized performance at design speed (increased efficiency about 8 points) but resulted in a sharp decrease in lower speed off-design performance. Figure 13 shows the performance with vane schedules that optimized performance at each blade speed. This optimization procedure is reported by P&WA [20].

Centrifugal Compressors

The decision to devote more research effort to the components of relatively small gas turbine engines generated a need for more knowledge and understanding of the design and performance of the centrifugal compressor. The Centrifugal Compressor Section (under the direction of Mr. Jerry R. Wood) was formed to meet that need. To assure relevant research, study contracts were let with GE, Detroit Diesel Allison (DDA), and AiResearch to project technology improvements that could be achieved by the 1990's and to define the optimum compressor staging arrangement (centrifugal, axial, or axial centrifugal) for each of three flow sizes (2, 5, and 10 lb/sec). From these studies, the axial-centrifugal compressor configuration emerged as the strongest contender for use in efficient and cost-effective future engines in the 10-lb/sec size. The axial-centrifugal and two-stage centrifugal configurations were judged to be optimum for 5-lb/sec engines. The centrfigual compressor was the popular selection for the smallest engine size (2 lb/sec) evaluated.

The current system for designing and analyzing centrifugal compressors uses several two-dimensional inviscid flow analysis codes and two-dimensional boundary layer flow codes to critique new design configurations. One recent improvement to the design-analysis system is the availability of a three-dimensional inviscid flow code. This code was developed by Professor John Denton of Cambridge University [21]. Dr. Denton is currently modifying the code to accommodate splitter blades within the flow passage and to make the inviscid flow calculations interactive with a two-dimensional integral boundary layer code.

Under contract with NASA, the Naval Postgraduate School (NPGS) at Monterey, California, is building a radial diffuser cascade. This facility will operate under the direction of Mr. John Irwin. It will be used to experimentally study various flow concepts and to provide data to verify analytical code output. In particular, verification data will be needed to compare with a new three-dimensional viscous flow code to calculate flows in radial diffusers being developed by Mr. Harry McDonald of Scientific Research Associates, Inc., for NASA.

Unsteady Flows

In 1975, a symposium on unsteady flows [22] held at the University of Arizona clearly indicated that unsteady flow effects would soon be a major area of interest. Initial unsteady flow studies at Lewis have been directed toward support of blade-flutter, forced-vibration, and stall-recovery research, as shown in figure 14. Obviously the unsteady aerodynamic codes must be coupled with structural dynamic codes to form a reliable aeroelastic prediction system. The studies are all directed toward providing a more fundamental understanding of the physical phenomena involved, developing reliable analytical codes to predict the unsteady flows and aerodynamic forces under various operating conditions, and verifying the analytical codes.

Some very significant advances toward understanding and predicting flutter have been made. The supersonic and subsonic flow types of flutter and the compressor operating conditions at which they occur are noted in figure 14. Analytical codes to predict the onset of flutter with supersonic flow have been developed [23,24] and have been reasonably success. However, a flow model to reliably predict the onset of the subsonic-transonic stall flutter regions is not yet available.

Experimental data in and near flutter have been obtained from cascades and from high-speed, single-stage tests. At UTRC, Dr. Frank Carta is investigating the periodicity of an oscillating cascade of blades. At NASA Lewis an oscillating linear cascade was built and is now operation- al. Both flow visualization and dynamic flow measurements are provided. Figure 15 shows the facility as well as schlieren photographs of the flow over the blade section.

Under contract with GE and P&WA, high-speed, single-stage tests provided experimental data during operation in and close to supersonic and subsonic flutter conditions. These data [25,26] included both steady-state and dynamic flow measurements as well as dynamic measurements of blade movement. One interesting concept that came from these studies was that the flutter boundaries could be moved by rearranging the blades around the rotor - called mistuning. It was deduced that the natural frequency of the individual blades will vary and that, by judiciously arranging the blades about the periphery of the rotor, the flutter boundary could be controlled to some extent. Additional tests are needed to explore the generality of this concept.

Both the forced-vibrations program and the stall-recovery program are in formative stages. The goal of each program is to develop the analysis methods for predicting both the unsteady air loads due to nonaxisymmetric flows and the stalling performance characteristics of the compression system. Experimental data from singleand multistage compressors will be used to validate the analytical models.

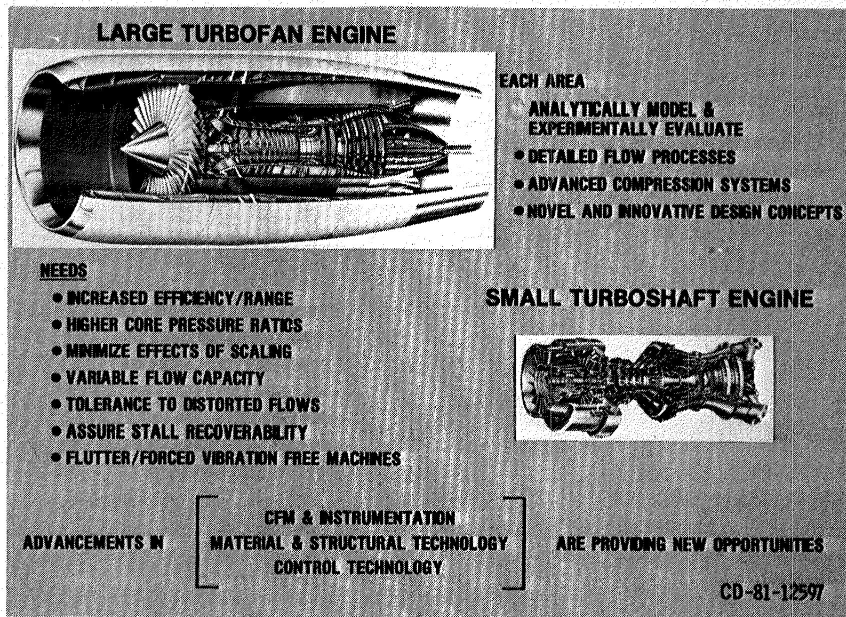


Figure 5. - Fan and compressor research areas.

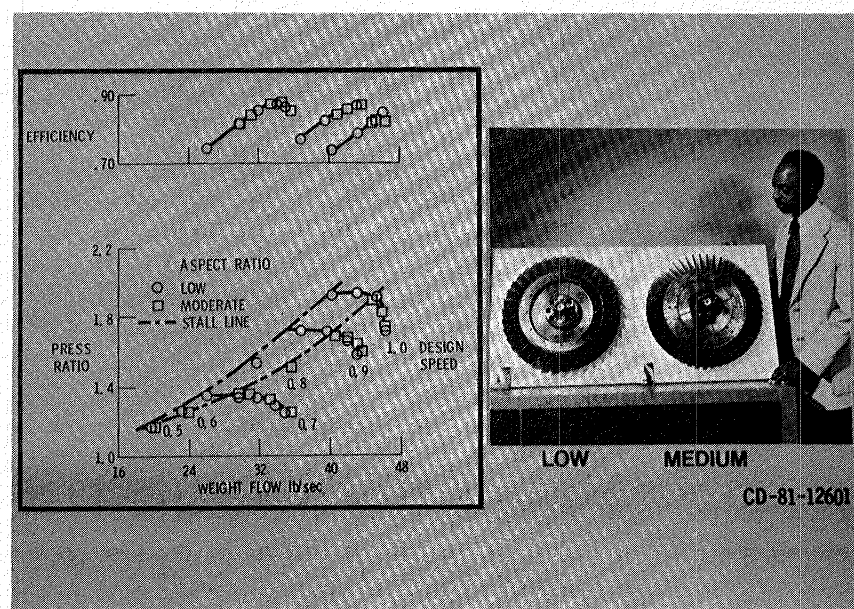


Figure 6. - Effect of aspect ratio on performance of high-tip-speed core inlet stage.

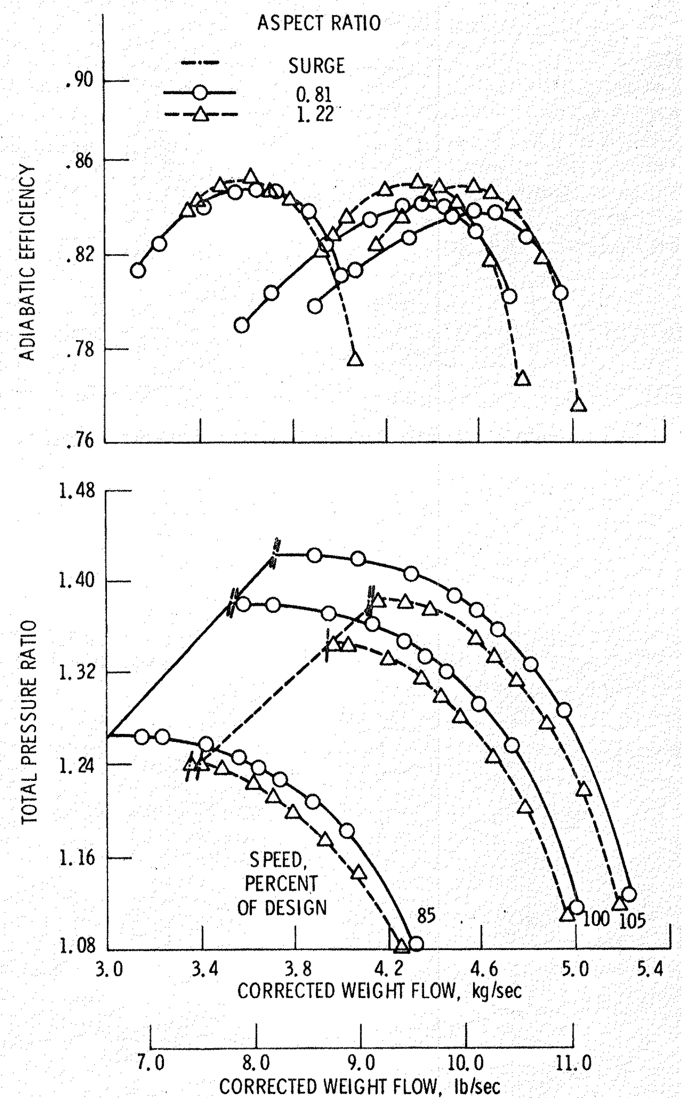


Figure 8. - Effect of aspect ratio on overall performance, based on average of six repeated test speedlines.

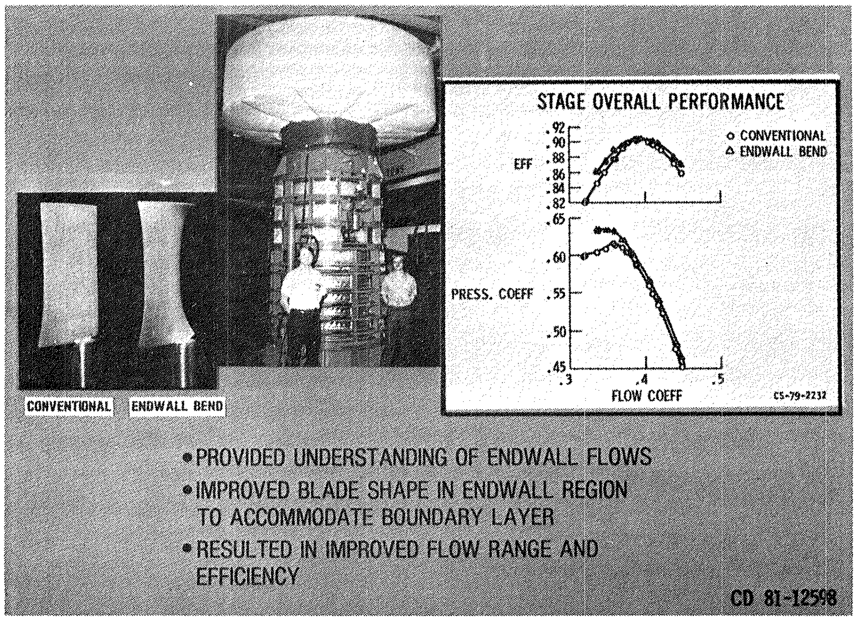


Figure 9. - Large low-speed compressor research - end-wall flow fundamental experiments.

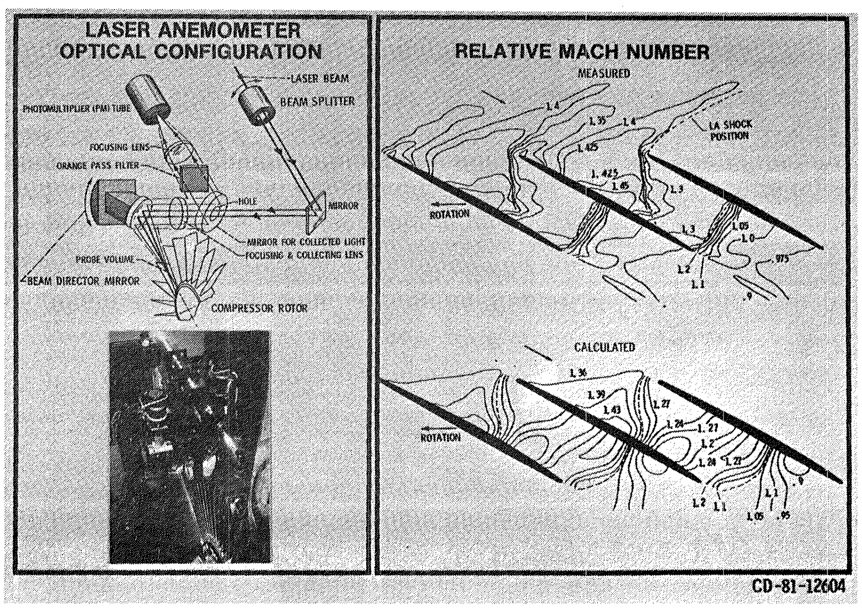


Figure 10. - Advanced methods for compressor flow research.

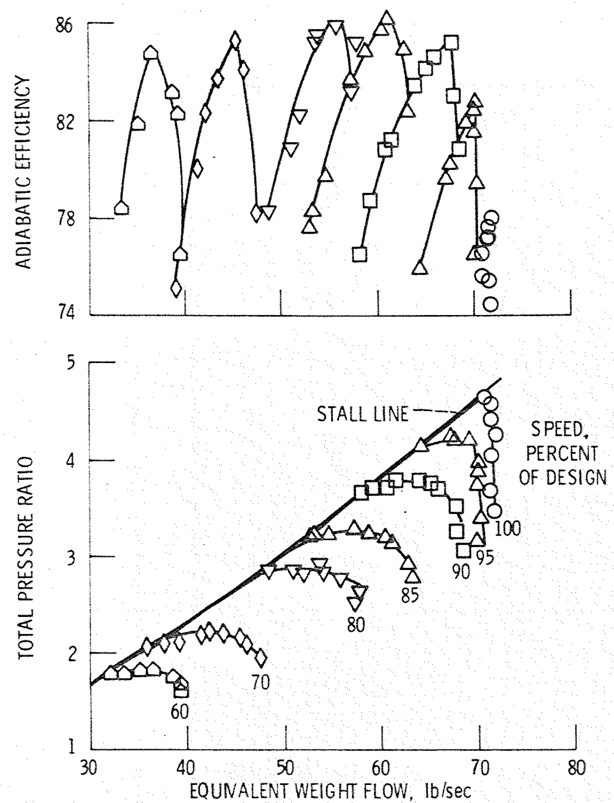


Figure 11. - Overall performance with design inlet guide vane and stator vane settings - three-stage compressor 74A2.

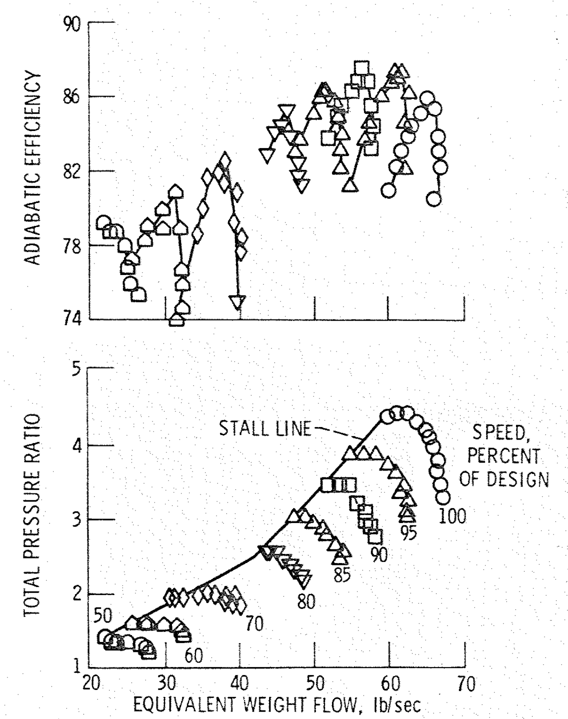


Figure 12. - Overall performance with vanes scheduled for optimum design-speed performance - three-stage compressor 74A2.

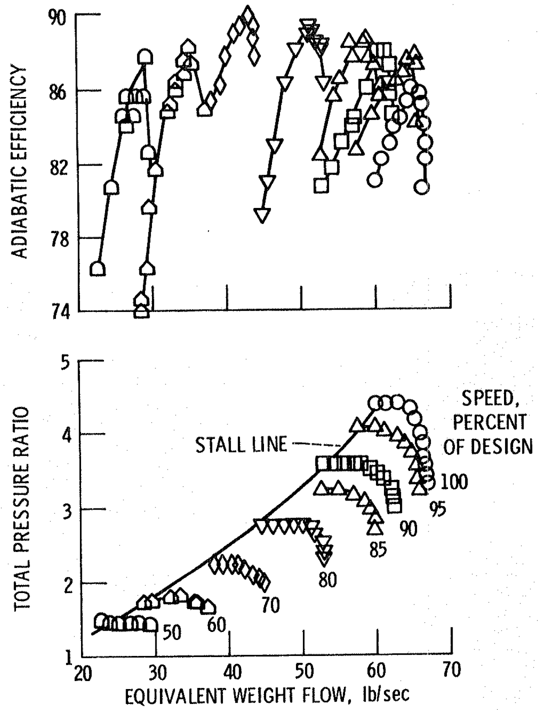


Figure 13. - Overall performance with vanes scheduled for optimum performance at each speed - three-stage compressor 74A2.

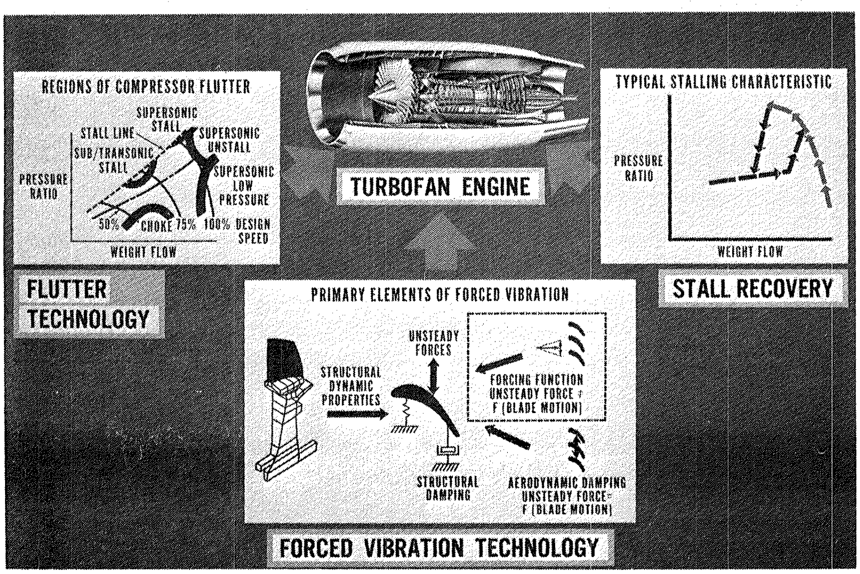


Figure 14. - Turbomachinery unsteady-flow aerodynamics research.

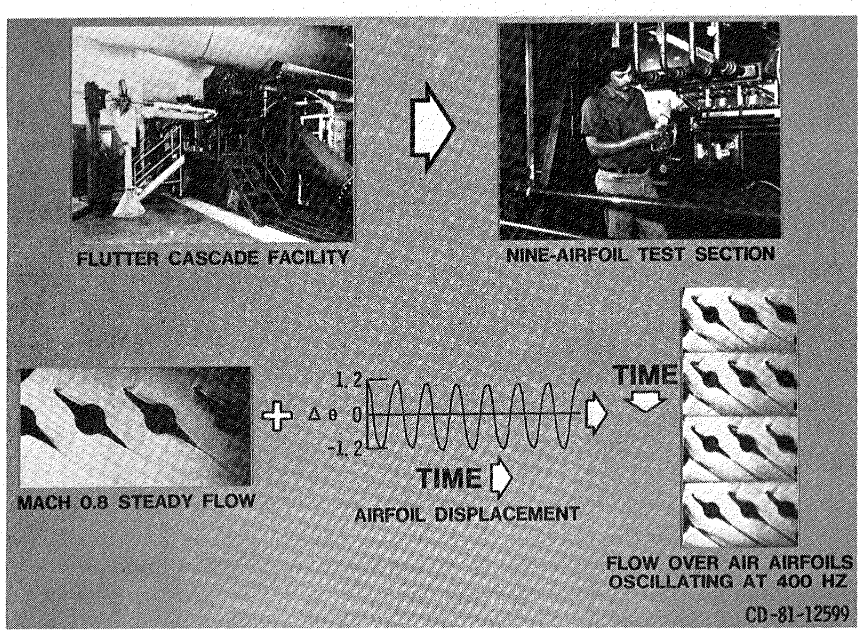


Figure 15. - Fan and compressor transonic flutter research.

TURBINE RESEARCH

Current aerodynamic design technology consists largely of two-dimensional flow field computer codes with empirically determined loss correlations for various blade-shape, stage-loading, and end-wall effects. Heat transfer calculations include two-dimensional boundary layer codes based on flat-plate data and modified by geometry and heat transfer empirical correlations. This technology provides highly efficient aerodynamic blade shapes for large turbines that perform as predicted. The heat transfer techniques, however, result in uncertainties as high as 35 and 25 percent in gas-side and coolant-side heat transfer coefficients, with consequent uncertainties up to 100 K (180° R) in local metal temperatures. This, in turn, results in life prediction uncertainty factors greater than 10. In small axial turbines, efficiencies range from 2 to 10 percentage points lower than those of large turbines with comparable loading because of size-related penalties in such areas as inlet boundary layer thickness, surface roughness, and low aspect ratio. Small radial turbines perform with high-design-point aerodynamic efficiency but require excessive coolant flows and have less than satisfactory part-power performance.

The improvements in turbine design technology required for continued U. S. leadership in the aircraft engine industry will come largely from a thorough understanding of boundary layer behavior in turbine passages and the concomitant ability to predict this behavior. Critical elements in the development of rigorous computer codes for hot-gas flow field prediction include precise, noninterfering instrumentation, thorough experiments for accurate modeling, and experiments in near-engine environments to validate the computer codes. Figure 16 shows schematically the current technology, expected technology 10 years from now, and the general efforts required to get there.

For this presentation the NASA Lewis turbine research program is divided into three areas: fundamentals, axial turbines, and radial turbines.

Fundamental Fluid Mechanics and Heat Transfer

The objective of work in fundamental fluid mechanics and heat transfer is to increase knowledge and understanding of basic flow and heat transfer mechanisms so that more accurate models of boundary layer behavior can be developed. Heavy emphasis is placed on boundary layer transition as it is influenced by turbulence, surface curvature, and unsteadiness in the flow. Also, separated regions, secondary flows, and effects of rotation are being studied. Coolant flows inside the blades, where maximum heat transfer is desired, are being studied for effects of trip strips, pin fins, multipass channels, and rotation.

Figure 17 shows the result of an experiment made to refine the prediction capability for heat transfer on internal pin fins [27]. Note that the measured heat transfer on the pin surfaces is only about half of the reference value from the literature that had been used in pin fin design. One current Lewis grant is a study of end-wall flows with two cylinders simulating vane leading edges. A technique for visualizing end-wall flow with ink dots was devised by Professor L. S. Langston of the University of Connecticut [28]. The technique has been used to look at end-wall and blade-surface flows in a two-dimensional cascade of vanes. Figure 18 shows the flow patterns as visualized from the ink dots. Note that the entire inlet boundary layer rolls up into the horseshoe vortex structure and exits the vane passage in the suction-surface end-wall corner flow.

Axial-Flow Turbines

Detailed flow and heat transfer measurements are being made in cascades and rotating blade rows to develop viscous flow analysis and performance prediction techniques for improved aerodynamics, cooling, and variable geometry. The environmental factors that influence coolant-side and hot-gas-side heat transfer are being studied to improve the accuracy of metal temperature prediction and to advance cooled turbine technology for future engines. Current specific programs are studying the effects of combustor exit flow profiles on turbine aerodynamics and heat transfer, the effects of interspool duct losses on turbine performance [29], definition of the real engine turbine environment, the effects of size and the losses associated with variable geometry. Figure 19 shows the effect of interspool duct boundary layers on the performance of a small turbine. The separated boundary layer resulted in a turbine efficiency loss of 7 percent from the efficiency measured with the unseparated flow pictured for the accelerating duct. One more configuration with very thin inlet boundary layers will be studied to further define the performance penalty associated with turbine inlet boundary layer thickness.

Flow field mapping with noninterfering techniques is very important and very difficult. A technique was recently developed at NASA Lewis to measure the radial component of velocity in a turbine vane cascade. This very small component is measured with a line-of-sight laser system that employs a Doppler-shifted signal to separate the velocity signal from the background noise [30]. Figure 20 shows an example of the signal and background noise separated to determine the radial component of velocity.

Radial-Flow Turbines

NASA Lewis programs in radial-inflow turbines are related to applications in high-performance engines for helicopters and inexpensive engines for automobiles. Both applications require very high inlet temperatures and good part-power performance. Much of the effort therefore involves cooling, ceramic parts, and variable geometry. High-work stages are employed. There is a companion effort in the modeling of inlet scroll flow.

Figure 21 shows a section through a variable-geometry engine designed to provide a 2:1 power output range with no change in the engine cycle and a corresponding 2:1 range in engine flow [31]. There are variable compressor inlet guide vanes, variable diffusers, and variable turbine stators. This engine employs translating end walls in the compressor diffusers and the radial turbine stator. NASA Lewis currently supports contract experiments to determine performance and detailed loss characteristics for this radial turbine.

Another contract effort is developing a new approach in fabricating radial turbine rotors with very complex internal cooling passages [32].

Figure 22 shows the split-blade concept. The rotor is cast with the blade split as shown. Iron inserts having holes and slots filled with a high-temperature material are then hot-isostatic-press bonded in the blades. The iron inserts are subsequently leached out leaving internal passages with reversing flow, pin fins, and trip strips that allow minimum-loss ejection of the coolant largely from the trailing edge.

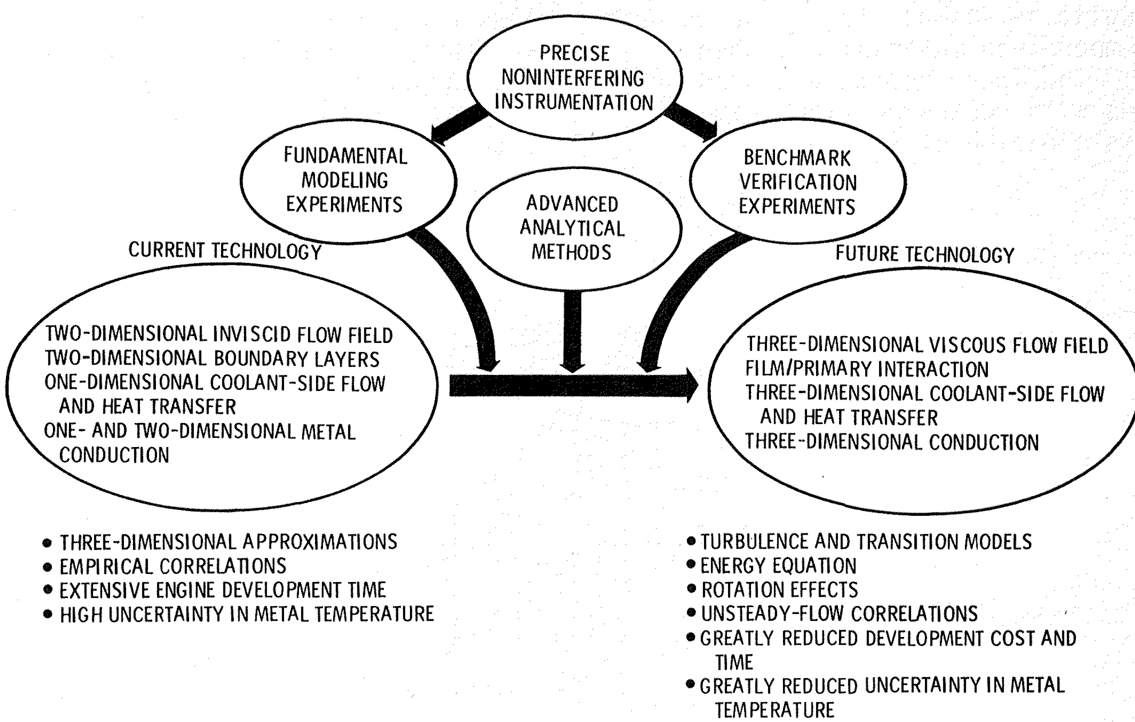


Figure 16. - Turbine research overview.

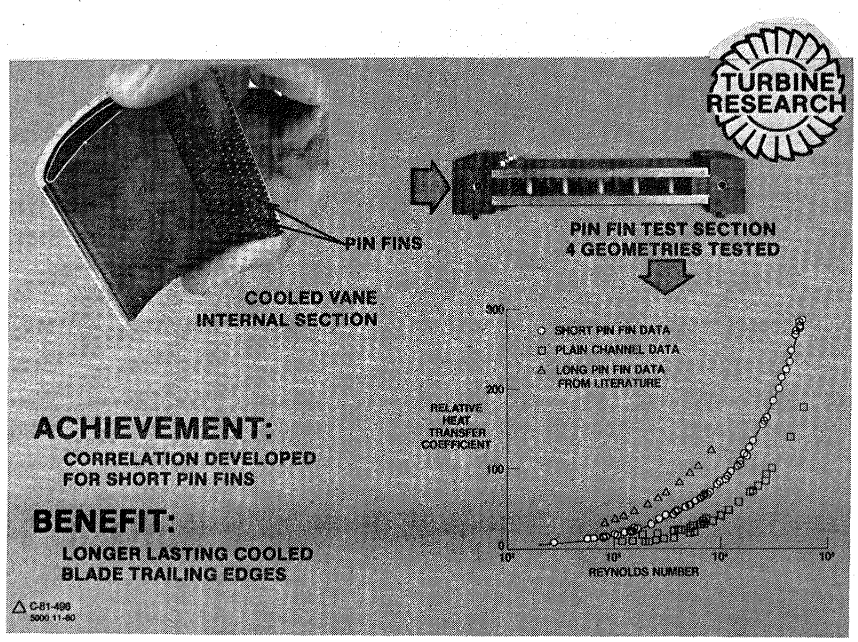


Figure 17. - Short-pin-fin heat transfer.

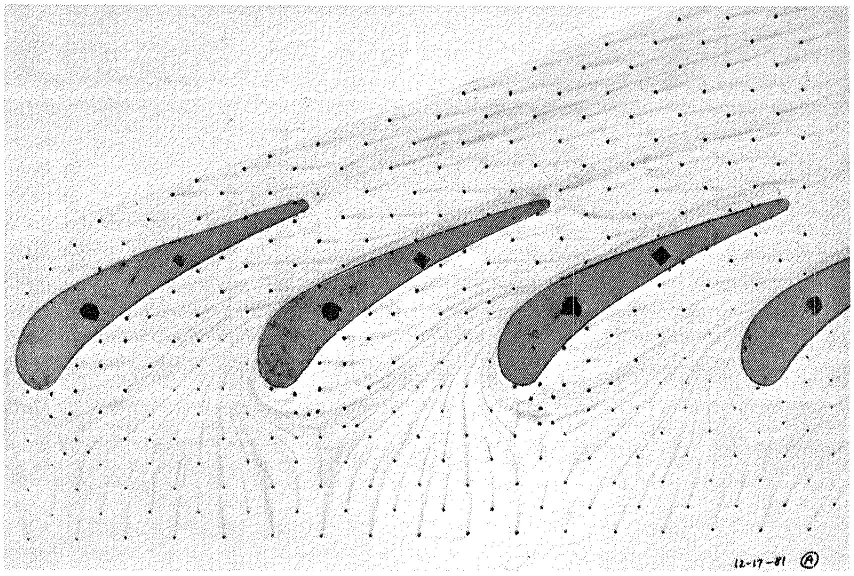


Figure 18. - Technique for using ink dots to visualize end-wall flow.

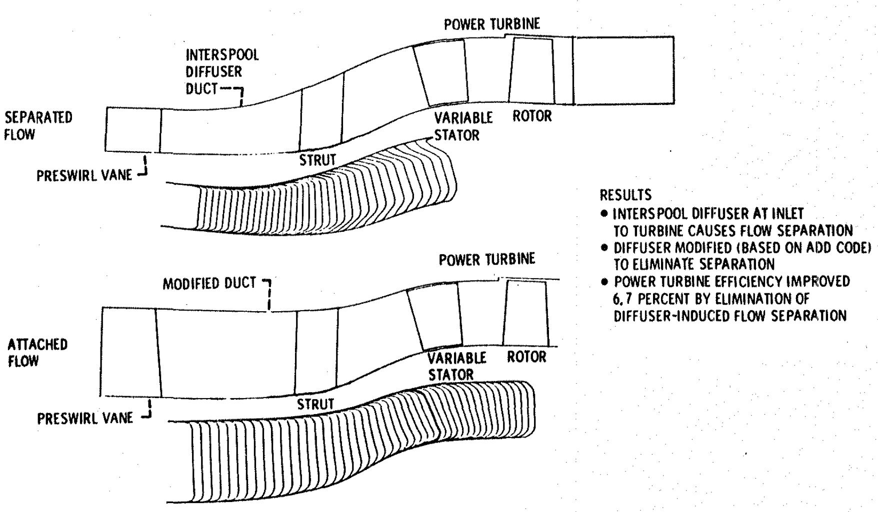
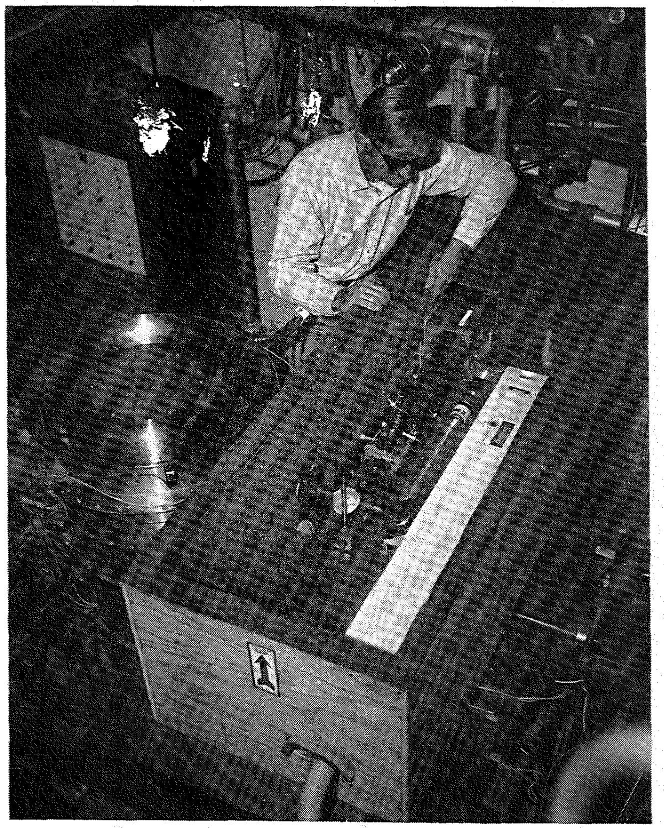
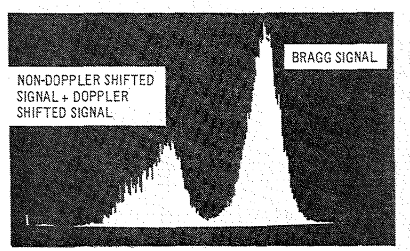


Figure 19. - Improvement in small axial turbine performance.

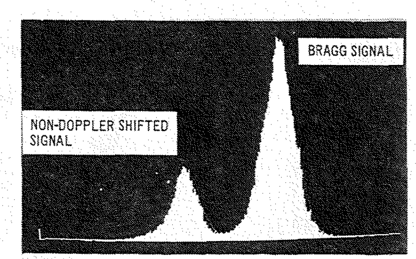
LASER AND CASCADE



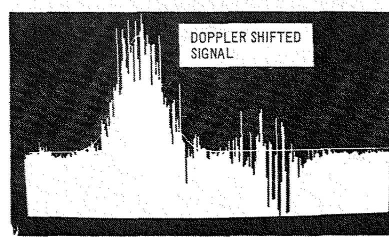
ANNULAR CASCADE LINE-OF-SIGHT
VELOCITY COMPONENT MEASUREMENT



SEED ON



SEED OFF



DOPPLER-SHIFTED SIGNAL(= A - B)

Figure 20. - Line-of-sight laser anemometer and measurement.

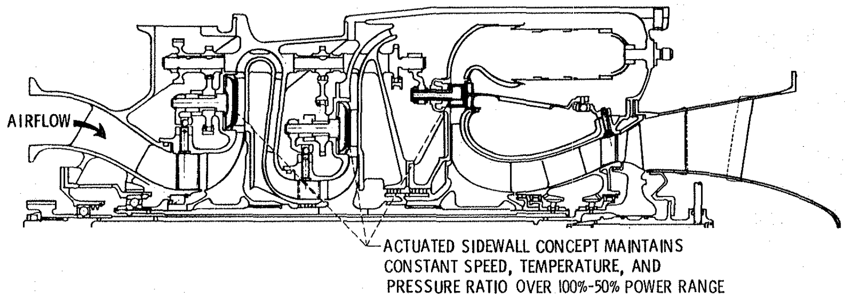


Figure 21. - Army-NASA radial-inflow turbine technology program.

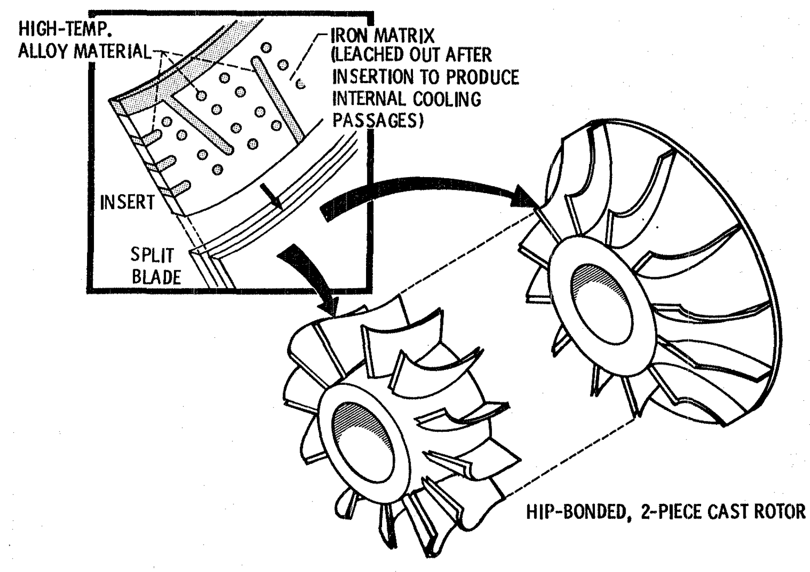


Figure 22. - Fabrication of cooled radial-inflow turbine rotor.

MATERIALS RESEARCH

The historical growth in the performance of aircraft gas turbine engines has been largely controlled by advances in the closely related areas of materials development and materials processing (fig. 23).

High-performance alloys, ceramics, polymers, and composites have become available for use in components and have allowed increases in engine operating temperatures, lightened engine weight, and extended engine life. To manufacture these complex components, new materials processing procedures have been developed, for example,

(1) Directional solidification of superalloys, leading to oriented and single-crystal airfoils with high axial strength and increased thermal fatigue resistance [33]
(2) Sintering and reaction bonding of ceramics, leading to high density and improved reproducibility of airfoil parts
(3) Powder metallurgical techniques plus hot isostatic processing, allowing alloy compositions that were almost impossible to cast to be fabricated to near net shape [34]
(4) Polymerization of monomeric reactants, raising organic composite densities and lowering costs

The quantitative growth in performance allowed by use of these materials is reflected in the increases in material surface temperature that have been achieved over the last 30 years (fig. 24). Extending beyond conventionally cast and directional airfoils, near-term future growth will depend on oxide-dispersion-strengthened superalloys [35]. In the long term, fiber-reinforced superalloys and ceramics [36,37] currently offer the best potential for improving materials. In all cases where components are air cooled, the use of insulating thermal barrier coatings [38] offers a way to further extend operating temperatures or to extend lives at current temperatures.

Metallic Materials

Currently superalloys are the mainstay materials for components in the hot section of a gas turbine engine. These nickel-and cobalt-base alloys contain many additional elements for strengthening and environmental resistance.

At least four strategic elements are critical to advanced engine manufacture - cobalt, chromium, tantalum, and niobium. From 90 to 100 percent of these elements are imported. Some of the sources of these metals are politically unstable. Thus the metals are subject to cost fluctuations and supply instabilities. NASA Lewis is managing a research effort aimed at eventually minimizing U.S. dependence on such unstable sources. The effort is called COSAM (Conservation of Strategic Aerospace Materials) [39], figure 25.

Various organizations are pursuing scrap reclamation, improved mineral detection, etc. However, NASA Lewis is aiming at minimizing the use of strategic materials by means of basic research to develop the needed understanding for element substitution, by dissimilar-metal joining of materials to use alloys high in critical elements only where necessary, and by identification of possible alternatives (i.e., high-strength iron-base alloys and intermetallics).

Another way to conserve the use of strategic elements is by advanced processing. One new processing technique that offers many opportunities in this regard is a rapid solidification rate process called melt spin ning (fig. 26). With cooling rates greater than 1 million degrees per second, this process is capable of producing materials of new compositions and microstructures that were not achievable by former means. Thus new opportunities will open for reductions in critical elements as well as for further improvements in engine alloys, etc.

Beyond conventional and directional metallic alloys we can add very high-strength and high-melting-point fibers to a metal matrix to achieve another 100° to 300° F use advantage. These materials are called fiber-reinforced superalloys (FRS) (fig. 27). Current efforts on FRS are focused on developing the necessary fabrication and consolidation processes as well as on optimizing fiber-matrix strengths and compatability. Early results indicate current potential for simple and/or uncooled airfoils [40]. The future goal of such research is to make turbine blades of FRS.

Nonmetallic Materials

Understanding the mechanical and physical behavior of each constituent is essential to the identification of potentially useful composite materials. Studies of the tensile fracture of ceramic fibers have been conducted since this property controls such composite mechanical properties as ultimate tensile strength, fracture toughness, and impact resistance (fig. 28). The understanding gained through studies of those deformation and fracture mechanisms that limit the tensile strength of commercially available boron fibers has led to the development of improved and cost-effective processing treatments. For example, the application of an etching and high-temperature oxidation treatment has substantially increased the average strength of boron fibers. A second highly desirable feature of this treatment is the production of a narrower range of fiber strengths [41]. These improved fiber characteristics should result in boron-aluminum and boron-epoxy composite materials with strength and toughness values at least twice those of current production composites.

The limited thermal stability of epoxy resins restricts the application of fiber-reinforced epoxies to temperatures not exceeding 350° F. The intractable nature of high-temperature-resistant polymers has made it impossible to fabricate high-quality, defect-free structural components. Investigators at NASA Lewis have developed a novel class of polyimides known as polymerization-of-monomer-reactant (PMR) polyimides [42,43]. Fiber-reinforced PMR polyimides have superior processing characteristics and exhibit excellent retention of mechanical properties during continuous use up to 600° F [44]. Now commercially available, these composites are being used to fabricate a variety of components. For example, a T300 graphite fiber and PMR-15 composite has been used in the construction of the outer duct for GE's F-404 engine used on the Navy's F-18 fighter (fig. 29). The composite duct is scheduled for production in 1985.

NASA Lewis conducted the first systematic evaluation of a large number of candidate ceramic materials in a closely controlled and realistic simulation of a gas turbine environment. In this evaluation the outstanding potential of silicon carbide and silicon nitride was identified. Research efforts have led to sinterable silicon nitride with improved high-temperaturestability and to such advanced processing techniques as hot isostatic pressing and high-pressure nitrogen sintering.

The Lewis hot isostatic press (HIP) facility shown in figure 30 is an advanced processing tool, one of a few in the country, capable of 3990° F and 20 000-psi conditions in a 6-inch-diameter by 6-inch-long hot zone. Research studies are under way to evaluate the effects of the HIP processing technique on the microstructure and material properties of structural ceramics [45].

Coatings and Life Prediction

Application of coating materials over a structural alloy is one way of providing environmental resistance to high-temperature turbine components. Coatings research has been performed on both metallic and thermal barrier coatings (TBC). Metallic coatings physically separate the structural alloy from the environment with an alloy layer capable of forming a protective oxide scale. Studies conducted at NASA Lewis have shown that metallic overlap coatings deposited by cladding, physical vapor deposition, or plasma spraying have compositional flexibility and improved protective capabilities [46-48]. Thermal barrier coatings are expected to significantly improve the durability and performance of turbine components [49]. NASA Lewis researchers have investigated the use of duplex TBC [50], where the inner layer is a metallic bond coating [51] and the outer layer is a compositionally optimized ceramic [52]. The advantage of using partially stabilized zirconia for the ceramic layer has been demonstrated. Most investigators considered a fully stabilized zirconia with greater than 12 weight percent yttria to be most desirable. However, Lewis compositional studies have shown that the optimum concentration of yttria is at a partially stabilized level of 6 weight percent (fig. 31).

Research into the processes of oxidation and hot corrosion is the cornerstone of life prediction and surface protection efforts. Protection at high temperatures depends on the formation of a dense, adherent, and slowly growing oxide scale. The growth of protective aluminum oxide scales (fig. 32) has been followed by unique transmission electron microscopy techniques. The results verify a scale growth model and suggest that grain size might offer a means to control oxidation rates [53]. Additional studies have led to the development of an oxidation life prediction model [54,55] and the identification of the effectiveness of silicon [56] and zirconium [57] in improving oxide scale adherence. Hot-corrosion research has led to improved fundamental understanding of such areas as flame chemistry, deposition rate theory, oxide scale fluxing, and chemical mechanisms of corrosion [58-60]. Current work is directed toward development of a unified life prediction method for the environmental attack of hot-section turbine components.

Nondestructive evaluation via ultrasonics is being used at NASA Lewis to measure material properties such as fracture toughness, yield strength, and ultimate tensile strength for metals; density for ceramics; and fatigue strength for composites. The application of ultrasonics to the measurement of fracture toughness for metals is illustrated in figure 33. A calibration curve constructed by using an ultrasonic, computer-automated technique developed at NASA Lewis allows fracture toughness and related properties to be determined without massive specimens, complicated procedure, and the high costs inherent in destructive mechanical tests [61-64].

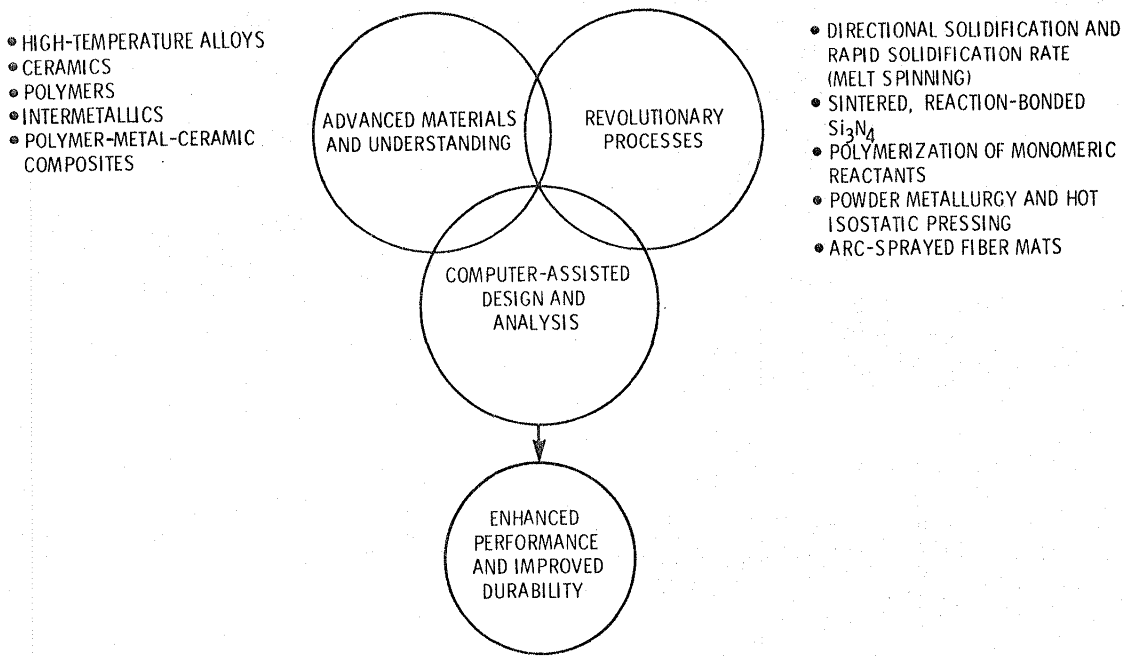


Figure 23. - Keys to gas turbine technology growth.

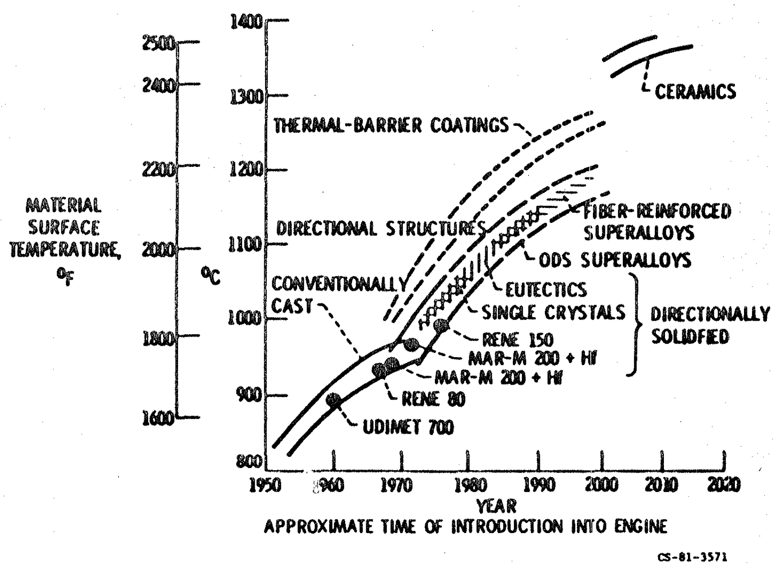


Figure 24. - Temperature capabilities of turbine blade materials.

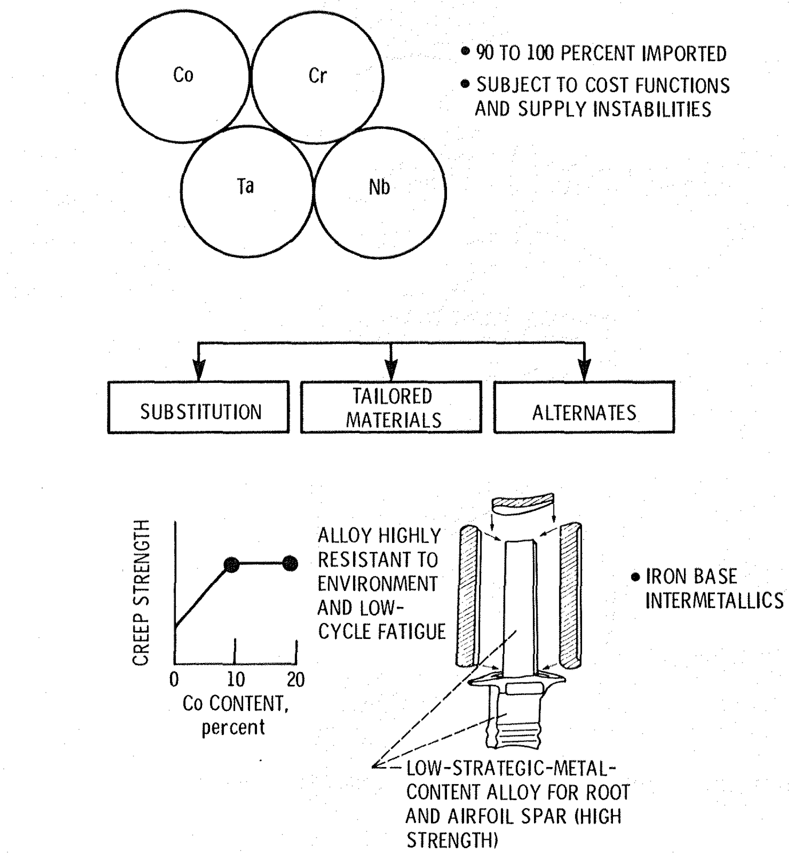


Figure 25. - Conservation of strategic aerospace materials.

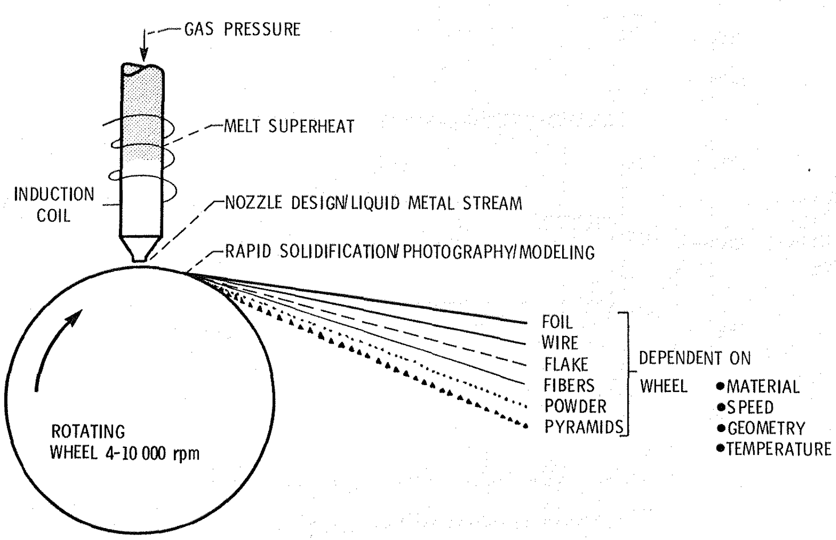


Figure 26. - Melt spinning process.

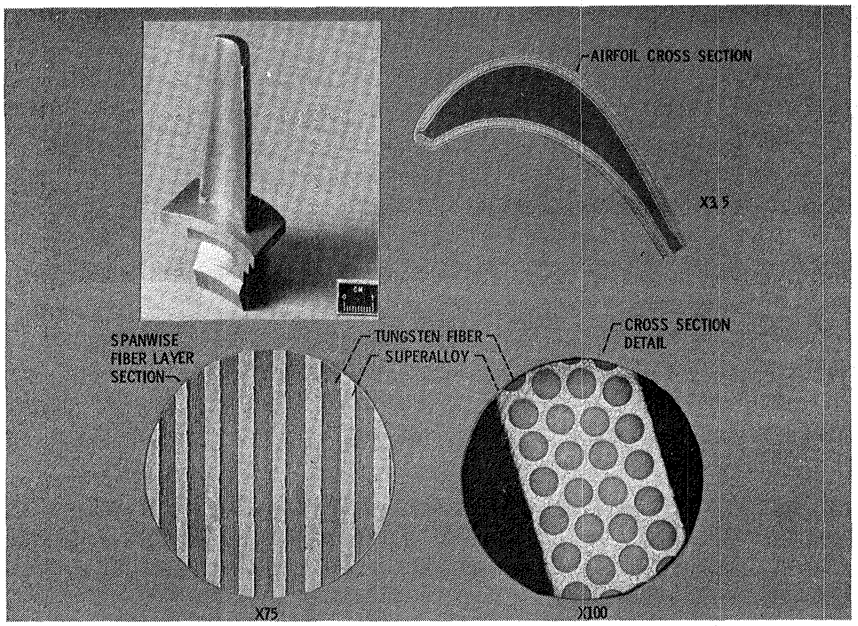


Figure 27. - Tungsten fiber - superalloy composite blade.

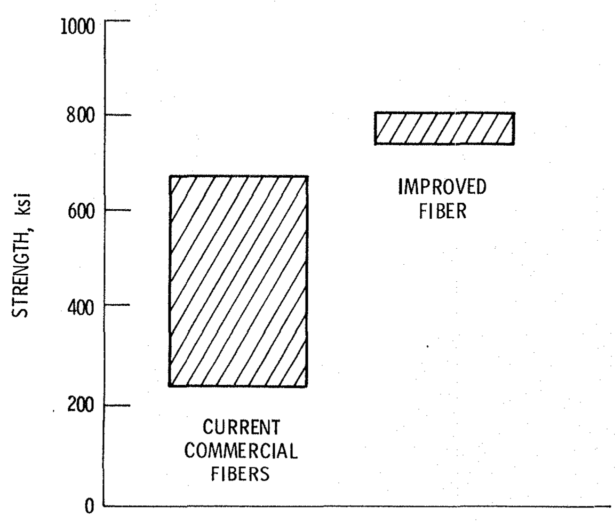


Figure 28. - Boron fiber improvement.

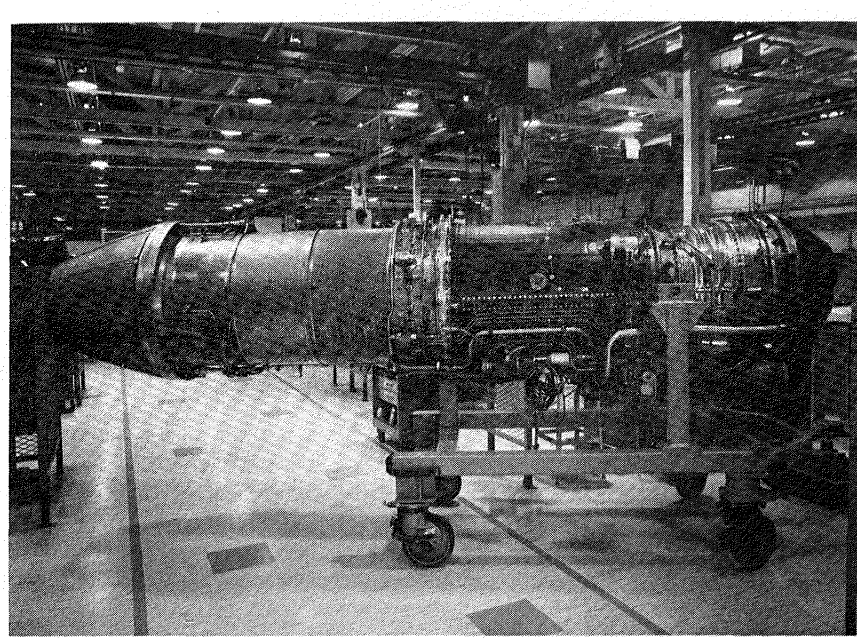


Figure 29. - T300 graphite fiber - PMR-15 outer duct installed in F104 engine. (Composite duct located directly above carriage.)

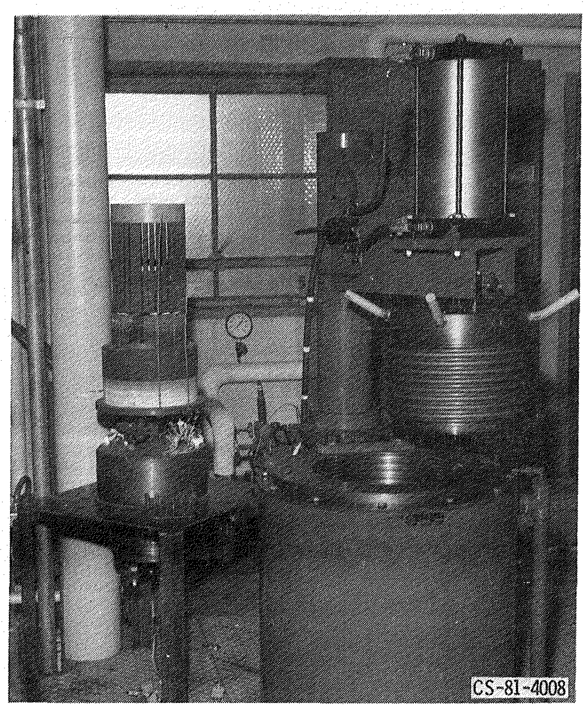


Figure 30. - Hot isostatic press facility.

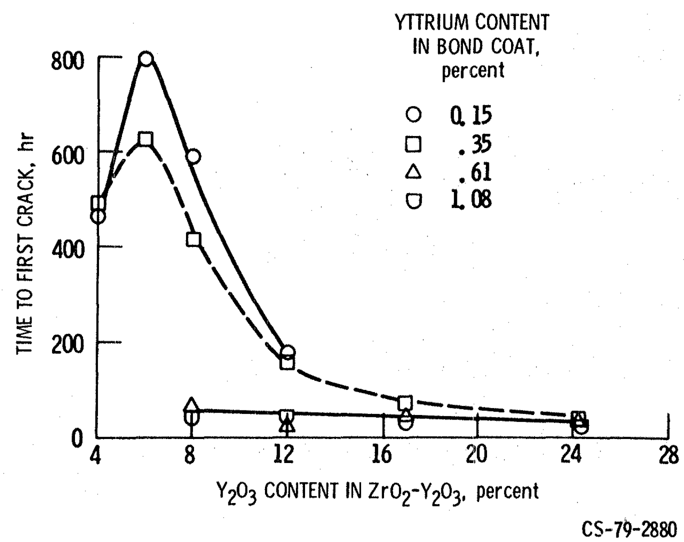


Figure 31. - Effect of coating composition on coating life.

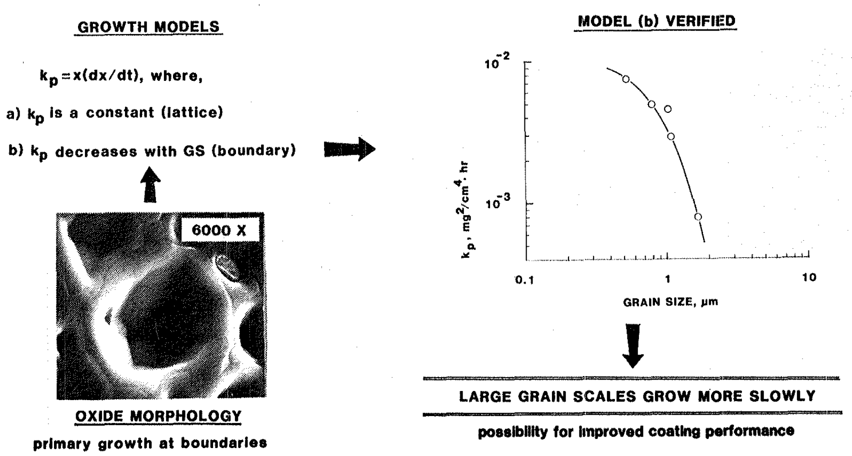
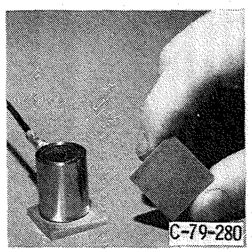
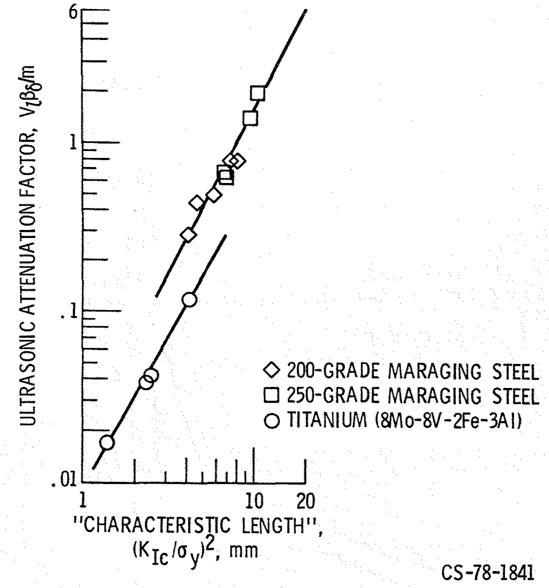


Figure 32. - Fundamentals of protective Al_2O_3 growth: importance of grain boundary diffusion.



CORRELATION OF ULTRASONIC AND FRACTURE TOUGHNESS FACTORS FOR THREE METALS



COMPUTERIZED SIGNAL ACQUISITION & PROCESSING SYSTEM

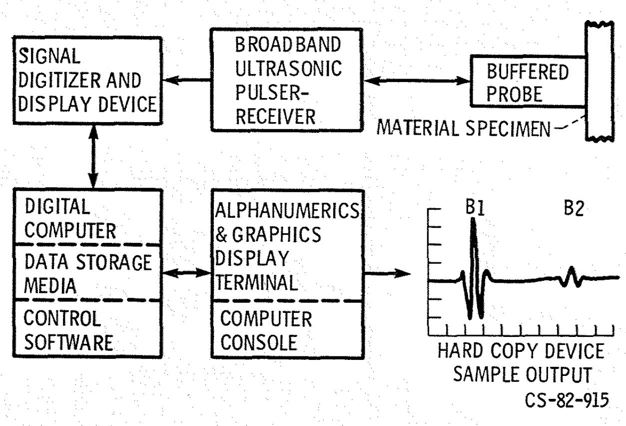


Figure 33. - Measuring fracture toughness with ultrasonics.

STRUCTURES AND MECHANICAL TECHNOLOGIES RESEARCH

NASA Lewis conducts and directs research on structures and mechanical components as they apply to problems associated with propulsion systems. Included is fundamental research and exploratory developments in strength of materials (fracture mechanics, mechanical and thermal fatigue, and creep), in structural and structural dynamic analyses, and in bearing, seal, lubrication, gearing, shafting, transmission, rotor dynamics, and friction studies.

NASA's Turbine Engine Hot Section Technology (HOST) project began in January 1981 (fig. 34). The overall objective of HOST is to improve the accuracy of the analysis methods that are used to design the hot-section combustor and turbine components. A more accurately designed component will achieve greater durability (i.e., longer life) and therefore incur lower maintenance costs.

Structures

Structural concepts research has led to the development of a number of promising advanced structural design concepts for commercial as well as military aircraft turbine engine applications. These design concepts include (1) composite material containment for fan blades (fig. 35) (about 120-lb weight reduction per large engine); (2) fiber composite material fan exit guide vanes (fig. 36) (up to 20-percent weight savings); (3) low-cost composite frame (fig. 35) (about 30-percent weight savings); and (4) superhybrid composite fan blades (fig. 36) (up to 30-percent weight savings). The details of the development of these design concepts were presented at technical society meetings (ASME, AIAA, ASTM, SAMPE, and SPI) and are published in the proceedings and technical journals of these societies. Composite material containment is one of the most successful of these research efforts. The fan blade containment program resulted from the need to provide a lightweight structure to protect the passenger cabin, wing, other engines, and engine components from the effects of a fan blade failure. Current practice is to use a heavy armored steel ring structure to contain failed blades and blade fragments within the engine envelope. Because the all-metallic containment ring structures do not fully contain failed blades and blade fragments, significant damage usually occurs to adjacent blades and other engine components downstream.

The composite containment concept uses a combination of Kevlar cloth (bullet-proof vest material) and thin metallic sheets and honeycomb to construct a lightweight structure that will fully contain failed blades and blade fragments. The concept was successfully demonstrated by the complete containment and nesting of a fan blade released from a rotating T-34 fan disk. Benefits of the concept include a weight saving of approximately 120 pounds for a large engine, as well as the minimization of secondary engine damage from the effects of a failed blade.

Recent research in advanced structural analysis (figs. 37 and 38) has contributed to the development of several unique generaland special-purpose computer programs for engine structures subject to extreme loads, high temperatures, and dynamic interaction of complex components. These advanced analyses are (1) interactive finite element analysis for bearing-shaft interaction [65]; (2) coupled Eulerian-Lagrangian finite element impact analysis [66]; (3) self-adaptive solution strategies for nonlinear problems [67]; (4) special finite element analysis for embedded discontinuities [68]; (5) functional theory for nonlinear constitutive relationships [69]; (6) dynamic stress intensity factor for layered structures [70]; and (7) singularity composite mechanics. A pioneering analysis of vibration and aeroelastic response of bladed disks with nonidentical blades (mistuning) has shown that the potential exists to design shroudless fans that avoid flutter. As another example, to model the entire engine with interactions between rotors and case including rubs, the computer program TETRA was developed under contract [71]. The development details of these advanced analyses and theories have been presented at professional society conferences and published in proceedings and technical journals.

Fatigue and Fracture Mechanics

The major maintenance and durability problems encountered in gas turbine engines are associated with hot-section components, and the hotsection components account for a large percentage of the initial engine cost. The ability to meaningfully predict the lives of combustor and turbine parts subjected to high temperatures, large thermal-mechanical load cycles with resulting creep-fatigue damage interaction, and environmental attack becomes very important. The path one follows, including theoretical damage considerations, systematic collation of experimental results, and detailed analyses, constitutes a life prediction methodology.

The state of the art in the development of life prediction methodologies is summarized in figure 39. Uniaxial creep-fatigue experiments provide the first-order information on material cyclic stress-strain response and cyclic life under simple, well-documented and controlled conditions. Damage accumulation mechanisms, including initiation and early propagation of microcracks, are identified from microstructural analysis. Results from the uniaxial experiments and microstructural analyses are incorporated into a life prediction methodology. With the help of sophisticated finite element thermal and stress analyses, the life prediction methodology is applied to rig experiments that simulate high-temperature-fatigue conditions under which turbomachinery components operate. The confidence gained from rig verification permits the next step to be taken, that is, application to full-scale engine components and ultimate use as a design tool.

Some of the life prediction methodologies developed at NASA Lewis are being employed in the aircraft gas turbine industry. Strainrange partitioning [72] is used by some manufacturers in the design of combustor liners and turbine vanes, and the Manson-Coffin Rule [73] is widely applied to many components and conditions. More sophisticated life prediction methodologies [74-76] are currently under development at NASA Lewis and will address complex loading systems, anisotropic materials, and damage mechanisms not incorporated in present life prediction methodologies.

Tribology

All moving mechanical components require lubrication to prevent mechanical failure and to reduce friction and wear. In advanced machine elements, both liquid and solid lubricants are used [77]. Liquids are still the most widely used lubricants, but they have definite limitations that restrict their use with respect to environment and temperature range [78].

In hostile environments such as the vacuum of space and strongly oxidative, reducing, and generally corrosive environments, solid lubricants are preferred.

When using liquids as lubricants, two of the properties of greatest concern are the oxidation and thermal degradation properties of the fluid [79]. Oxidation stability is important because most machinery operates in an air environment. Thermal stability is important because of the ever increasing operating temperatures being experienced by such mechanical components as bearings and gears. Figure 40 indicates the oxidative degradation behavior of an oil at 353° C determined by using gel permeation chromatography for the detection of the breakdown products. Both higher and lower molecular weight fragments that were not present in the unused oils are found in the fluids. These products can combine the lower molecular weight fragments with each other and with higher molecular weight fragments as well as the higher molecular weight fragments with like molecular weights to form sludge in the oil. This sludge then can clog lines of practical lubrication systems, settle out, and trap wear debris that may be abrasive to mechanical elements [80]. Research is in progress to understand the degradation process and the role played by metals in catalyzing oxidative degradation. Some new types of fluids are also being examined.

Solid lubricants have application [81-83] in those environments where liquid lubricants cannot be used. One such environment is air at a temperature beyond the oxidative and thermal degradation limits of all fluids [79]. For example, beyond 300° C most fluids are not useful [84]. Figure 41 indicates the temperature range over which solid lubricants are being examined. The figure also indicates some of the materials that are being investigated for use at the various temperatures [85-87]. At the very high temperatures, lubrication is accomplished with ceramics such as calcium fluoride and glass. Even at temperatures where liquids do not degrade, there are many solids such as graphite and molybdenum disulfide that provide outstanding lubricating characteristics with friction properties less than those of many oils [88].

Bearings, Gearing, and Transmissions

NASA Lewis began basic research into the mechanism of bearing failures about three decades ago. This research [89-93], which is continuing today, has resulted in marked improvements in bearing life and reliability as well as significant extensions of bearing speeds and temperatures (fig. 42). NASA's contributions have included (1) the development of rolling-element bearing materials with greatly improved resistance to pitting fatigue (e.g., VIM-VAR AISI M-50), which has increased service lives from the 300 hours of 1950's engines to 30 000 hours in present-day commercial jet engines; (2) the development of honing as a substitute for grinding and polishing, which has resulted in better surface finishes and enhanced lubrication at temperatures up to 600° F; and (3) the demonstration that greatly improved bearing lives can be achieved by ensuring that the rolling elements are slightly harder than the raceways [91,92]. These research developments at NASA Lewis have been incorporated into the production specifications for rolling-element bearings by all major jet engine manufacturers. At present, bearing research is being extended to overcome the problems associated with operating bearings at extremely high DN values approaching 3 million.

It has long been a requirement to provide technology to obtain long-life, efficient, low-cost, lightweight, compact, and quiet mechanical power transmissions for commercial and military helicopters as well as turboprop aircraft. Strength design criteria are needed for internal gears to improve the strength-to-weight ratio and to increase reliability. Research is being conducted on gear geometry, materials, and lubrication [94,95]. Spiral-bevel gear geometry, when better defined, will enable the designer to assure improved contact fatigue life, reduced noise, and reduced dynamic loading. Gear noise modeling will identify the noise source and enable better designs of the gear tooth profiles (fig. 43). Improved lubricants and lubrication modes will improve efficiency and life [96]. Life and reliability models for spiral-bevel gears will provide design criteria for longer gear life. Planetary gear life modeling will provide criteria for increased life of internal-external and helical gears in a planetary application.

NASA transmission research is directed toward improving both specific mechanical components and the technology for combining these into advanced transmission systems. Lewis has two unique helicopter transmission test stands in addition to bearing and gearing test rigs. The transmission stands are a single-input, 500-horsepower capacity (fig. 44) and a two-input, 3000-horsepower capacity. Both stands are the power regenerative type [97].

Beside conventional geared transmission systems, new innovations in helicopter "transmissions" must be evaluated for future generation helicopter drive systems. One such innovation is the traction transmission [98,99]. These gearless transmissions have the potential of reducing weight and cost for helicopters as well as for many commercial applications ranging from machine tools to constant-speed electrical drives for aircraft. These transmissions are relatively quiet. Derivations of these traction drives called hybrid transmissions incorporate gears as well as traction rollers. Hybrid transmissions (fig. 45) are currently being investigated as replacements for current helicopter transmissions, which are particularly noisy [97,99].

Seals and Rotor Dynamics

The application of refractory ceramics for turbine blade tip seals has led to dramatic performance increases in today's advanced gas turbine engines (fig. 46). NASA Lewis concepts developed in 1974 and 1975 have already been adopted for service in the 2037 engine and are projected for near-term service in the JT9D and T700 engines [100-106]. The current use of these seals in the JT9D alone allows turbine temperatures of 2300° F as well as improved sealing and results in a projected fuel saving of over $500 000 per year per aircraft. Future research is focused on 3000° F service seals with improved durability and insulating properties (fig. 47). They are projected to result in a 10-percent increase in the basic thermodynamic efficiency of advanced engines.

Research breakthroughs in the application of self-acting geometries to shaft-riding seals have resulted in 50-percent increases in previous seal speeds (fig. 48). The reduced leakage of these seals has resulted in a 2-percent thrust improvement for retrofitted Army T700 engines [107-113]. Future research into the flow thermodynamics, pumping performance, and stability of self-acting seals is projected to result in 2-percent fuel consumption improvements for gas turbine engines and at least a 2000-pound additional payload capacity for future space shuttle missions.

Today's lightweight supercritical rotor systems result in lighter weight, higher performance engine systems. A key to their success has been the development of high-speed rotor damper systems to control unbalance forces and rotor instabilities [114-116]. New analyses to predict rotor forces and response levels have been essential to providing these advances (fig. 49). New elastomeric dampers are currently being designed into cruise missile engines [117], and unique high-force dampers [118] are being developed to control large transient unbalance in gas turbine engines. Balancing theories codeveloped with the Army for flexible rotor systems have been adapted by the Army, the Air Force, and the Navy in high-speed balancing facilities for T-53 and T-55 engine overhaul with greatly increased engine performance and minimized overhaul costs [119-122].

Future research is directed toward understanding and analyzing rotor-dynamical behavior of multispooled engines in order to improve engine damping, bearing, and sealing systems. Also, dampers for extreme service environments are being developed to control axial and rotor-induced turbine stage vibrations. Cryogenic rotor damper systems using magnetic devices are being researched for hydrogen service applications and are expected to improve space shuttle turbomachinery performance as well.

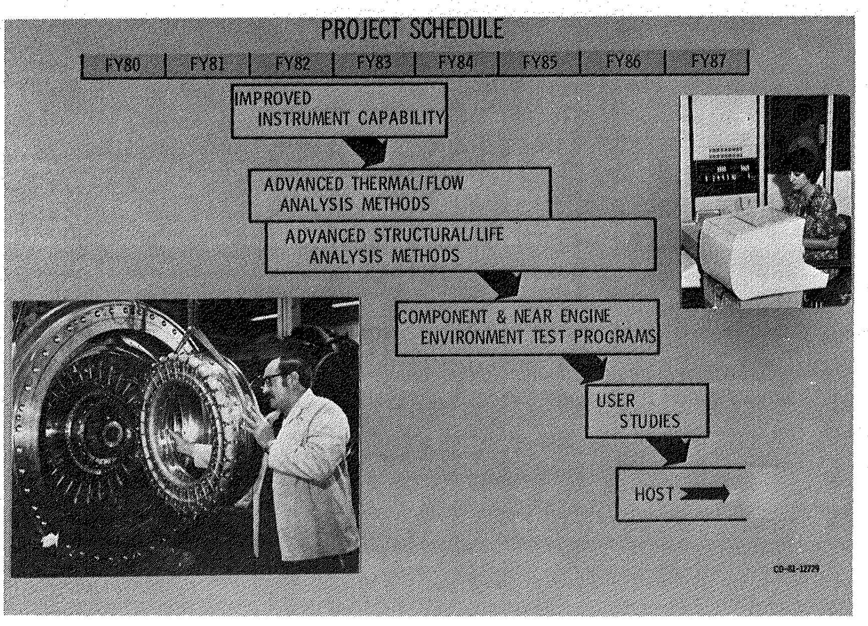


Figure 34. - Turbine engine hot-section technology.

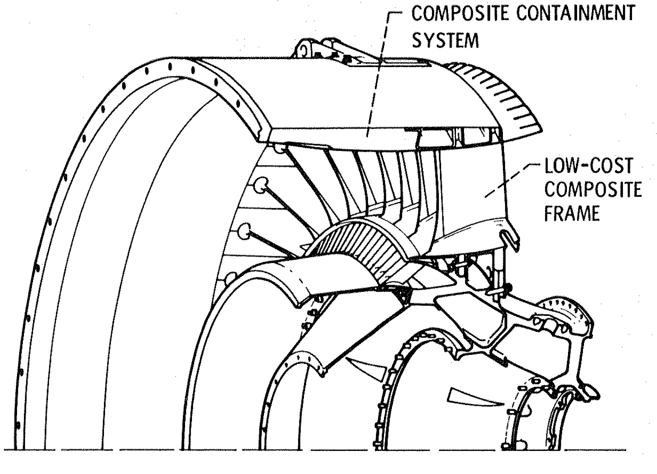


Figure 35. - Advanced structural design concepts - composite containment system and low-cost composite frame.

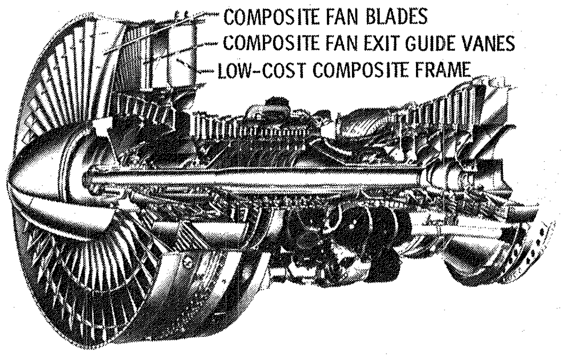


Figure 36. - Advanced structural design concepts -- composite rotating and static components.

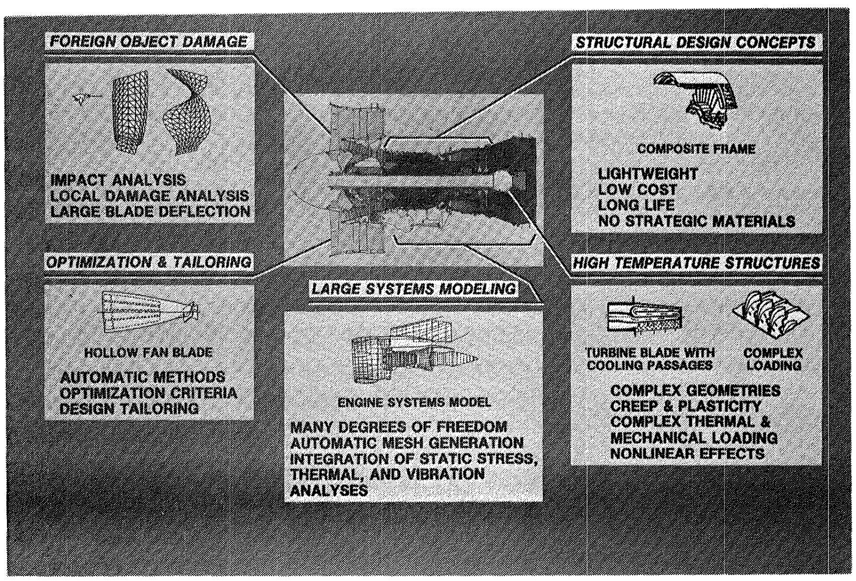


Figure 37. - Structural mechanics.

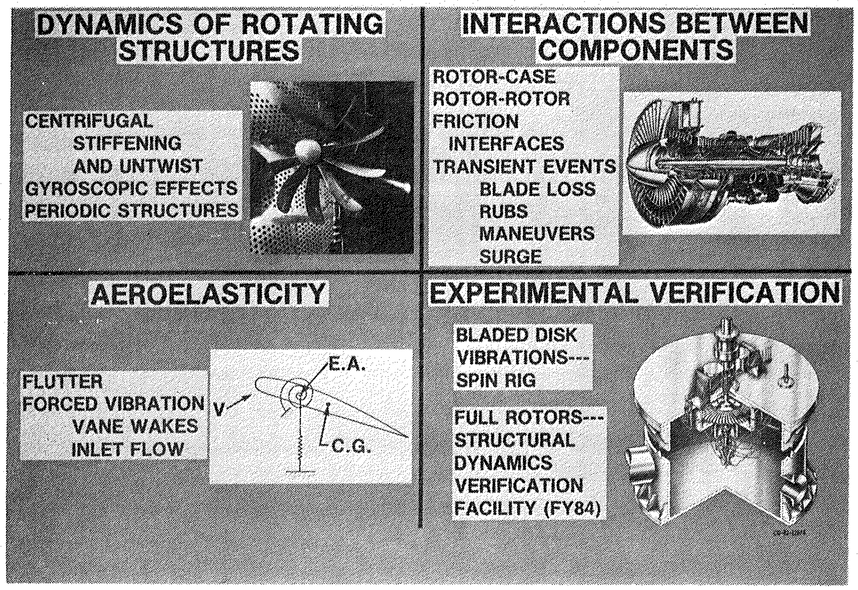


Figure 38. - Structural dynamics.

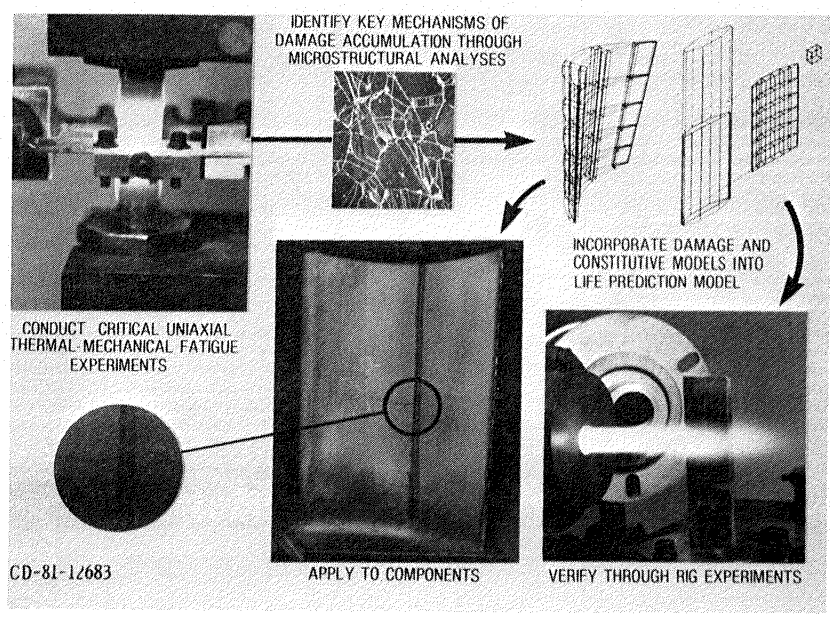


Figure 39. - Development of life prediction methodology.

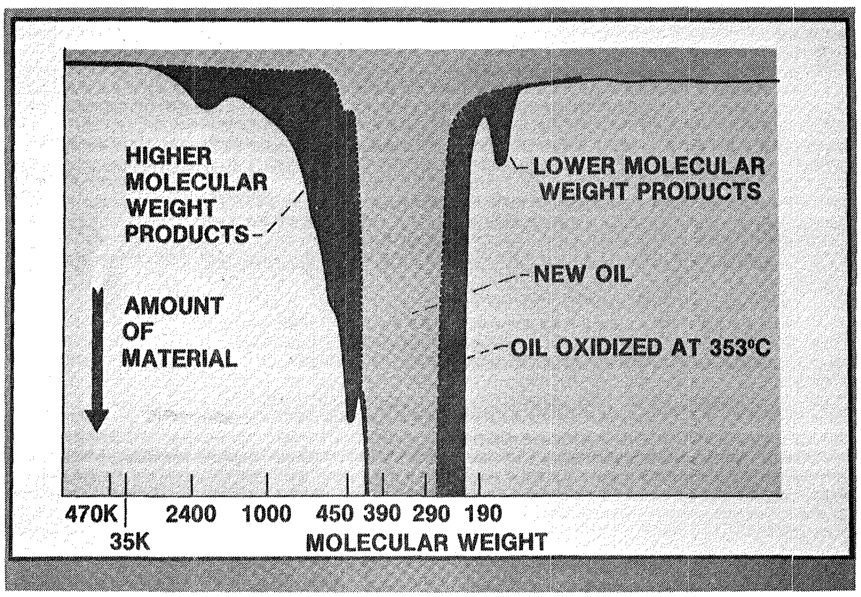


Figure 40. - Analysis of new and used oil by gel permeation chromatography, illustrating formation of lubricant breakdown products.

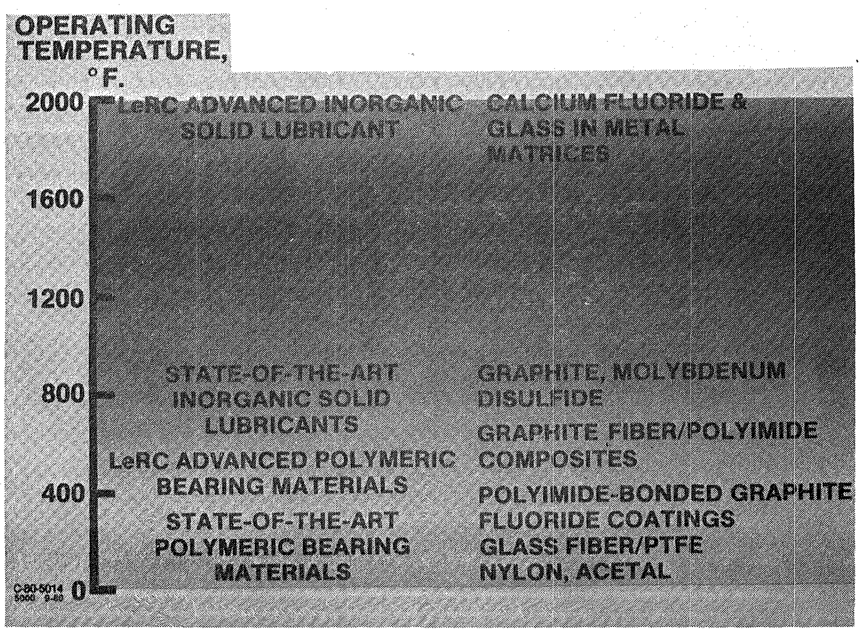


Figure 41. - Solid lubricants research.

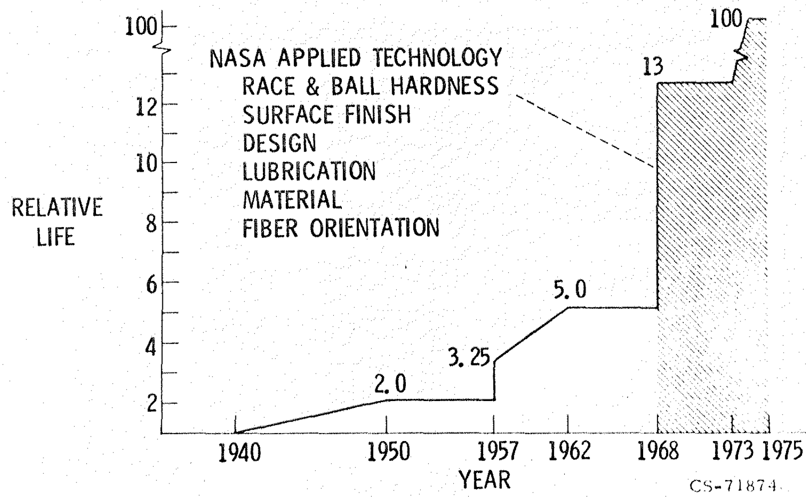


Figure 42. - State-of-the-art rolling-element bearing history.

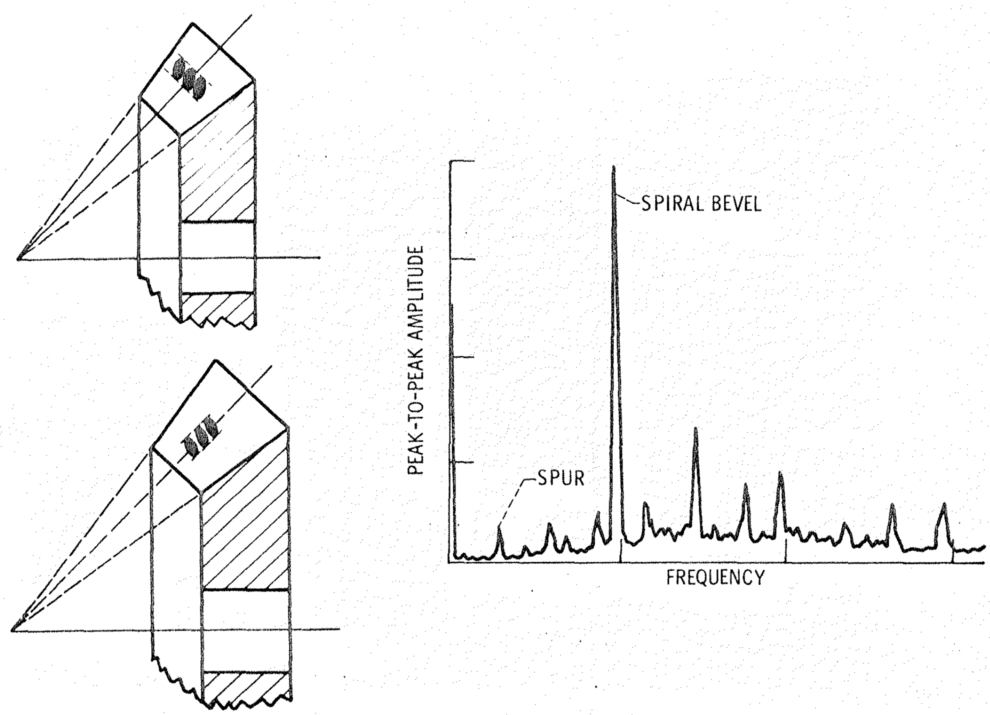


Figure 43. - Spiral-bevel gear tooth profile and noise modeling.
(a) Formation of bearing contact.
(b) Baseband frequency spectrum showing spiral bevel and spur amplitudes.

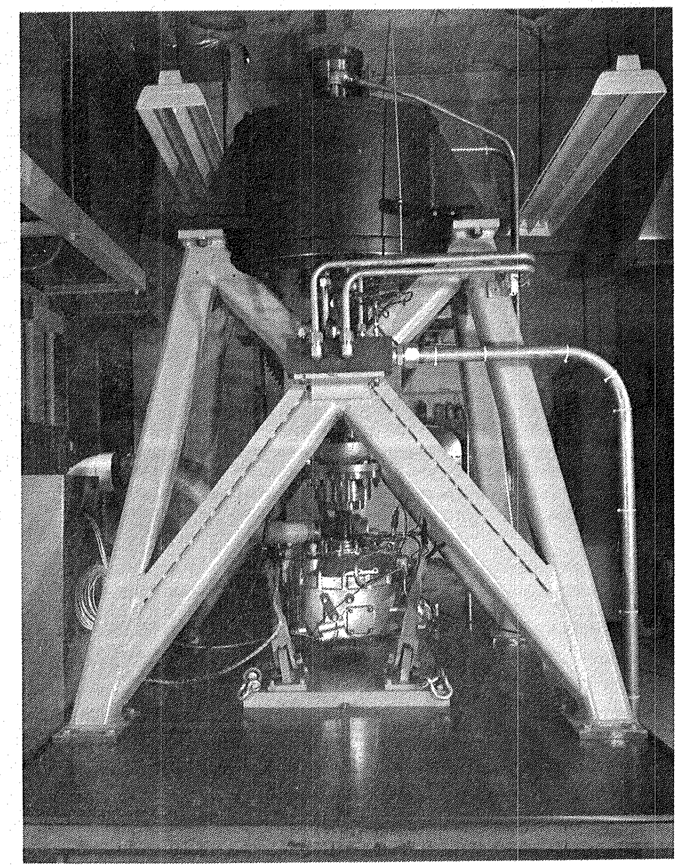


Figure 44. - 500-Horsepower helicopter transmission test stand with OH-58 helicopter transmission.

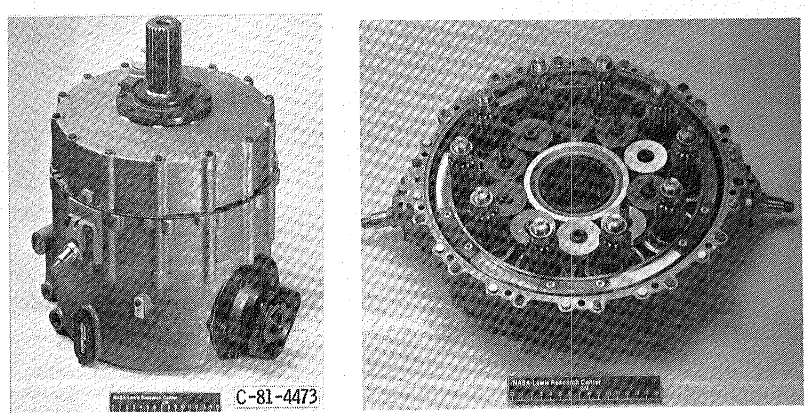


Figure 45. - 500-Horsepower hybrid helicopter transmission.

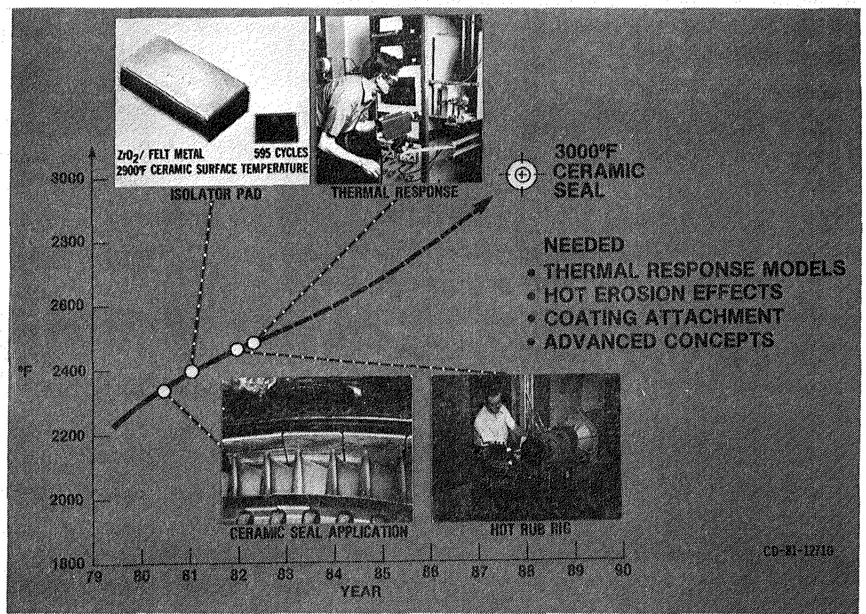


Figure 46. - Ceramics seal development.

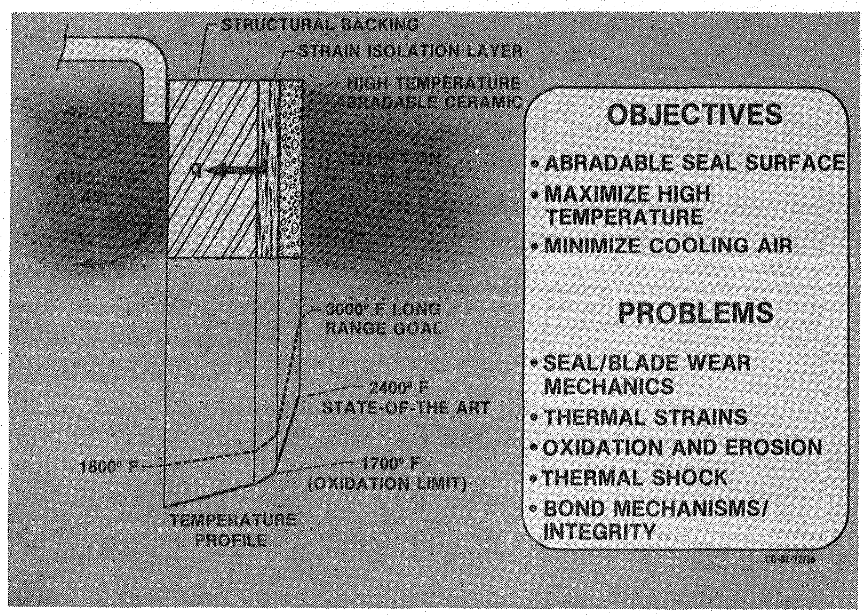


Figure 47. - High-temperature gas path seal program.

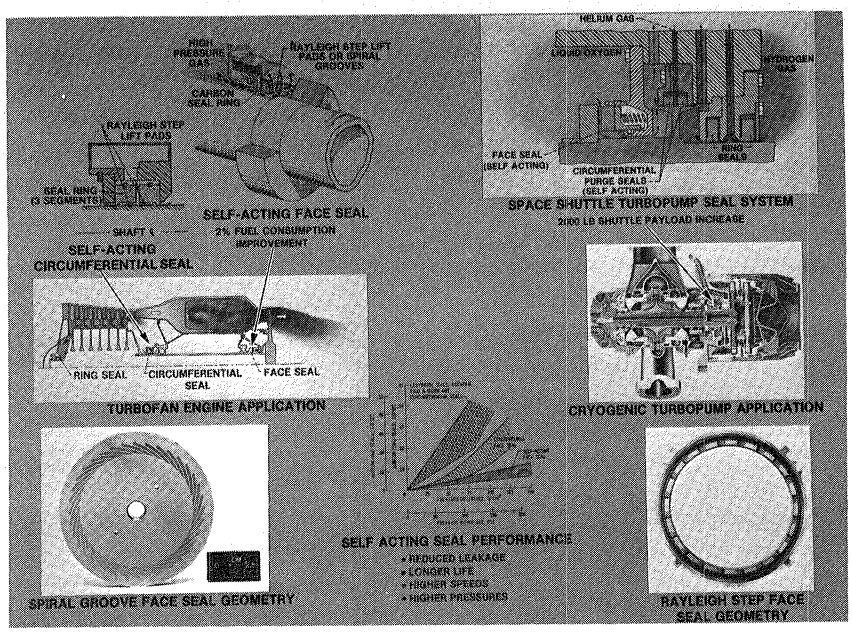


Figure 48. - Main shaft seals.

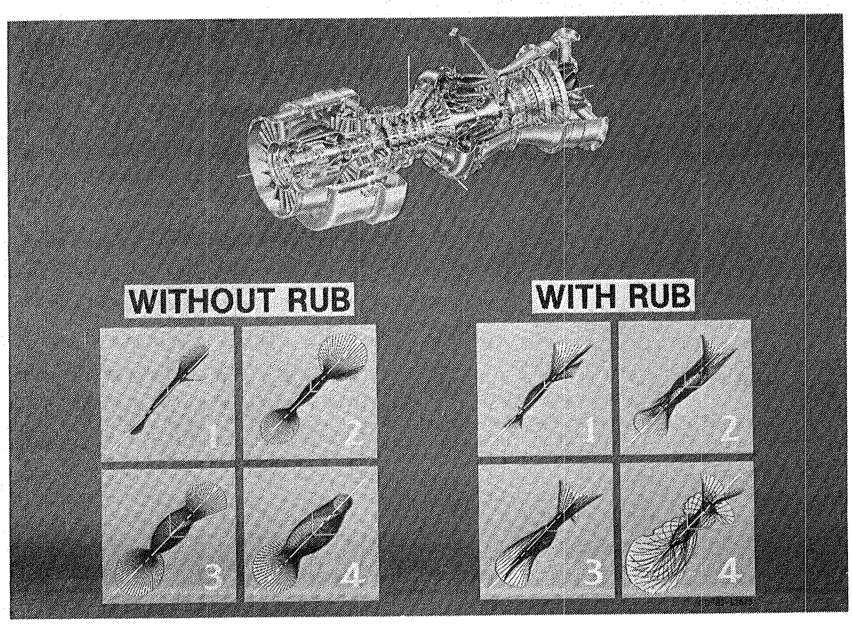


Figure 49. - Effects of turbine blade loss.

COMBUSTION RESEARCH

The major areas of gas turbine combustion research being conducted by NASA Lewis are directed at providing (fig. 50)

(1) The required technology base for meeting future advanced-mission challenges of high operating temperatures, pressures, and heat release rates

(2) The evolution of much needed design tools through analytical modeling of individual combustion processes and their interreactions

(3) Improved, more durable combustion systems being evolved through generic research exploring advanced combustion concepts and subcomponents

Research areas include

(1) Fundamental experiments that are needed to provide both the data required for improved understanding of the combustion processes and bench-mark data to assess the predictive capability of combustion analytical models [123,124]. Shown in figure 50 is an experiment aimed at determining the effects of boundary layers on flashback and autoignition.

(2) Adverse effects of alternative fuels on combustion performance. Shown in figure 50 are increases in combustor liner temperature resulting from reductions in fuel hydrogen content [125,126].

(3) Analytical modeling of fluid flow and combustion phenomena, which has recently become more practical because of the emergence of modern high-speed computers [127]. Current research efforts involve two and three-dimensional steady-state and two-dimensional unsteady solutions of the governing flow equations [128-131]. In evolving models, improving numerics, whereby computation times are reduced to a minimum and outputs are meaningful to other users, is a major consideration. Shown in figure 50 are typical results from a new approach to analytically modeling the two-dimensional, unsteady, turbulent flow field with combustion that quite successfully mimics the behavior of the real flow [130,131].

(4) Generic research in combustors and subcomponents that is being conducted for both large and small (rotorcraft, commuter, and general aviation) uses. Shown in figure 50 is a combustor being evolved for operation at 40 atmospheres and 4000^{o} F exit temperatures [132,133]. Also shown is an experiment in which a fuel injector spray is being characterized for droplet size distribution with a laser optical system. Detailed examination of sprays such as that shown here is yielding improved understanding of the spray formation mechanisms [134]. Other combustor subcomponent research in progress (not shown) is aimed at evolving advanced concepts for primary zones, metallic and nonmetallic liners, dilution jet mixing, and turning sections for reverse-flow application.

Combustion modeling efforts are aimed at obtaining a better understanding of individual combustion processes and their interrelationships with the other simultaneous aerodynamic and chemical kinetic processes. This understanding is essential to developing models that predict combustor performance. These predictive methods, once evolved, will provide designers with the tools

(1) To reduce combustor development costs and time significantly by permitting an early focus on approaches of greatest potential

(2) To design more durable hot-section components by better optimizing combustion systems

(3) To evolve more advanced concepts for technically challenging advanced missions

Modeling work incorporates a series of sequential steps. Multiple iterative approaches employing analytical and experimental efforts are used.

Typical examples depicting this work are illustrated in figure 51. Analytical modeling results are illustrated in the left photograph. Shown is a computer-generated reacted flow field that illustrates predicted velocity patterns and particles as vortex blobs that follow the velocity and diffuser by a random process [130]. The center figure illustrates a comparison of preliminary analytical results with experimental results. As can be seen, initial predictions vary considerably from the experiment. By modifying the turbulent flow field model, better agreement was obtained [129].

Before analytical models can be used with confidence, the overall model as well as the individual process models must be verified by detailed experimental measurements. One such experiment is shown in the right photograph. Recent developments in advanced diagnostic techniques now make detailed measurements possible. For example, nonintrusive diagnostic systems can be used to measure instantaneous velocities, turbulence levels, mass diffusion rates, particle sizes, temperatures, and hot-gas compositions [135,136].

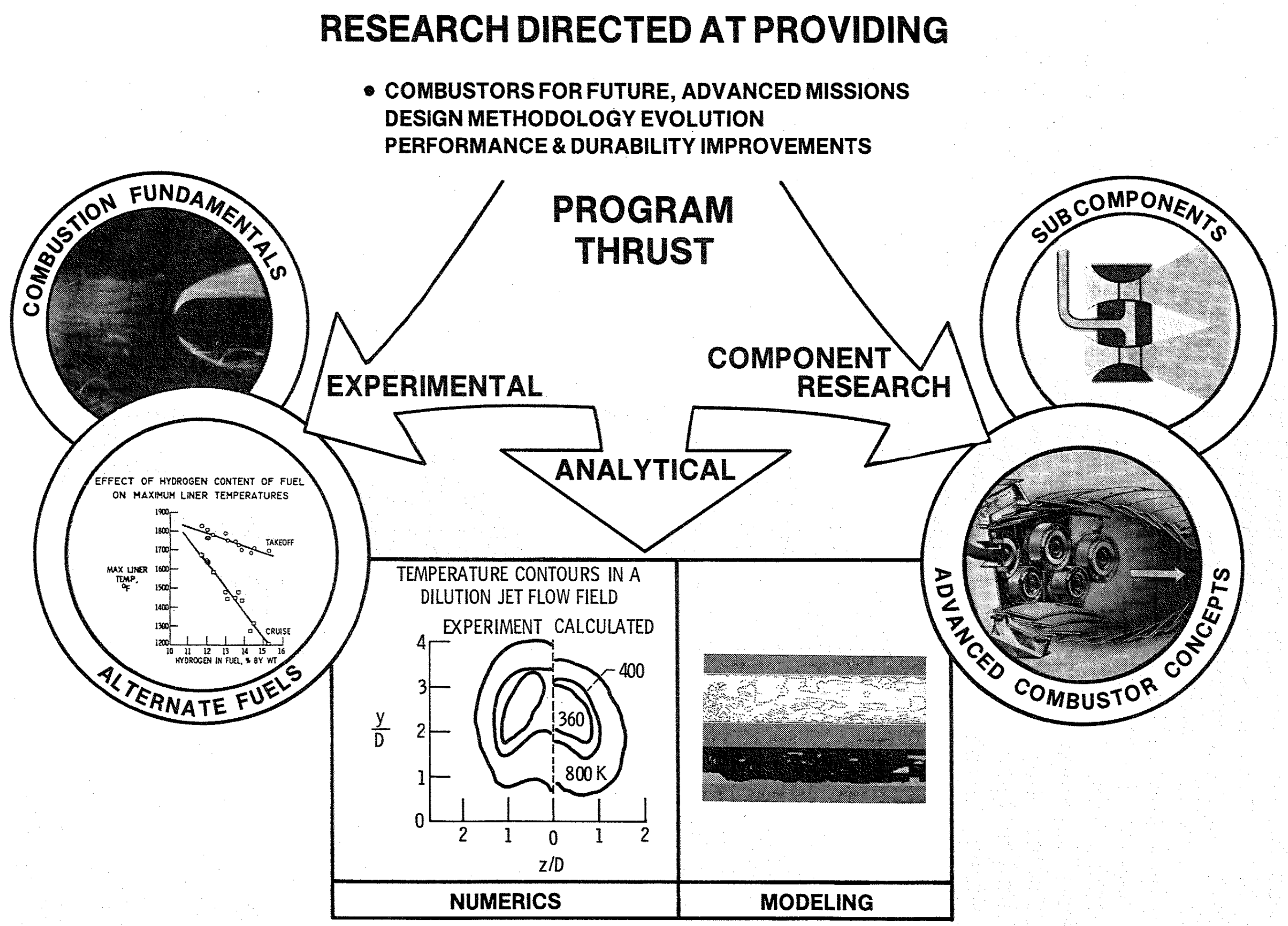
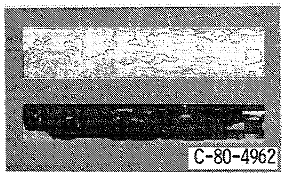


Figure 50. - Combustion research.

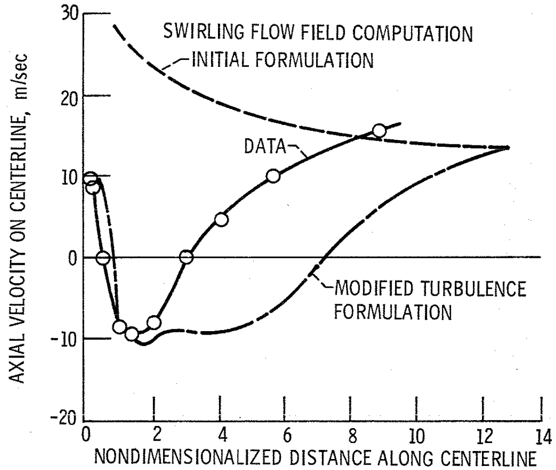
EFFORTS WILL PERMIT COMBUSTOR DESIGNERS TO

- SIGNIFICANTLY REDUCE "CUT AND TRY" EXPERIMENTATION
- DESIGN INCREASED LIFE INTO HOT COMPONENTS
  EVOLVE ADVANCED HIGH-PERFORMANCE ENGINE CONCEPTS

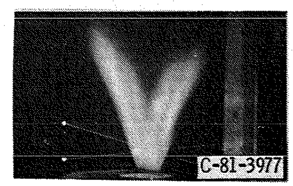
MODELING WORK INCORPORATES:



NUMERICAL COMPUTER
MODELING TECHNIQUES



BASIC IMPROVEMENT BY
MODEL COMPUTATION



EXPERIMENTAL
VALIDATION
OF MODEL

Figure 51. - Combustion modeling.

FUELS RESEARCH

The objectives of fuels research (fig. 52) are

(1) To develop a fundamental knowledge and understanding of the characteristics of potential alternative fuels and their effects on the performance, durability, reliability, and safety of both airframe and engine components and systems

(2) To explore conceptual approaches that permit and/or extend the applicability of these fuels [137-140]

Fuels research is directed toward assessing the viability of alternative fuels, determining their properties and effects on fuel system components and materials, and evaluating concepts for using these fuels in advanced aircraft-engine systems. A more fundamental program in kinetics and thermodynamics is designed to evolve fundamental data on the combustion characteristics and mechanisms of thermal instability for hydrocarbon fuels and to develop and verify analytyical models for predicting thermodynamic and transport properties and chemical reaction rates.

Thermal stability effects. - Hydrocarbon fuels for gas turbine engines, when exposed to high temperatures in various parts of the fuel system, tend to become unstable and form gums, sediment, and solid deposits on metal surfaces. These deposits can clog filters or seriously degrade fuel injector spray patterns and hence limit combustor performance. Although present stability specifications for currently used jet fuels appear to be adequate for present engine cycle conditions, the poorer stability characteristics of future alternative fuels and the higher engine cycle temperatures of advanced design engines are expected to present a major problem that will affect fuel availability, fuel-related systems costs, and engine performance and durability. The objectives of the NASA Lewis program are to investigate techniques for assessing thermal stability at simulated engine conditions and to determine the stability characteristics of potential future fuels [141]. The program encompasses fundamental studies of thermal degradation mechanisms and rates, more effective means of predicting the thermal stability effects in actual systems, techniques for improving the stability of marginal fuels, and system studies to investigate fuel system design changes that will be more tolerant of poorer quality fuels [142,143]. The thermal stability facility illustrated in figure 53 is expected to provide a bridge for rating fuel stability between the laboratory jet fuel oxi(-PROMPT-)ter (JFTOT), which is used in a standard ASTM testing procedure, and the actual aircraft fuel system. Parametric studies will be conducted on a matrix of research fuels and base fuels doped with different contaminants. The parameters include temperature, pressure, flow rate, oxygen content, and surface material. Flat-plate deposit specimens produced in the simulator will be analyzed by a variety of advanced analytical techniques in both in-house and university grant studies to determine the composition and nature of the deposits.

Fuel freezing-point effects. - Alternative hydrocarbon fuels may have higher freezing points than conventional jet fuel, and hence part of the fuel in the tanks may freeze on long flights with subsequent pumpability problems and unavailability of the fuel for the engines. The NASA Lewis program addresses a number of aspects of the problem, from basic studies characterizing the low-temperature behavior of current and alternative jet fuels to investigations of fuel tank geometry and recirculation pattern effects on heat transfer and the assessment of various fuel heating schemes (144-146]. Figure 53 illustrates a contracted study in which a fuel tank simulator was used with various alternative fuels to simulate actual flight temperature profiles and to determine the amount of fuel holdup in the tank. Actual fuel temperature measurements in flight for a Lockheed L1011 aircraft and computer modeling studies have been used to verify the simulator experiments with good results. These studies will be continued with a simulator capable of varying tank geometry and recirculation patterns.

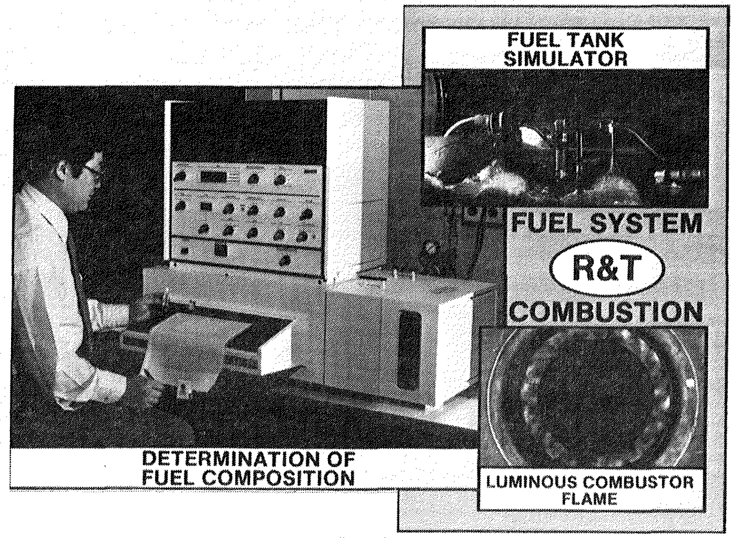


Figure 52. - Alternative fuels program.

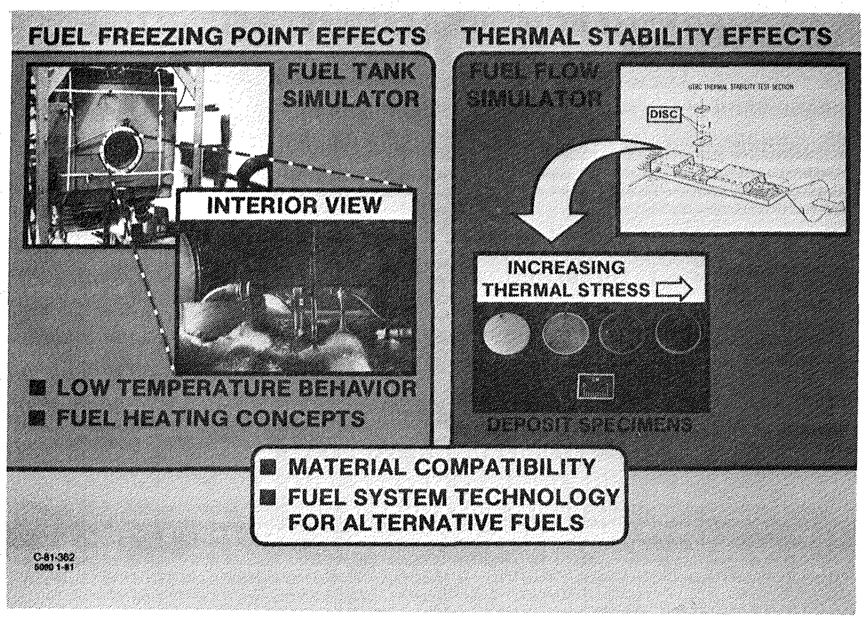


Figure 53. - Alternative fuels - fuel system research.

CONTROLS RESEARCH

The NASA Lewis propulsion controls research program is aimed at providing advanced technology for airbreathing engine electronic propulsion control systems. The research is motivated by the increasing complexity of airbreathing engines. Engines with seven control inputs are in service, and engines with 10 control inputs are being tested. The increasing complexity has made it more difficult to provide hydromechanical controls that have high reliability at low cost and weight. As a result, supervisory electronic controls are already in service and full-authority digital electronic controls are in development.

The scope of research includes control theory and methodology, real-time propulsion system simulation, electro-optical control components, integrated flight-propulsion controls, and stall recovery research. Multivariable control design methods have been developed [147] to allow straightforward, computer-aided design of control logic for propulsion systems with multiple inputs and outputs. Such controls can be readily implemented on full-authority digital control computers.

Real-time engine simulations have been developed [148] to assist in the development and checkout of multivariable controls. These simulations are currently implemented on hybrid (digital-analog) computers. However, in the future, such simulations will be implemented on microcomputers operating in parallel. The custom microprocessor shown in figure 54 was developed at NASA Lewis for this purpose. It runs 10 times faster than available off-the-shelf computers. The very high speed is required to fulfill the demanding requirements of real-time, high-fidelity engine simulation.

Research on innovative controls hardware is concentrated on electro-optical sensors, actuators, and computers for use in full-authority electronic contols with fiber-optic data links. The fiber-optic temperature sensor shown in figure 54 was developed by United Technologies Research Center under contract to NASA Lewis [149]. It consists of a fiber loop doped with a rare-earth element having temperature-sensitive absorption properties. The average temperature of the loop is calculated from the measured ratio of transmitted to incident light intensity.

Research on integrated controls, emphasizing V/STOL and rotorcraft systems, is conducted in cooperation with NASA Ames by using piloted simulators. Detailed simulations of the propulsion system and its control are provided by NASA Lewis [150]; simulations of the aircraft and its control are developed by NASA Ames. Integrated control modes are developed and evaluated as a cooperative effort [151].

Digital Electronic Controls

A multivariable controls (MVC) program was conducted on the Pratt & Whitney Aircraft (P&WA) F-100 engine. The control laws were designed by using linear quadratic regulator theory (LQR) [147] by P&WS and Systems Control, Inc. under a contract jointly sponsored by NASA Lewis and the Air Force Aero Propulsion Laboratories. The control laws were implemented on a digital mini-computer at NASA Lewis and were checked out [152] by using a real-time dynamic simulation of the F-100 engine [148] programmed on the Lewis hybrid computer facility (fig. 55). After the simulation phase, the LQR control was used to provide full-authority control of an F-100 engine over its full-operating envelope in an altitude facility at NASA Lewis [153].

In a follow-on effort, sensor failure detection, isolation, and accommodation (FDIA) algorithms were developed [154] for the F-100 engine under a NASA Lewis contract to P&WA and SCI. Failure detection is based on range and residual checks. Isolation is accomplished by hypothesis testing of filter residuals. Failures are accommodated by reconfiguring a Kalman filter to produce estimates of all sensor outputs based on the set of available, or unfailed, sensor outputs. The FDIA algorithms will be programmed along with the MVC/LQR control modes on the recently developed Lewis microcomputer control facility. This facility includes two Intel-8086 microprocessors (fig. 55) that operate in parallel to provide the control function, an interface unit to allow exchange of information with simulations or engines, and a monitoring unit to record and display engine and control variables during a test. The FDIA algorithms will be checked out by using the real-time F-100 engine simulation and then evaluated on an F-100 engine.

Portable Engine Simulator

The hybrid computer (fig. 56) continues to be the workhorse for real-time, nonlinear, full-envelope aerothermodynamic simulation of engine systems at NASA Lewis. However, there are disadvantages associated with hybrid computing that motivate the development of a digital engine simulator. The hybrid computer is large (and hence not portable), relatively expensive, and relatively difficult to program. Some simplification of the aerothermodynamic steady-state performance models is required in order to allow real-time operation.

A program is under way to develop technology for a digital engine simulator using several microcomputers operating in parallel [155]. A custom microprocessor (fig. 56) has been designed and developed for this purpose at NASA Lewis. This microprocessor runs 10 times faster than available off-the-shelf microprocessors. Such great speed is needed because of the requirement for high-fidelity dynamic response in addition to steady-state accuracy across the operating envelope. Microprocessor-based simulators will be small and portable, inexpensive to purchase, and easy to program. Further miniaturization of electronic circuitry will eventually allow the possibility of in-flight real-time simulation for sensor reconstruction, condition monitoring, and adaptive control.

In addition to the simulator hardware, the research effort at NASA Lewis also includes the required software. Research is under way on compiler/translators, operating systems, and other user-friendly software support. Also, techniques for numerical integration [156] and simulation partitioning appropriate to parallel-processing simulation are being developed.

Dynamic Simulation

Dynamic simulation of a typical two-spool turbofan engine has been developed [157] that includes performance maps and lumped-volume dynamics for all components. One important application is in a program aimed at an understanding of factors that affect the recoverability of an engine following compressor stall. Engine stall is induced with a simulated fuel pulse or other disturbance, and the simulation calculates the poststall transient response. Depending on the choice of key parameters such as compressor bleed, the initial surge cycle terminates either in automatic recovery to normal operation or in a low-thrust, rotating-stall condition (fig. 57). The simulation will be used to study control modes for avoidance of and/or recovery from rotating stall, as well as to identify key engine design parameters that improve engine stall recoverability.

The overall effort includes experimental research, analysis, and simulation. Compressor rig testing will be conducted to determine the effect of key compressor design parameters on in-stall compressor operating maps. Analytical models will be developed to allow improved prediction of install and normal operating maps. Engine system testing will provide baseline data to validate and improve the engine system simulations. Control modes to avoid and/or recover from rotating stall will first be evaluated by using engine simulations and then verified by using engine system evaluation.

NEW CONTROL DESIGN METHODS

INPUT

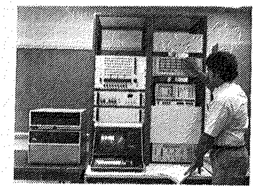
- LINEAR MODELS
- PERFORMANCE INDEX

OUTPUT

- CONTROL LOGIC

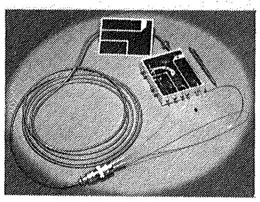
MULTIVARIABLE CONTROL DESIGN TECHNIQUES

ENGINE SIMULATION



PORTABLE ENGINE SIMULATOR
C-81-3885

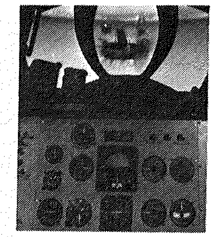
INNOVATIVE CONTROLS HARDWARE



FIBER-OPTIC TEMPERATURE SENSOR

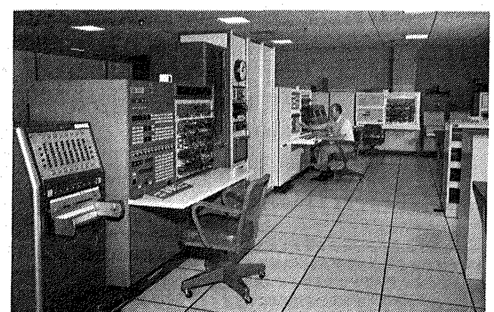
C-81-3932

INTEGRATED CONTROLS RESEARCH



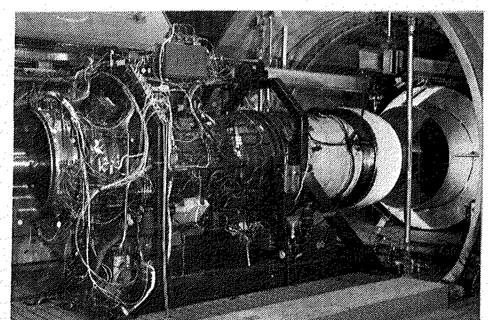
PILOTED SIMULATION OF AIRCRAFT-ENGINE CONTROL SYSTEM
C-81-4087

Figure 54. - Propulsion controls research.



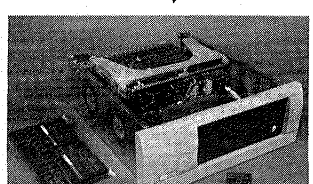
C-81-2363

LEWIS ENGINE SIMULATOR



C-75-729

ENGINE IN LEWIS ALTITUDE FACILITY



C-81-1669

DIGITAL ELECTRONIC CONTROLLER

BENEFITS OF ELECTRONIC CONTROL:

- LOWER COST
- GREATER RELIABILITY
- IMPROVED ENGINE PERFORMANCE
- REDUCED PILOT WORKLOAD
- SIMPLIFIED DESIGN

Figure 55. - Evolution of digital electronic controls.

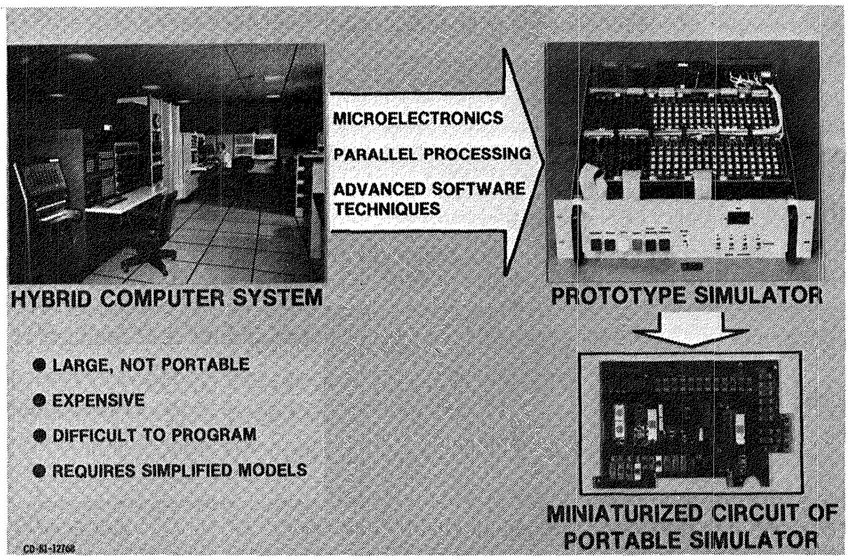


Figure 56. - Evolution of portable engine simulator.

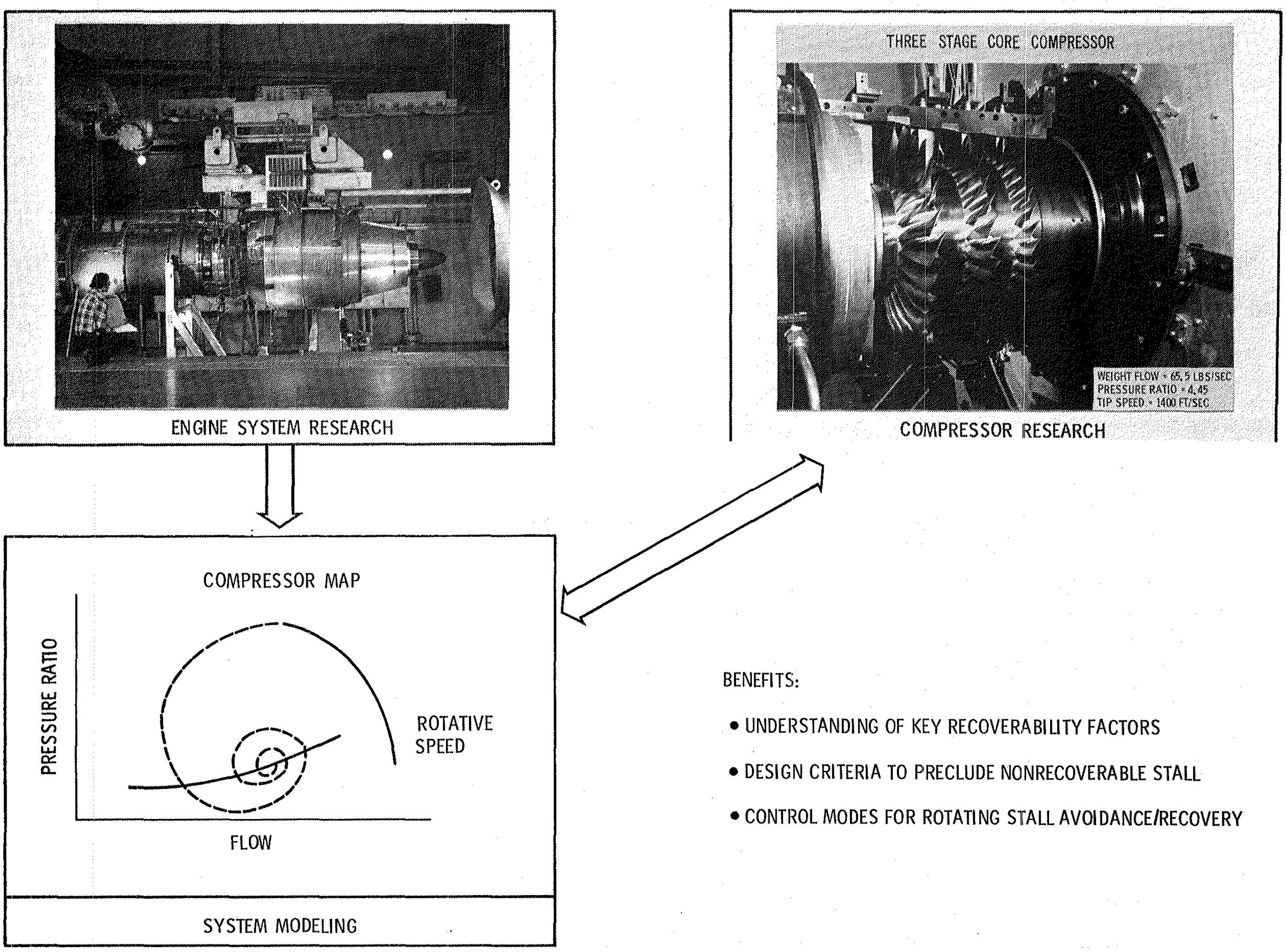


Figure 57. - Stall recovery research.

INSTRUMENTATION RESEARCH

The NASA Lewis instrumentation research program includes efforts directed at both research instrumentation and instrumentation for operational or flight use. The effort in research instrumentation covers the complete spectrum, including instrumentation for fundamental studies of basic phenomena, for engine components studies, and for experiments on full-scale engines.

Figure 58 shows a sampling of the kinds of research instrumentation covered by this program. Laser anemometry is used extensively in mapping gas flows in various engine components, including between the blades of rotating compressor stages. The probe efforts are concentrated on dynamic measurements. Shown in the figure are the sensing end of an "infinite line" dynamic pressure probe capable of sensing pressure fluctuation to 100 kilohertz, a drag force anemometer with a natural frequency of 40 kilohertz for making dynamic flow magnitude and flow direction measurements, and an optical clearance probe for making blade-tip-to-shroud clearance measurements of rotating fan, compressor, and turbine stages.

NASA research in miniature sensors is concentrated on using thin-film fabrication techniques to produce miniature sensors directly on the measurement surface. Shown in figure 58 are a thin-film thermocouple on a turbine blade and a thin-film strain gage on a compressor blade.

Another major aspect of the instrumentation research program is the development of "smart" instruments that incorporate microcomputers. The automatic exhaust gas analysis system shown in figure 58 is one example. This system is automated with respect to checkout prior to a test run, calibration when appropriate, operation including automatic range changing, a near-real-time display of the output in engineering units, and the flagging of questionable data. Such automated systems are vital in the operation of large facilities because of the high hourly facility operating costs. Automation insures that the instruments are operating properly prior to a run, allows the data to be examined as they are being taken to determine if they are valid, and permits the test operator to move rapidly through his test matrix knowing that valid data have been acquired at each point.

In the area of flight instrumentation, the program is focused in several subareas. The largest effort is in high-temperature electronics, where we are trying to establish the technology base for producing semiconductor devices based on silicon carbide technology that can operate continuously at temperatures up to 500° C. Such devices are needed in future high-performance aircraft applications, where it is desirable to have the electronics for instrumentation signal conditioning, control, and engine diagnostic systems operate in close proximity to the sensors, many of which are at ambient-temperature levels beyond the operational range of current silicon-based devices. As turbine engines become more electronic, it becomes increasingly unattractive to use conventional silicon-based electronic technology with fuel or air cooling because of the associated performance, weight, and reliability penalties. Other areas in flight instrumentation include development of high-temperature, precision pressure transducers and high-accuracy fuel flowmeters for measuring true mass flow rates.

The balance of this section on instrumentation examines in more detail the research instrumentation program in nonintrusive measurements and the program in miniature sensors.

Nonintrusive Measurements

The NASA Lewis nonintrusive instrumentation research program based on laser technology had its start in the early 1970's. One of the primary goals was to develop systems for measuring and visualizing gas flows in a variety of benchmark experiments. The purpose of these benchmark experiments was to generate accurate data to determine the accuracy and range of validity for various computer codes being developed in the NASA Lewis computational fluid mechanics program.

The laser Doppler velocimeter (which we call the laser anemometer) is the primary quantitative measurement tool. NASA Lewis contributions in this area include an extensive study of the particle tracking errors that occur in turbomachine flow passages [158-160], detailed measurements in a turbine stator cascade facility showing the effects of statistical biasing effort [161-165], and detailed measurements in the blade row of a transonic compressor research facility [166-168]. Our present research efforts involve improved methods for signal processing and signal analysis [169, 170], the development of a method for obtaining a line-of-sight velocity measurement in a turbomachine [30], and the development of techniques for applying laser anemometry to high-temperature - high-pressure flows.

The line-of-sight laser anemometer is shown in figure 59. It is used to measure the radial component of flow, which is a secondary flow in an axial-flow machine. The system uses a Fabry-Perot interferometer for directly measuring the frequency of the Doppler-shifted, backscattered light.

Another nonintrusive flow measurement technique in use at NASA Lewis is double-pulse holography. The primary application for holography is in visualizing and determining the position of shock waves in transonic flow components. We have performed an extensive study of the shock waves in atransonic, single-stage compressor [171]. A major contribution from this effort was the formulation of a theory that related the location of the observed optical fringes in the holograms to the location of the shock waves that produced them [172].

Presently, we are studying the time-varying shock wave structure in a transonic flutter cascade [173]. To study the time variations, we have developed the holographic cinematography system shown in figure 60 [174]. With this system we can make holographic motion pictures at framing rates of 20 per second. The goal for an advanced system is a framing rate of 1000 per second in order to study rapidly varying flow features. To achieve this goal will require development of a high-repetition-rate, high-energy-per-pulse laser system.

NASA Lewis' contributions in nonintrusive measurements in areas other than flow include an optical system for blade flutter measurements [175] and capacitance and optical probe systems for measuring blade-tip-to-casing clearances [176,177].

Miniature Sensors

In the quest for more durable engines, it becomes increasingly important to be able to measure the temperature, heat flux, and strain distributions over the surfaces in the hot sections of engines. Measurements of these quantities in the past have had only limited success. Mounting thermocouples and strain gages on airfoil surfaces produces airflow disturbances that can result in boundary layer trips and performance degradation. Burying sensors and leadwork into the airfoils leads to structural problems, especially on thin-walled, cooled turbine blades. In addition, the conventional sensors, whether installed on the blade surfaces or embedded into the blades, have relatively short lives in the hot-section environment.

A solution to many of these problems is the thin-film sensor. In this case the sensor consists of thin films of thermocouple or strain-gage alloy deposited (usually by vacuum sputtering) over an electrically insulating film covering the airfoil surface. The sensor films have thicknesses of only 10 to 15 micrometers so that no aerodynamic disturbance is generated. The electrically insulating film can be obtained by controlled oxidation of the protective MCrAlY coatings usually used on turbine blades and vanes. For surfaces with no MCrAlY coating (e.g., compressor blades), an insulating film can be sputtered directly onto the surface.

Thin-film thermocouples using Pt-PtRh alloys have been developed, applied to turbine blades (fig. 61) and tested under environments simulating use in an engine [178-180]. Further work on thin-film thermocouple technology is under way, with a primary objective of simplifying the processing operations and improving the yield of acceptable thermocouples.

Work is also under way to develop thin-film strain gages. Thin-film strain gages for dynamic strain measurements on compressor blades have been developed and are being tested (fig. 62). A program to develop static strain gages for turbine blade applications at 1800° F was started late in 1981. In this case alloys with sufficient stability of electrical resistance are not available, so the primary emphasis is on developing improved strain gage alloys. Once a suitable alloy has been identified and proved, development of a high-temperature, thin-film strain gage system will be addressed.

Miniature sensors for making heat flux measurements on combustor liners have been developed [181] are are being evaluated in a high-pressure combustor test rig. These sensors use conventional thermocouple material in conjunction with the combustor liner material (Hastelloy X) to make a differential thermocouple for measuring the temperature difference developed across the sensor by the conducted heat flux. Development of heat flux sensors for use on opearating turbine blades and vanes was started in the fall of 1982.

A successful conclusion to each of these miniature sensor development efforts will allow us to make accurate measurements of temperature, heat flux, and elastic strain on virtually all engine components over the entire range of engine operating conditions.

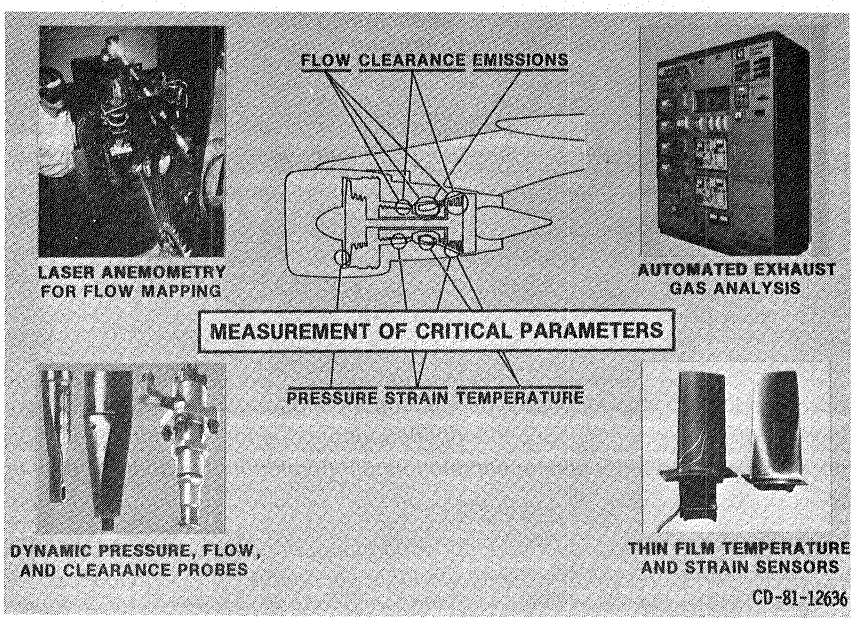


Figure 58. - Advanced instrumentation for propulsion research.

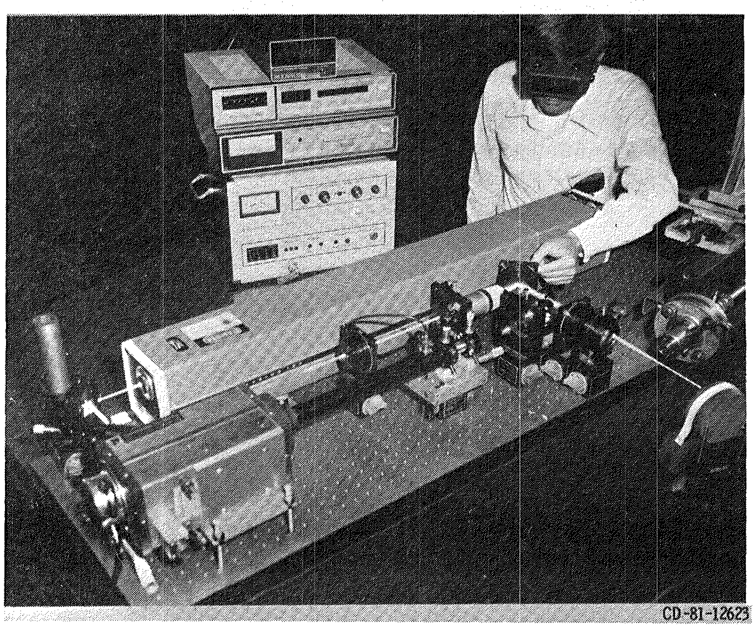


Figure 59. - Line-of-sight laser anemometer for measuring radial component of flow in an axial-flow machine.

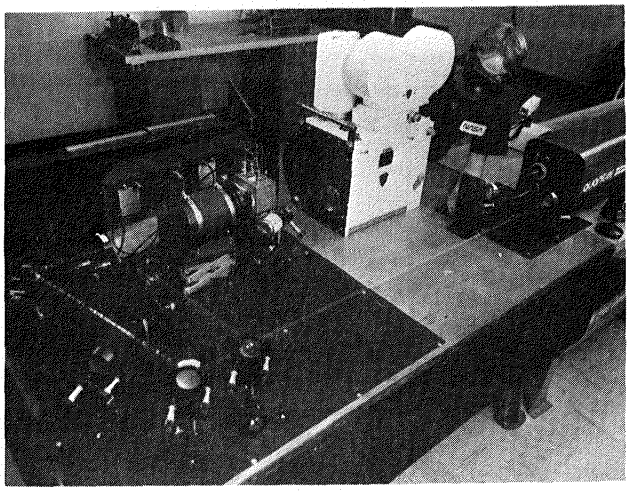


Figure 60. - Holographic motion picture system.

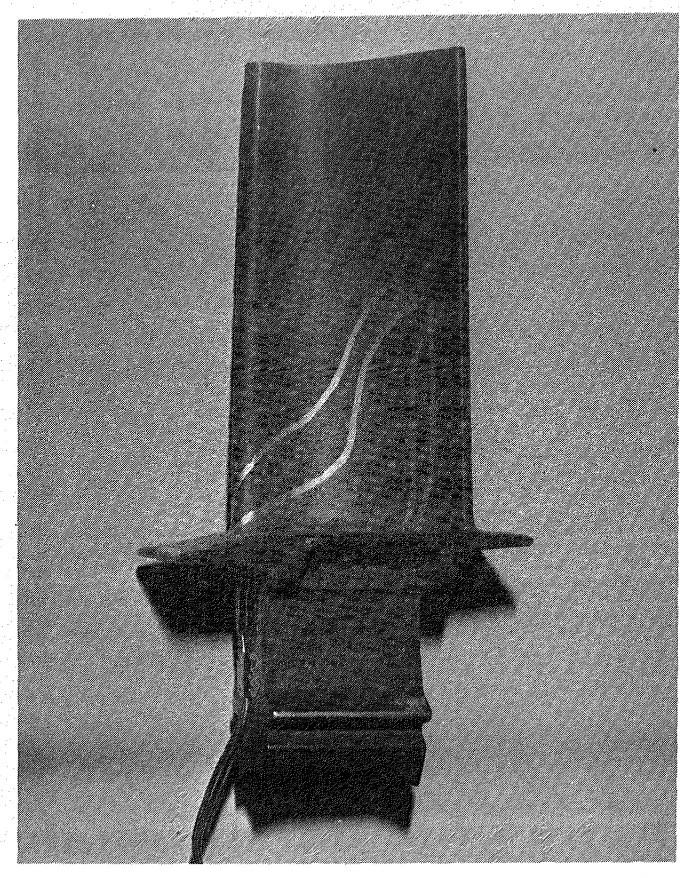


Figure 61. - Thin-film thermocouples for making minimally intrusive temperature measurements on turbine blades.

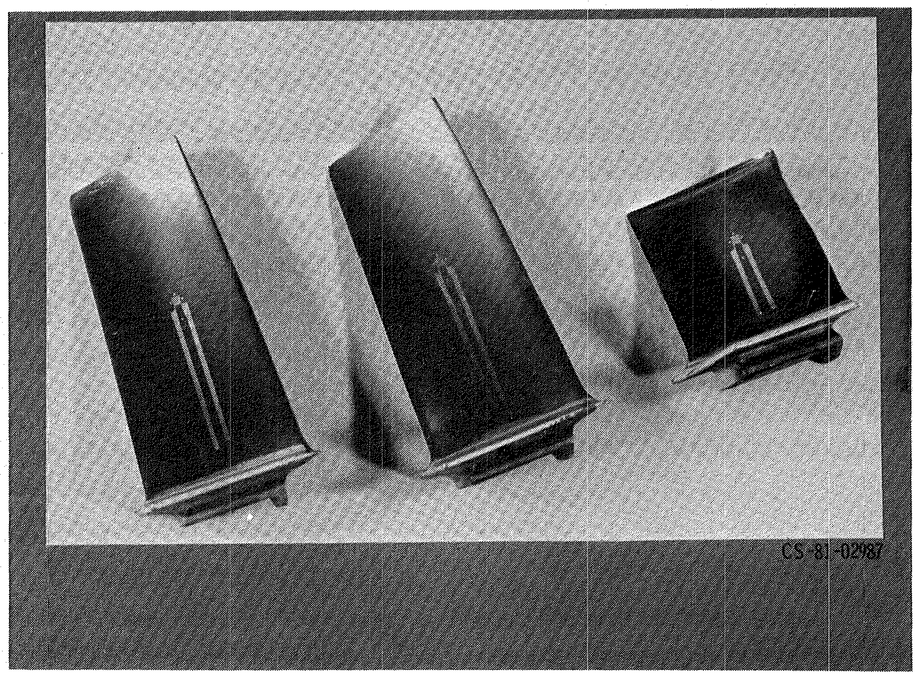


Figure 62. - Thin-film strain gages on steel and titanium compressor blades. Gages are Ni-30Cr 15 000 Å thick on Si_3N_4 insulating substrate 40 000 Å thick.

CONCLUDING REMARKS

Advanced research being conducted at the NASA Lewis Research Center in the numerous technologies that affect turbomachinery system operation has been reviewed. An extensive reference list allows much of this research to be pursued in more detail if desired.

In this broad overview it is not unusual to observe the same or closely associated research objectives being pursued in more than one technology area. For example, improved modeling of compressor stall and stall recovery is a goal of compressor unsteady flow research as well as of dynamic simulation research. This closely related research points to the considerable interaction of technologies and the need to coordinate effort in all of these related technologies if major gains in performance of turbomachinery systems are to be achieved.

In all or most of the research areas the achievements of advanced technology followed the same path - the development of improved analytical codes, controlled experiments for better modeling of the physical processes, and the application of new measurement techniques to provide more meaningful verification data. We have reached a time in history when computer power, laser power, microelectronics, etc., make a direct approach to research feasible.

Research in turbomachinery systems over the past three decades has resulted in a continual advancement to the present high level of performance. Additional performance gains are feasible, and although they may not be as large as some in the past, they will be equally important to advanced propulsion systems.

REFERENCES

Internal Flow Analysis Codes

1. Farrell, C. A. and Adamczyk, J. J., "Full Potential Solution of Transonic Quasi-3-Dimensional Flow Through a Cascade Using Artificial Compressibility," ASME Gas Turbine Conference, Houston, Tex., Mar. 1981, Paper 81-GT-70.
2. Bauer, F., Garabededian, P., Korn, D., and Jameson, A., "Supercritical Wing Sections II," Lecture Notes in Economics and Mathematical Systems, 108, Springer-Verlag, New York (1975).
3. MacCormack, R. W., "The Effect of Viscosity in Hypervelocity Impact Cratering," AIAA Paper 69-345 (1969).
4. Thompkins, W. T., "A FORTRAN Program for Calculating Three-Dimensional, Inviscid, Rotational Flows with Shock Waves in Axial Compressor Blade Rows. I - User's Manual," NASA CR-3560 (1982).
5. Chima, R. V. and Strazisar, A. J., "Comparison of Two- and Three-Dimensional Flow Computations with Laser Anemometer Measurements in a Transonic Compressor Rotor," NASA TP-1931 (1982).
6. Johnson, G. M., "Surrogate-Equation Technique for Simulation of Steady Inviscid Flow," NASA TP-1866 (1981).
7. Johnson, G. M., "Multiple-Grid Acceleration of Lax-Wendroff Algorithms," NASA TM-82843 (1982).
8. Chang, S. C. and Adamczyk, J. J., "A Semi-Direct Algorithm for Computing 3-D Inviscid Shear Flows," Presented at 5th AIAA Computational Fluid Dynamics Conference, Palo Alto, Calif., 1981.
9. Steger, J. L., Pulliam, T. H., and Chima, R. V., "An Implicit Finite Difference Code for Inviscid and Viscous Cascade Flow," AIAA Paper 80-1427 (1980).
10. Kreskovsky, J. P., Briley, W. R., and McDonald, H., "Prediction of Laminar and Turbulent Primary and Secondary Flows in Strongly Curved Ducts," NASA CR-3388 (1981).
11. Sanz, J. M., "Design of Supercritical Cascades with High Solidity," AIAA Paper 82-0954 (1982).
12. Sobieczky, H., Yu, N. J., Fung, H. Y., and Seebass, O. R., "New Method for Designing Shock-Free Transonic Configurations," AIAA Journal, 17, 7, pp. 722-729 (July 1979).
13. Smith, R. E., ed., Numerical Grid Generation Techniques, NASA CP-2166 (1980).

Compressor Research

14. Crouse, J. E. and Gorrell, W. T., "Computer Program for Aerodynamic and Blading Design of Multistage Axial-Flow Compressors," NASA TP-1946 (1981).
15. Dulikravich, D. S. and Sobieczky, N., "Shockless Design and Analysis of Transonic Blade Shapes," NASA TM-82611 (1981).
16. Behlke, R. F., Burdsall, E. A., Canal, E., Jr., and Korn, H. D., "Core Compressor Exit Stage Study. II - Final Report," NASA CR-159812 (1979).
17. Wisler, D. C., "Core Compressor Exit Stage Study. III - Data and Performance Report for Screening Test Configurations," NASA CR-159499 (1980).

18. Strazisar, A. J. and Powell, J. A., "Laser Anemometer Measurements in a Transonic Axial Flow Compressor Rotor," NASA TM-79323 (1980).
19. Strazisar, A. J. and Chima, R. V., "Comparison Between Optical Measurements and a Numerical Solution of the Flow Field Within a Transonic Axial-Flow Compressor Rotor," Paper 80-1078 AIAA (1980).
20. Garberoglio, J. E., Song, J. O., and Boudreaux, W. L., "Optimization of Compressor Vane and Bleed Settings," ASME Paper 82-GT-81 (1981).
21. Denton, J. D., "A Time Marching Method for Two- and Three-Dimensional Blade to Blade Flow," ARC R&M 3775 (1975).
22. "Unsteady Aerodynamics," Vols. I and II. Proceedings of Symposium held at University of Arizona, Mar. 18-20, 1975, R. B. Kinney, ed.
23. Adamczyk, J. J., "An Analysis of Supersonic Bending Flutter in an Axial Flow Compressor by Actuator Disk Theory," NASA TP-1345 (1978).
24. Goldstein, M. E., Braun, W., and Adamczyk, J. J., "Unsteady Flow in a Supersonic Cascade with Strong In-Passage Shocks," J. Fluid Mech., 83, 3 (1977).
25. Stargardter, H., "Subsonic/Transonic Stall Flutter Study - Final Report," NASA CR-165256 (1979).
26. Jutras, R., "Subsonic/Transonic Stall Flutter Investigation of a Rotating Rig - Final Report," Proposed NASA CR.

Turbine Research

27. VanFossen, G. J., "Heat Transfer Coefficients for Staggered Arrays of Short Pin Fins," ASME Paper 81-GT-75 (1975).
28. Langston, L. S. and Boyle, M. T., "A New Surface Streamline Flow Visualization Technique," Proposed ASME Paper for Journal of Fluid Mechanics.
29. McLallin, K. L., Kofskey, M. G., Wong, R. Y., and Westerkamp, E. J., "Effects of Interstage Diffuser Flow Distortion on the Performance of a 15.41 cm Diameter Variable-Area Stator Axial Power Turbine," NASA TM-82644 (1982).
30. Seasholtz, R. G. and Goldman, L. J., "Laser Anemometer Using a Fabry-Perot Interferometer for Measuring Mean Velocity and Turbulence Intensity along the Optical Axis in Turbomachinery," NASA TM-82841 (1982).
31. Rogo, C. and Holbrook, M. R., "Cooled Variable Nozzle Radial Turbine for Rotorcraft Applications," NASA CR-165397 (1981).
32. Hammer, A. H., "Fabrication Technique for Cooled Radial Turbine Rotor." (NASA Contract NAS3-22513.) Proposed NASA CR.

Materials Research

33. Sink, L. W., Hoppin, G. S., and Fujii, M., "Low-Cost Directionally-Solidified Turbine Blades, Vol. 1," AIRESEARCH-21-2953-1, NASA CR-159464 (Jan. 1979).
34. Eng, R. D. and Evans, D. J., "Manufacture of Low Carbon Astroloy Turbine Disk Shapes by Hot Isostatic Pressing," PWA-5574-Vol-1, NASA CR-135409 (Mar. 1978).
35. Merrick, H. F., Curwick, L. R. R., and Kim, Y. G., "Development of an Oxide-Dispersion-Strengthened Turbine Blade Alloy by Mechanical Alloying," NASA CR-135150 (Jan. 1977).
36. Hudson, S. M., "Ceramic Applications in Turbine Engines," Fifth International Symposium on Automotive Propulsion Systems, U. S. Department of Energy, Washington, D. C., Conf-800419, 1, pp. 235-246 (1980).

37. Hudson, S. M., Janovicz, M. A., and Rockwood, F. A., "Ceramic Applications in Turbine Engines," EDR-10156, NASA CR-159865 (May 1980).
38. Sevick, W. R. and Stoner, B. L., "An Analytical Study of Thermal-Barrier-Coated First Stage Blades in a JT9D Engine," PWA-5590, NASA CR-135360 (Jan. 1978).
39. Stephens, J. R., "NASA's Activities in the Conservation of Strategic Materials," NASA TM-81617 (1980).
40. Petrasek, D. W. and Signorelli, R. A., "Tungsten-Fiber-Reinforced Superalloys - A Status Review," NASA TM-82590 (1981).
41. DeCarlo, J. A. and Wagner, T. C., "Oxidation-Induced Contraction and Strengthening of Boron Fibers," NASA TM-82599 (1981).
42. Serafini, T. T., Delvigs, P., and Lightsey, G. R., "Thermally Stable Polyimides from Solutions of Monomeric Reactants," J. Appl. Polym. Sci., 16, pp. 905-915 (1972).
43. Serafini, T. T., Delvigs, P., and Lightsey, G. R., "Preparation of Polyimides from Mixtures of Monomeric Diamines and Esters of Polycarboxylic Acids," U. S. Patent 3,745,149, July 10, 1973.
44. Serafini, T. T., "Status Review of PMR Polyimides," NASA TM-79039, 1979.
45. Watson, G. K. and Moore, T. J., "Hot Isostatic Pressing of Structural Ceramics at NASA," Prepared for U. S. Dept. of Energy, Interagency Agreement DEAI01-77CS51040 (1981).
46. Gedwill, M. A. and Grisaffe, S. J., "Oxidation Resistant Claddings for Superalloys," NASA TM X-67925 (1971).
47. Merutka, J. P., "Progress in Protective Coatings for Aircraft Gas Turbines: A Review of NASA Sponsored Research," NASA TM-82740 (1981).
48. Gedwill, M. A., Glasgow, T. K., and Levine, S. R., "A New Diffusion-Inhibited Oxidation-Resistant Coating for Superalloys," NASA TM-82687 (1981).
49. Levine, S. R., Miller, R. A., and Stecura, S., "Improved Performance Thermal Barrier Coatings," Presented at the International Conference on High Temperature Corrosion, San Diego, Calif., Mar. 2-6, 1981.
50. Liebert, C. H., Jacobs, R. E., Stecura, S., and Morse, R., "Durability of Zirconia Thermal-Barrier Ceramic Coatings on Air-Cooled Turbine Blades in Cyclic Jet Engine Operation," NASA TM X-3410 (1976).
51. Stecura, S., "Two-Layer Thermal Coating for Turbine Airfoils - Furnace and Burner Rig Test Results," NASA TM X-3425 (1976).
52. Stecura, S., "Effects of Compositional Changes on the Performance of a Thermal Barrier Coating System," NASA TM-78976 (1979).
53. Smialek, J. L., "Microstructure of Al_2O_3 Scales Formed on NiCrAl Alloys," NASA TM-81676 (1981).
54. Barrett, C. A. and Lowell, C. E., "High-Temperature Cyclic Oxidation Furnace Testing at NASA Lewis Research Center," NASA TM-81773 (1981).
55. Lowell, C. E., Smialek, J. L., and Barrett, C. A., "The Cyclic Oxidation of Superalloys," Presented at the International Conference on High Temperature Corrosion, San Diego, Calif., Mar. 2-6, 1981.
56. Lowell, C. E. and Santoro, G. J., "The 1200° C Cyclic Oxidation Behavior of Two Nickel-Aluminum Alloys (Ni_3Al and NiAl) with Additions of Chromium, Silicon, and Titanium," NASA TN D-6838 (1971).
57. Barrett, C. A., Khan, A. S., and Lowell, C. E., "The Effect of Zirconium on the Cyclic Oxidation of NiCrAl Alloys," J. Electrochem. Soc., 128, 1, pp. 25-32 (Jan. 1981).
58. Stearns, C. A., Kohl, F. J., and Rosner, D. E., "Combustion System Processes Leading to Corrosive Deposits," NASA TM-81752 (1981).

59. Fryburg, G. C., Kohl, F. J., Stearns, C. A., and Fielder, W. L., "Chemical Reactions Involved in the Initiation of Hot Corrosion of B-1900 and NASA-TRW VIA," J. Electrochem Soc., 129, 3, pp. 571-585 (1982).
60. Stearns, C. A., Miller, R. A., Kohl, F. J., and Fryburg, G. C., "Mechanism of Beneficial Effect of Tantalum in Hot Corrosion of Nickel-Base Superalloys," J. Electrochem. Soc., 124, 7, pp. 1147-1148 (1977). (Also NASA TM-73600 (1977).)
61. Vary, A., "Correlations Among Ultrasonic Propagation Factors and Fracture Toughness Properties of Metallic Materials," Mater. Eval., 36, 7, pp. 55-64 (June 1978).
62. Vary, A., "Correlation Between Ultrasonic and Fracture Toughness Factors in Metallic Materials," Fracture Mechanics, ASTM STP 677, pp. 563-578 (1979).
63. Vary, A., "Concepts and Techniques for Ultrasonic Evaluation of Material Mechanical Properties," Mechanics of Nondestructive Testing, pp. 123-141, Plenum Publishing (1980).
64. Vary, A., "Computer Signal Processing for Ultrasonic Attenuation and Velocity Measurements for Material Property Characterization, " Proceedings of the Twelfth Symposium on Nondestructive Evaluation, American Society for Nondestructive Testing, Columbus, Oh., pp. 33-46 (1979).

Structures and Mechanical Technologies Research

65. Padovan, J., Adams, M., Fertis, J., Zeid, I., and Lam, P., "Engine Dynamic Analysis with General Nonlinear Finite Element Codes, II - Bearing Element Implementation, Overall Numerical Characteristics, and Benchmarking," NASA CR-165214 (1980).
66. Chan, S. T. K., Lee, C. H., and Brashears, M. R., "Three-Dimensional Finite Element Analysis for High Velocity Impact," NASA CR-134933 (1975).
67. Padovan, J., "Self-Adaptive Predictor-Corrector Algorithm for Static Nonlinear Structural Analysis," NASA CR-165410 (1981).
68. Wang, S. S. and Mandell, J. F., "Analysis of Delamination in Unidirectional and Crossplied Fiber-Composites Containing Surface Cracks," NASA CR-135248 (1977).
69. Walker, K. P., "Research and Development Program for Nonlinear Structural Modeling with Advanced Time-Temperature Dependent Constitutive Relationships," NASA CR-165533 (1981).
70. Sih, G. C. and Chen, E. P., "Moving Cracks in Layered Composites," NASA CR-159537 (1981).
71. Gallardo, V. C., Gaffney, E. F., Bach, L. J., and Stallone, M. J., "Blade Loss Transient Dynamics Analysis," NASA CR-165373 (1981).
72. Manson, S. S., Halford, G. R., and Hirschberg, M. H., "Creep-Fatigue Analysis by Strain Range Paritioning," Proceedings of the First Symposium on Design for Elevated Temperature Environment, San Francisco, Calif., May 10-12, 1971, pp. 12-24.
73. Manson, S. S., "Behavior of Materials Under Conditions of Thermal Stress," NACA TN-2933 (1953).
74. Halford, G. R. and Manson, S. S., "Practical Implementation of Double Linear Damage Rule and Damage Curve Approach for Treating Cumulative Fatigue Damage," Int. J. Fracture, 17, 2, p. 169 (1981).
75. Kaufman, A. and Hunt, L. E., "Elastic-Plastic Finite-Element Analysis of Thermally Cycled Double-Edge Wedge Specimens," NASA TP-1973 (1982).

76. Moreno, V., Meyers, G. J., Kaufman, A., and Halford, G. R., "Nonlinear Structural and Life Analysis of a Combustor Liner," NASA TM-82846 (1982).
77. Buckley, D. H., "Surface Effects in Adhesion, Friction, Wear and Lubrication," Elsevier Scientific Publishing Co., Amsterdam-Oxford-New York, 1981.
78. Jones, W. R., Jr., "Contact Angle Measurements of a Polyphenyl Ether to 190° C on M-50 Steel," NASA TM-82628 (1981).
79. Jones, W. R., Jr., "The Effect of Oxygen Concentration on the Boundary Layer Lubricating Characteristics of a C-Ether and a Polyphenyl Ether to 300° C," Wear, 73, 1, p. 123, (Nov. 1981).
80. Jones, W. R., Jr. and Loewenthal, S. H., "Analysis of Wear Debris from Full-Scale Bearing Fatigue Tests Using the Ferrograph," ASLE Trans., 24, 3, pp. 323-330 (1981).
81. Miyoshi, K. and Buckley, D. H., "Tribological Properties and Surface Chemistry of Silicon Carbide at Temperatures of 1500° C," ASLE Journal, 81-LC-5A-1 (April 1981).
82. Spalvins, T. and Buzek, B., "Frictional and Morphological Characteristics of Ion-Plated, Soft, Metallic Films," NASA TM-81723 (1981).
83. Jones, W. R., Jr. and Hady, W. F., "Effect of § Irradiation on the Friction and Wear of Ultrahigh Molecular Weight Polyethylene," Wear, 70, pp. 77-92 (1981).
84. Hamrock, B. J., "Lubrication Fundamentals," NASA TM-81762 (1981).
85. Fusaro, R. L., "Effect of Load, Area of Contact, and Contact Stress on the Wear Mechanisms of a Bonded Solid Lubricant Film," Wear, Netherlands, 75, pp. 403-422 (1982). (Also NASA TM-81563 (1982).)
86. Fusaro, R. L., "Mechanisms of Lubrication and Wear of a Bonded Solid-Lubricant Film," ASLE Trans., 24, 2, pp. 191-204 (1981).
87. Fusaro, R. L., "Tribological Properties and Thermal Stability of Various Types of Polyimide Films," NASA TM-81765 (1981).
88. Cusano, C. and Sliney, H. E., "Dynamics of Solid Dispersions in Oil During Lubrication of Point Contacts. I - Graphite," NASA TM-81683 (1981).
89. Anderson, W. J. and Zaretsky, E. V., " Rolling-Element Bearings - A Review of the State of the Art." Proceedings of the Tribology Workshop, F. F. Ling, ed., National Science Foundation, Washington, D. C., Apr. 1974, pp. 233-325.
90. Parker, R. J., "Lubrication of Rolling-Element Bearings. Bearing Design - Historical Aspects, Present Technology and Future Problems," W. J. Anderson, ed., ASME, pp. 87-110 (1980).
91. Bamberger, E. N., Zaretsky, E. V., and Signer, H., "Endurance and Failure Characteristics of Main-Shaft Jet Engine Bearing at 3×10^6 DN," J. Lubr. Technol., Trans. ASME, Ser. F, 98, 4, pp. 580-585 (Oct. 1976).
92. Parker, R. J., "Present Technology of Rolling-Element Bearings," Advanced Power Transmission Technology. NASA CP-2210 (1982).
93. Zaretsky, E. V., Parker, R. J., and Anderson, W. J., "NASA Five-Ball Fatigue Tester - Over 20 Years of Research," Proceedings of the International Symposium on Contact Rolling Fatigue Testing of Bearing Steel, Philadelphia, Pa. (1982).
94. Zaretsky, E. V., Townsend, D. P., and Coy, J. J., "NASA Gear Research and Its Probable Effect on Rotorcraft Transmission Design," NASA TM-79292 (1979).
95. Coy, J. J., "Geared Power Transmission Technology," Advanced Power Transmission Technology, NASA CP-2210 (1982).

96. Townsend, D. P., "The Application of Elastohydrodynamic Lubrication in Gear Tooth Contacts," NASA TM-68142 (1972).
97. Zaretsky, E. V., "NASA Helicopter Transmission System Technology Program," Advanced Power Transmission Technology, NASA CP-2210, 1982.
98. Loewenthal, S. H., Anderson, N. E., and Nasvytis, A. L., "Performance of a Nasvytis Multiroller Traction Drive," NASA TP-1378 (1978).
99. Loewenthal, S. H., "A Historical Perspective of Traction Drives and Related Technology," Advanced Power Transmission Technology, NASA CP-2210 (1982).
100. Ludwig, L. P., "Gas Path Sealing in Turbine Engines," NASA TM-73890 (1978).
101. Bill, R. C., Shiembob, L. T., and Stewart, O. L., "Development of Sprayed Ceramic Seal Systems for Turbine Gas Path Sealing," NASA TM-79172 (1978).
102. Kennedy, F. E. and Bill, R. C., "Thermal Stress Analysis of Ceramic Gas Path Seal Components for Aircraft Turbine Engines," NASA TP-1437 (1979).
103. Bill, R. C., Wisander, D. W., and Brewe, D. E., "Preliminary Study of Method for Providing Thermal Shock Resistance to Plasma-Sprayed Ceramic Gas Path Seals," NASA TP-1561 (1980).
104. Bill, R. C., Sovey, J., and Allen, G. P., "A Sputtered Zirconia Primer for Improved Thermal Shock Resistance," NASA TM-81732 (1981).
105. Clingman, D. L., "Abradable Dual Density Ceramic Turbine Seal System," NASA CR-165309 (1981).
106. Eaton, H. E. and Novak, E. T., "Development of Low-Modulus Materials for Use in Ceramic Gas Path Seal Systems," NASA CR-165469 (1981).
107. Zuk, J. and Smith, P. J., "Quasi-One-Dimensional Compressible Flow Across Face Seals and Narrow Slots, " NASA TN D-6787 (1972).
108. Zuk, J., "Computer Program for Quasi-One-Dimensional Compressible Flow with Area Change and Friction - Applications to Gas Film Seals," NASA TN D-7481 (1974).
109. O'Brien, M., "Development of Spiral Groove Self-Acting Seals for Helicopter Engines," NASA CR-159622 (1979).
110. O'Brien, M., "Experimental Evaluation of a High-Speed Seal for an Aircraft Transmission," NASA CR-159709 (1979).
111. Zuk, J., "Fundamentals of Fluid Sealing," NASA TN D-8151 (1976).
112. Cheng, S. and Cheng, H. S., "Dynamic Response and Stability of a Gas Lubricated Rayleigh Step Pad Seal," NASA CR-121156 (1973).
113. Sehnal, J., Sedy, J., Zobens, A., and Etzion, I., "Energy-Efficient Face Seal," NASA CR-165591 (1982).
114. Nelson, H. D., Meacham, W. L., Fleming, O. D., and Kascak, A. F., "Nonlinear Analysis of Rotor Bearing Systems Using Component Mode Synthesis," ASME Paper 82-GT-303 (Mar. 1982).
115. Mitchell, L. D. and Mellan, D. M., "Torsional Lateral Coupling in a Geared High-Speed Rotor System," ASME Paper 75-DET-75 (May 1975).
116. Rotor Dynamic Instability Problems in High-Performance Turbomachinery, NASA CP-2133 (1980).
117. Darlow, M. and Zorzi, E., "Mechanical Design Handbook for Elastomers," NASA CR-3423 (1981).
118. Bhat, S. T., Buono, D. F., and Hibner, D. H., "Analysis of High-Load Dampers," NASA CR-165503 (1982).
119. Tessarzik, J. M., "Flexible Rotor Balancing by the Influence Coefficient Method - Multiple Critical Speeds with Rigid or Flexible Supports," NASA CR-2553 (1955).

120. DeMuth, R. S., "Experiments on Multiplane Balancing Using a Laser for Material Removal," NASA CR-3105 (1979).
121. Smalley, A. J. and Tessarzik, J. M., "Balancing Techniques for High-Speed Flexible Rotors," NASA CR-2975 (1978).
122. Martin, M. R., "T55 Power Turbine Rotor Multiplane-Multispeed Balancing Study," NASA CR-167891 (1982).

Combustion Research

123. Fundamentals of Gas Turbine Combustion, NASA CP-2087 (1979).
124. Combustion and Fuels Fundamentals Research Review. (April 1981).
125. Grobman, J., "Alternative Jet Aircraft Fuels," Aeropropulsion 1979, NASA CP-2092 (1979).
126. Aircraft Research and Technology for Future Fuels, NASA CP-2146 (1980).
127. Groves, R. A., Jr., "Computational Fluid Dynamics, the Coming Revolution." Astronaut. Aeronaut., 20, 3 (Mar. 1982).
128. Lilley, D. G. and Rhode, D. L., "STARPIC: A Computer Code for Swirling Turbulent Axisymmetric Recirculating Flows in Practical Isothermal Combustor Geometries," NASA CR-3442 (1981).
129. Srivivason, R. and Mongia, H. C., "Numerical Computations of Swirling Recirculating Flow," NASA CR-165196 (1980).
130. Ghoniem, A. F., Chorin, A. J., and Oppenheim, A. K., "Numerical Modeling of Turbulent Flow in a Combustion Tunnel," Lawrence Berkeley Laboratory, LBL-11520, University of California, Berkeley (Sept. 1980).
131. Vaneveld, L., Hom, K., and Oppenheim, A. K., "Secondary Effects in Combustion Instabilities Leading to Flashback," Proceedings of the AIAA 20th Aerospace Sciences Meeting, Orlando, Fla., Jan. 11-14, 1982. (AIAA 82-0037 (1982).)
132. Cochran, R. P., Norris, J. W., and Jones, R. E., "A High-Pressure, High-Temperature Combustor and Turbine-Cooling Test Facility." NASA TM X-73445 (1976).
133. Wear, J. D., Trout, A. M., and Smith, J. M., "Performance of Semi-Transpiration-Cooled Liner in High-Temperature-Rise Combustor." NASA TP-1806 (1981).
134. Ingebo, R. D., "Capillary and Acceleration Wave Break-up of Liquid Jets in Axial-Flow Airstreams," NASA TP-1791 (1981).
135. Johnson, B. V. and Bennett, J. C., " Mass and Momentum Turbulent Transport Experiments with Confined Coaxial Jets," NASA CR-165574 (1981).
136. Dyer, T. M., Witze, P. O., Johnson, S. C., and Smith, J. R., "Application of New Diagnostic Techniques in Engines," AIAA Paper 82-0235 (Jan. 1982).

Fuels Research

137. Longwell, J. P. and Grobman, J., "Alternative Aircraft Fuels," J. Eng. Power, 101, 1 (Jan. 1979).
138. Grobman, J., "Alternative Jet Aircraft Fuels." Aeropropulsion 1979, NASA CP-2092 (1979).
139. Grobman, J. and Reck, G. M., "The Impact of Fuels on Aircraft Technology Through the Year 2000," NASA TM-81492 (1980).
140. Aircraft Research and Technology for Future Fuels, NASA CP-2146 (1980).
141. Taylor, W. F., ed., "Jet Fuel Thermal Stability," NASA TM-79231 (1979).
142. Vranos, A. and Marteney, P. J., "Experimental Study of the Stability of Aircraft Fuels at Elevated Temperatures," NASA CR-165165 (1980).

143. Buttrill, S. E., Jr., Mayer, Frank R., Lan, Bosco, St. John, G. A., and Dulin, D., "Oxidation and Formation of Deposit Precursors in Hydrocarbon Fuels," NASA CR-165534 (1982).
144. Friedman, R. and Stockemer, F. J., "Temperature and Flow Measurements on Near-Freezing Aviation Fuels in a Wing-Tank Model," ASME Paper 81-GT-63 (1981).
145. Reck, G. M., "Advanced Fuel System Technology for Utilizing Broadened-Property Aircraft Fuels," NASA TM-81538 (1981).
146. Stockemer, F. J., "Experimental Study of Fuel Heating at Low Temperatures in a Wing Tank Model," NASA CR-165391 (1981).

Controls Research

147. DeHoff, R. L., Hall, W. E., Adams, R. J., and Gupta, N. K., "F111 Multivariable Control Synthesis Program," Vols. I and II, AFAPL-TR-77-35 (June 1977).
148. Szuch, J. R., Seldner, K., and Cwynar, D. C., "Development and Verification of a Real-Time Hybrid Computer Simulation of the F111-PW-111(3) Turbofan Engine," NASA TP-1134 (1977).
149. Morey, W. W., Glenn, W. H., Decker, R. O., and McClurg, W. C., "Design, Fabrication, and Testing of an Optical Temperature Sensor," NASA CR-165125 (1981).
151. Mihaloew, J. R., "A Nonlinear Propulsion System Simulation Technique for Piloted Simulators," NASA TM-82611 (1981).
151. Mihaloew, J. R., Roth, S. P., and Creekmore, R., "A Real-Time Pegasus Propulsion System Model for VSTOL Piloted Simulation Evaluation," NASA TM-82771 (1981).
152. Szuch, J. R., Soeder, J. F., Seldner, K., and Cwynar, D. S., "F111 Multivariable Control Synthesis Program - Evaluation of a Multivariable Control Using a Real-Time Engine Simulation," NASA TP-1156 (1977).
153. Lehtinen, B., Soeder, J. F., Costakis, W. G., and Seldner, K., "F111 Multivariable Control Synthesis Program - Results of Engine Altitude Tests," NASA TP-2164 (1982).
154. Beattie, E. C., LaPrad, F. F., McGlone, M. E., Rock, S. M., and Akhter, M. M., "Sensor Failure Detection System," NASA CR-165515 (1981).
155. Blech, R. A. and Arpasi, D. J., "An Approach to Real-Time Simulation Using Parallel Processing," NASA TM-81731 (1981).
156. Krosel, S. M. and Milner, E. J., "Application of Integration Algorithms in a Parallel Processing Environment for the Simulation of Jet Engines," NASA TM-82746 (1982).
157. Wenzel, L. M. and Bruton, W. B., "Analytical Investigation of Nonrecoverable Stall," NASA TM-82792 (1982).

Instrumentation Research

158. Maxwell, B. R. and Seasholtz, R. G., "Velocity Lag of Solid Particles in Oscillating Gases and in Gases Passing Through Normal Shock Waves," NASA TN D-7491 (1974).
159. Maxwell, B. R., "Particle Flow in Turbomachinery with Application to Laser-Doppler Velocimetry," AIAA J., 12, 11, pp. 1297-1298 (Oct. 1974).
161. Maxwell, B. R., "Tracer Particle Flow in a Compressor Rotor Passage with Application to LDV," AIAA J., 13, 9, pp. 1141-1142 (Sept. 1975).
161. Seasholtz, R. G., "Laser Doppler Velocimeter Measurements in a Turbine Stator Cascade Facility," Proceedings of the Second International

Workshop on Laser Velocimetry, vol. 2, H. D. Thompson and W. H. Stevenson, eds., Bull. 144, Purdue Univ., pp. 199-215 (1974).
162. Goldman, L. J., Seasholtz, R. G., and McLallin, K. L., "Velocity Surveys in a Turbine Stator Annular-Cascade Facility Using Laser Doppler Techniques," NASA TN D-8269 (1976).
163. Seasholtz, R. G., "Laser Doppler Velocimeter System for Turbine Stator Cascade Studies and Analysis of Statistical Biasing Errors," NASA TN D-8297 (1977).
164. Goldman, L. J. and Seasholtz, R. G., "Laser Anemometer Measurements in an Annular Cascade of Core Turbine Vanes and Comparison with Theory," NASA TP-2018 (1982).
165. Goldman, L. J. and Seasholtz, R. G., "Comparison of Laser Anemometer Measurements and Theory in an Annular Turbine Cascade with Experimental Accuracy Determined by Parameter Estimation," Presented at the ASME Symposium on Engineering Applications of Laser Velocimetry, Phoenix, Ariz., Nov. 14-19, 1981.
166. Powell, J. A., Strazisar, A. J., and Seasholtz, R. G., "Efficient Laser Anemometer for Intra-Rotor Flow Mapping in Turbomachinery," J. Eng. Power, 103, 2, pp. 424-429 (Apr. 1981).
167. Strazisar, A. J. and Powell, J. A., "Laser Anemometer Measurements in a Transonic Axial Flow Compressor Rotor," J. Eng. Power, 103, 2, pp. 430-437 (Apr. 1981).
168. Powell, J. A., Strazisar, A. J., and Seasholtz, R. G., "High-Speed Laser Anemometer System for Intra-Rotor Flow Mapping in Turbomachinery," NASA TP-1663 (1982).
169. Edwards, R. V., "A New Look at Particle Statistics in Laser-Anemometer Measurements," J. Fluid Mech., 105, 317 (1981).
170. Edwards, R. V. and Jensen, A. S., "Particle Sampling Statistics in Laser Anemometers: Sample and Hold Systems and Saturable Systems," Presented at International Symposium on Applications of Laser-Doppler Anemometry to Fluid Mechanics, Lisbon, Portugal, July 1982.
171. Decker, A. J., "Holographic Flow Visualization of Time-Varying Shock Waves," Applied Optics, 20, pp. 3120-3127 (1981).
172. Decker, A. J., "Fringe Localization Requirements for Three-Dimensional Flow Visualization of Shock Waves in Diffuse-Illumination, Double-Pulse Holographic Interferometry," NASA TP-1868 (1982).
173. Boldman, D. R., Buggele, A. E., and Decker, A. J., "Three-Dimensional Shock Structure in a Transonic Flutter Cascade," AIAA Journal, to be published in Aug. or Sept. 1982.
174. Decker, A. J., "Holographic Cinematography of Time-Varying Reflecting and Time-Varying Phase Objects Using a Nd:YAG Laser," Optics Letters, 7, pp. 122-123 (1982).
175. Nieberding, W. C. and Pollack, J. L., "Optical Detection of Blade Flutter," Presented at ASME Gas Turbine Conference and Products Show, Philadelphia, Pa., Mar. 27-31, 1977, Paper 77-GT-66.
176. Barranger, J. P., "In-Place Recalibration Technique Applied to a Capacitance-Type System for Measuring Rotor Blade Tip Clearance," NASA TP-1110 (1978).
177. Barranger, J. P. and Ford, M. J., "Laser-Optical Blade Tip Clearance Measurement System," J. Eng. Power, 3, 2, pp. 457-460 (1981).
178. Grant, H. P. and Przybyszewski, J. S., "Thin-Film Temperature Sensor," NASA CR-159782 (1980).
179. Grant, H. P., Przybyszewski, J. S., and Claing, R. G., "Turbine Blade Temperature Measurements Using Thin-Film Temperature Sensors," NASA CR-165201 (1981).

180. Grant, H. P., Przybyszewski, J. S., Claing, R. G., and Anderson, W. L., "Thin-Film Temperature Sensors, Phase III," NASA CR-165476 (1982).
181. Atkinson, W. H. and Strange, R. R., "Development of Advanced High Temperature Heat Flux Sensors," NASA CR-165618 (1982).

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-82949		

4. Title and Subtitle	5. Report Date
ADVANCED TECHNOLOGIES FOR TURBOMACHINERY SYSTEMS - AN OVERVIEW	August 1982
	6. Performing Organization Code: 505-32-4A
7. Author(s): Melvin J. Hartmann	8. Performing Organization Report No.: E-1302
	10. Work Unit No.
9. Performing Organization Name and Address: National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered: Technical Memorandum
12. Sponsoring Agency Name and Address: National Aeronautics and Space Administration, Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

This is an extended version of the talk presented at the Eleventh Annual Turbomachinery Symposium sponsored by Texas A&M University, Houston, Texas, December 14-16, 1982.

16. Abstract

The next generation of turbofan and turbojet engines that will power our planes will be based on the advancements to the technology base that are being generated today. This paper presents a brief overview and status of the research being conducted by NASA's Lewis Research Center to advance turbomachinery system components plus a number of associated technologies. Specific technologies reviewed include the compressor, turbine, internal flow analysis methods, combustion, fuels, materials, structures, bearings, seals, and lubrication, dynamics and controls, and instrumentation. The research includes that conducted at Lewis as well as that sponsored by Lewis with industry and universities. More specific details of most of the research discussed can be obtained from the large number of references listed. The overview indicates a consensus effort in most technologies to develop improved analytical procedures as a path to improved performance. It also reflects the strong interaction between the various technologies if turbomachinery performance gains are to be realized.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Turbomachinery Computational fluid mechanics Combustion fuels Instrumentation controls	Unclassified - unlimited STAR Category 07

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		

* For sale by the National Technical Information Service, Springfield, Virginia 22161

End of Document