NASA Technical Memorandum 83505

The Trend of Future Gas Turbine Technology

Melvin J. Hartman
Lewis Research Center
Cleveland, Ohio

Prepared for the
Tokyo International Gas Turbine Congress
cosponsored by the GTSJ, ASME, IMechE, JSME, and VDI
Tokyo, Japan, October 23-28, 1983

NASA

The Trend of Future Gas Turbine Technology

Melvin J. Hartmann[1]

E-1844

ABSTRACT

Future gas turbine technology will be based on contributions to the technology base being made today. At the NASA Lewis Research Center in Cleveland, Ohio, research is being conducted on turbomachinery system components and in a number of associated disciplines to advance the technology of aviation turbofan and turbojet engines. Areas of research include compressors, turbines, internal flow analysis, combustion, fuels, materials, structures, bearings, seals, lubrication, dynamics and controls, and instrumentation. A review of the research directions being taken in these areas and the steady advances being made provides a reasonable glimpse at gas turbine technology of the future.

INTRODUCTION

The long history of gas turbine technology indicates a continuing advance in performance capability and a broadening range of application. During the last 35 years a considerable research and development effort has resulted in advances in all technical areas including aerothermodynamics and structural performance as well as durability and reliability. Fortunately during this time new and expanded applications have resulted in a strong market to support and focus these research and development efforts. This long-term extensive research activity along with the high levels of performance achieved has raised the thought that gas turbine technology may already be near its ultimate level. Can a continued payoff be expected from future investment of resources in this area? General observations indicate that the overall rate of advance has continued to increase. Advances have been achieved in a variety of directions: in some cases aerothermodynamic performance has been improved; in other cases greater durability or lower costs have been the major advance. Over this period no single simple measure of advance has been sufficient. Even though the overall answer to this question cannot be quantified in a simple manner, it is of considerable importance to the gas turbine community. It is of critical importance to those of us who presently work in this area of technology.

The purpose of this dissertation is to consider the research and development process and some of its present activities and to indicate some potential trends in gas turbine technology. Since my experience has been totally in the field of gas turbines for aeropropulsion systems, my remarks will be from this particular field. Aeropropulsion applications are particularly demanding of the gas turbine system and have benefited from a relatively high level of technology resources. Trends in the aeropropulsion area may have some application to other gas turbine areas. A few pertinent historical trends and events will be considered along with some of the advanced methods now available to the gas turbine technologist. From these, a few comments on future trends will be made. Restated - What does the future hold? How will future gains be achieved?

THE RESEARCH AND DEVELOPMENT PROGRAM

The continued advance of aeropropulsion systems has been highly dependent on the level of gas turbine technology. Advanced gas turbines result from a development cycle including some 5 years of ground testing followed by 2 or 3 years of improvement during flight operations. Prior to this cycle, design decisions for the gas turbine are based on stringent performance and durability guarantees that must be met. Furthermore the final propulsion system must be sufficiently advanced that it will be competitive and saleable during a period 7 to 25 years after the design parameters are selected. The designers of these gas turbines must gamble that performance and durability can be achieved through the development process without excessive effort. Thus the designers are always pushed beyond known and existing levels of capability. If sufficient advanced capability is not designed into the system, the propulsion system is not selected for future applications and the development fails to be profitable. The competitive nature of the aeropropulsion industry has been a driving force for the advance of gas turbine technology and to some extent applies to other areas in which gas turbines are used.

The overall research and development process has resulted in an extensive experimental data base for gas turbine components. The resulting empirical system has greatly advanced the capability of these components. The fact that the usable stage pressure ratio of axial-flow compressors has been increased from less than 1.1 to over 2.0 typifies these substantial gains. This advance has been achieved primarily by the application of the empirical base. Past theoretical predictions of the maximum stage pressure ratios have been substantially exceeded. This is partially due to the two-dimensional

---

[1] NASA Lewis Research Center, Cleveland, Ohio.

boundary layer separation criteria being an oversimplification of the three-dimensional flow field. The development of concepts to operate compressor rotors efficiently with transonic and supersonic flows has made possible the application of machinery at very high rotational speeds. Stage pressure ratios then are limited by stress and aeroelastic phenomena. The result of systematically removing or overcoming limiting conditions or phenomena has been the continued increase in axial-flow compressor stage pressure ratio and performance. Gas turbine components applicable to aeropropulsion systems have been substantially advanced through this active research and development process.

Gas turbine component advances generally require increasing the capability in a number of closely related disciplines or technical areas. For example, the operational capability of high-temperature, high-speed turbines depends strongly on a number of discipline areas. Important areas are fluid mechanics, heat transfer, structural dynamics, high-temperature materials, and manufacturing techniques. Compromises are reached in these and other technical areas to achieve an optimized high-temperature turbine for the given application. The exact compromise depends on the level of capability available to the design/development team in each area. Likewise propulsion systems are optimized according to the level of component technology available to the team. Thus, in the area of aeropropulsion systems, it has been necessary to carry on research in a range of related and applicable disciplines and component areas.

The objectives of the technology programs have changed remarkably over the past years. For example, the objective of combustion and combustor research has continuously changed. At one time achieving high combustion efficiencies was the main concern. Now the range of operating conditions over which nearly 100 percent efficiency could be achieved has been expanded. The reduction of pollutants has also been a major objective of advanced combustor studies. Recently, improve durability with fuels of broadened specification has been a major objective. Extremely short, durable combustors appear to be feasible if new materials and new cooling approaches are used. Advanced analytical methods will contribute to the control of the temperature profile and pattern factor to the turbine. Thus the driving motivation of combustor research has varied depending on the needs of the current application and the prevailing economics or other concerns.

The aeropropulsion research and development process carried on over the past 35 years has had a substantial effect on the advance of gas turbines. These few comments are included to characterize this process:

(1) The long-term R&D process requires the application of design parameters that are beyond the existing capability of the design team but are judged to be feasible in the development process.

(2) Past achievements have been based more on the available empirical base than on analytical or theoretical information.

(3) As the level of technology has increased, it has become increasingly important to bring together advanced capabilities in related discipline and component areas.

(4) As component capability has progressed, the emphasis in a given area has changed depending on the need for performance, durability, adaptability, or the environmental or economic concerns of the time.

These few comments have been made to characterize the wide variety of the R&D activities in aeropropulsion that have resulted in substantial advances in gas turbine technology. It is not meant to be all inclusive. It is recognized that the aeropropulsion area is only partially applicable to the overall field of gas turbine technology. The technologist working in other areas of gas turbine application must interpret the applicability of these remarks to his/her own area.

IMPROVING COMPONENTS

Continued advances in gas turbine technology have required and will continue to require improved compressor, combustor, and turbine components. The intensive research program of the past 35 years has been characterized by an increasing data base and new measuring and analytical methods. During the last 5 years there has been a substantial increase in the numerical methods available to the fluid mechanics and structural mechanics technologist. Three-dimensional analytical solutions can be expected to be practical when a major scientific computer is available. Researchers must now verify, through detailed experiments, that controlling or limiting physical phenomena are captured in these solutions. Even more difficult is the problem of learning how to use these analytical methods to improve components for specific applications.

It is indeed fortunate that similar progress is under way in advanced physical measurement systems that are potentially capable of displaying similar detail to that computed by advanced analytical and numerical methods. The advanced instrumentation systems can be illustrated by the laser velocimeter system shown in Fig. 1. This system has been made practical by advanced data processing technology. The system can measure the Mach number distribution in high-speed rotor blading. These data compare favorably with computed results. The measurements are made without intruding and disturbing the flow field. These data give some degree of assurance that the calculated results provide a meaningful model of the flow conditions. Thus computer-based studies using the numerical model could be useful in optimizing the component for a given application. On the other hand, the experimentalist has an instrument to determine how the blading could be changed to control the observed flow field. Future turbomachinery components can be optimized on the basis of the detailed flow phenomena rather than overall considerations as has been done in the past.

The new capabilities in analytical and numerical calculations and the measurement of detailed physical phenomena can be expected to increase performance and other desirable capabilities. Components can be designed to meet unique requirements of new applications. It would be expected that this capability could also be used to substantially shorten the required development time, thus making it possible to respond quickly to new or changing requirements.

Some of the perceived needs for advanced compressor components are indicated in Fig. 2. The figure indicates the desired gains in both the large turbofan propulsion system and the smaller turboshaft engines. It is expected that the improved analytical and numerical computation system and the advanced measuring systems will make it possible to achieve these gains.

Similarly, computational and experimental methods are becoming available in the turbine area.

These require the incorporation of detailed heat transfer to optimize the cooling systems. Detailed studies indicate approaches to avoid the problem of the horseshoe vortex caused by "scrubbing" the cooling air away from the annulus walls. This requires a detailed knowledge of the flow phenomena as indicated in Fig. 3, where ink dots show the flow configuration. In a related area, short crossflow pins are used to enhance the heat transfer in turbine blades (Fig. 4). It has been necessary to obtain a broadened data base for the relative heat transfer when crossflow pins are as long as their diameter.

A number of current areas of combustion research are shown in Fig. 5. Fuel injection and jet breakup can now be studied in detail. The continued move to higher pressures and temperatures as well as the use of high-temperature materials requires a complete understanding of flashback from the combustion zone. The use of low-hydrogen-content fuels may considerably increase radiation to the combustor walls. Simplified combusting flows have been modeled with a considerable degree of success. Also, the numerical modeling of a crossflow jet into a combusting zone has produced a temperature distribution similar to those measured. The overall flow and combustion field in a complete combustor may be beyond present computational capability (Fig. 6). It is possible, however, that the detailed modeling will provide information with which to control the cooling and temperature distribution at the turbine inlet in very short high-performance combustors.

It is obvious that a substantial portion of the increased capability of gas turbine components must be credited to new instrumentation and measurement systems. To obtain detailed aerothermal and structural dynamic data, instrumentation must provide minimal interference to the phenomena being measured (Fig. 7). In many cases new instrumentation is completely nonintrusive. These systems depend extensively on laser technology such as the laser anemometer, which has been applied extensively in all flow research areas. These measurement systems use substantially improved signal processing and analysis methods. The line-of-sight laser anemometer (Fig. 8) can measure all velocity components including the radial-flow component in machinery blade rows during a single survey. The holographic cinematography system provides a new method to examine shock motion effects. Similar classes of instrumentation and measurement systems are available for the study and development of improved dynamic characteristics of structural components and systems.

MATERIALS AND STRUCTURES

A wide range of materials for advanced aeropropulsion systems are potentially available. The fabricability of fiber-reinforced PMR polyimides for use at higher temperature levels has been considerably improved. Graphite fiber/PMR-15 composite has been used in the construction of the outer duct for the F-104 engine (Fig. 9). Such components will be used in increasing number in future applications.

Continuous progress in the extension of superalloy metallic materials to higher temperature capability can be expected. Figure 10 indicates that, beyond the single-crystal technology, eutectic, directionally solidified, and fiber-reinforced superalloys appear to be available for higher temperature applications. Even higher gas temperatures can be achieved if thermal-barrier coatings or monolithic ceramic components are used. Continued improvement in ceramic materials and processing makes this a very attractive area for future high-temperature structural applications.

A method of conserving expensive strategic materials and achieving improved properties through new processing methods is illustrated in Fig. 11. Melt spinning produces a material formed with local solidification rates greater than 1 million degrees per second. New compositions and microstructures are achieved that cannot be achieved by any other method to provide improved material properties potentially suitable for very high-temperature applications.

Structural analytical methods are now becoming available to improve the structural performance of gas turbine systems. Figure 12 indicates the applicability of these methods. The large engine structural model provides the opportunity to investigate the dynamic interaction of the various engine components. Foreign object damage of machinery blades can be evaluated, and optimization techniques can be applied to tailor blade design for a specific requirement. The aerothermal environment during cyclic conditions requires the adaptation of nonlinear methods to structural analysis and life prediction.

Uniaxial creep-fatigue experiments provide first-order information on cyclic stress-strain response and life prediction (Fig. 13). Damage accumulation mechanisms, including the initiation and propagation of microcracks, can be identified through advanced methods for microstructural analysis. These studies are incorporated into life prediction methods for components that encounter the environment in aeropropulsion gas turbine systems.

In aeropropulsion systems over one-third of the weight is rotated at very high speeds. This has required a continuous increase in capability in all of the mechanical components of bearings, seals, and the necessary gears and lubrication systems (Fig. 14). Because rotating elements operate near or beyond resonant conditions, they require extremely precise balancing and the use of high-load damping devices. Since blade rubs on the housings are inevitable, special materials must be selected to avoid excessive rub forces. Analytical and experimental data must be sufficient to provide designs that avoid major catastrophic failures as a result of these rubs. Figure 15 indicates the computed rotor orbiting that would result if a turbine blade was lost. The calculation indicates that, if the blade tips did not rub the casings, fairly large but stable shaft orbiting would result. On the other hand, if a substantial rub force is applied, the orbiting rotor appears to be unstable and a severe failure could be expected. These few comments are meant to indicate that new structural analysis methods can be expected to enhance the design and development of future aeropropulsion systems.

THE GAS TURBINE SYSTEM

Advanced components were integrated into an energy efficient engine (Fig. 16) to achieve a fuel saving of about 12 percent over the high-bypass-ratio turbofan engines presently in use. High-pressure-ratio stages were used in the compressor system. A very short, low-polluting combustion chamber and a substantial number of highly efficient turbine stages were incorporated. The bypass and core streams were mixed through a low-loss mixer. The successful operation of the engine indicates that the advanced components can be integrated into a high-performance propulsion system.

The energy efficient engine was operated with an advanced digital control system. A brief consideration of the trends in control and systems simulation technology is given in Fig. 17. Advanced sensing and electronic controls are necessary for the increasing number of control functions expected on future propulsion systems. In some cases performance improvements may be possible if control margins are reduced or recovery from undesirable operating conditions is improved. The design of a control logic to achieve a suitable recovery from system stall would require that the system be modeled dynamically. Figure 18 indicates that dynamic modeling requires a suitable model of the components and the engine system throughout the stalled regime. It is probable that future systems will be modeled and investigated to fully guide the development program.

GAS TURBINE TECHNOLOGY TRENDS

Considering the preceding discussion of gas turbine aeropropulsion technology a few general comments pertaining to future trends can be made:

1. Advanced computational methods in fluid mechanics, structural mechanics, and closely related areas coupled with advanced physical measurement can be expected to provide continued improvements in gas turbine components and systems.
2. The technologist must learn to deal with a very large amount of detailed information rather than overall conditions. The computer will be used more and more to augment the research and development program. Improved systems and components can be expected. The greatest advantage realized may be a substantial reduction in the development time required to field a new system.
3. To achieve major gains in the future, it will be necessary to increase capability in a number of related areas such as aerodynamic and structural dynamics, materials, heat transfer, and manufacturing methods.
4. Modifying or designing gas turbine components and systems to meet a unique application (rather than adapting an existing system) could be more feasible when the technical base is less dependent on empirical information.
5. Advanced control and simulation methods may result in improved operation of gas turbine systems through reduced control margins and controlled recovery from stall or other undesirable operating conditions.

These few comments pertaining to future trends in gas turbine technology are drawn from the author's thoughts and experiences in the aeropropulsion field. To some extent they may apply to other areas where gas turbines are used. This brief discussion should not be considered all inclusive. The trends will obviously depend on the level of technology available and the ingenuity of technologists working in the gas turbine field.

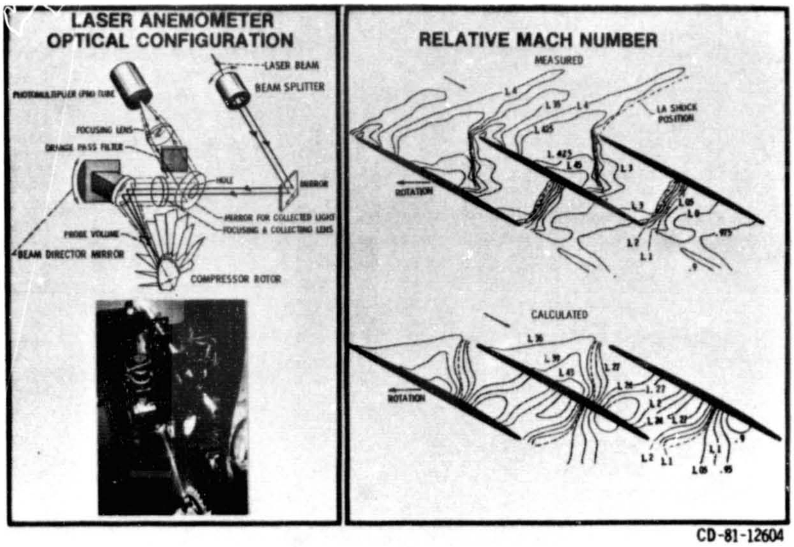
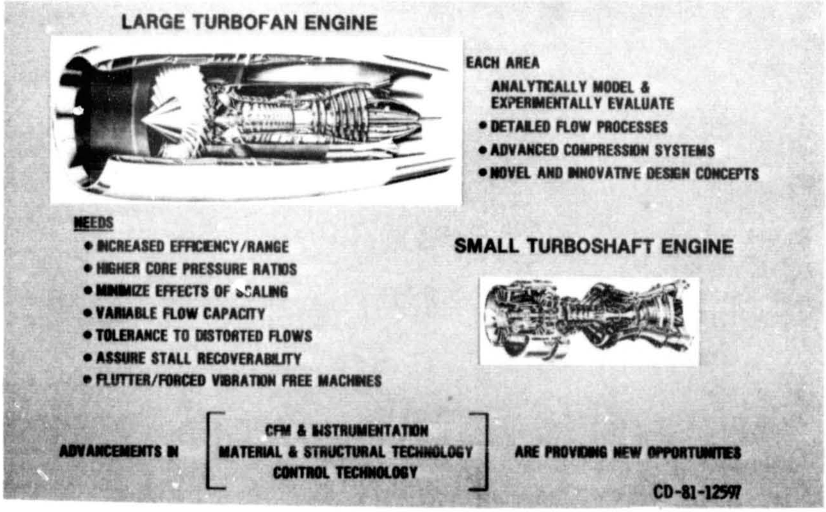


Fig. 1 Advanced methods for compressor flow research.


LARGE TURBOFAN ENGINE

EACH AREA

ANALYTICALLY MODEL &
EXPERIMENTALLY EVALUATE
- DETAILED FLOW PROCESSES
- ADVANCED COMPRESSION SYSTEMS
- NOVEL AND INNOVATIVE DESIGN CONCEPTS

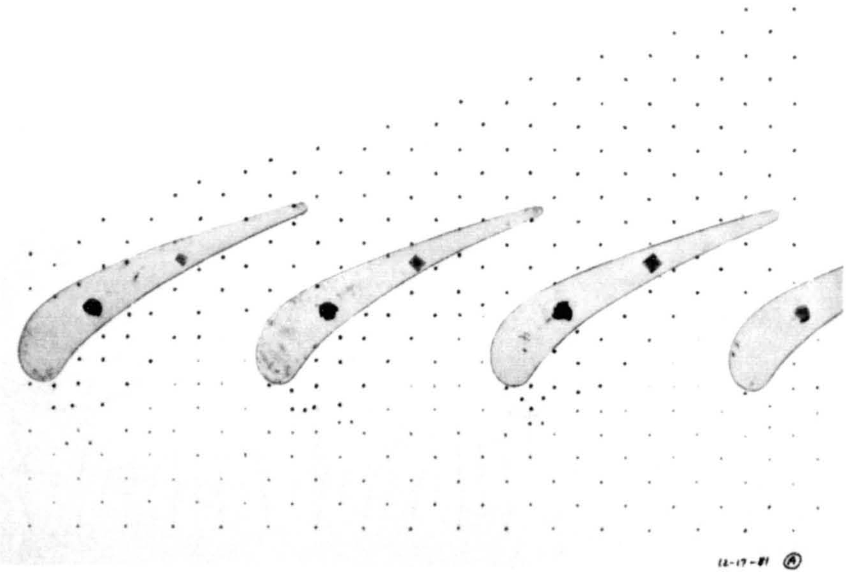
NEEDS
- INCREASED EFFICIENCY/RANGE
- HIGHER CORE PRESSURE RATIOS
- MINIMIZE EFFECTS OF SCALING
- VARIABLE FLOW CAPACITY
- TOLERANCE TO DISTORTED FLOWS
- ASSURE STALL RECOVERABILITY
- FLUTTER/FORCED VIBRATION FREE MACHINES

SMALL TURBOSHAFT ENGINE

ADVANCEMENTS IN [CFM & INSTRUMENTATION
MATERIAL & STRUCTURAL TECHNOLOGY
CONTROL TECHNOLOGY] ARE PROVIDING NEW OPPORTUNITIES

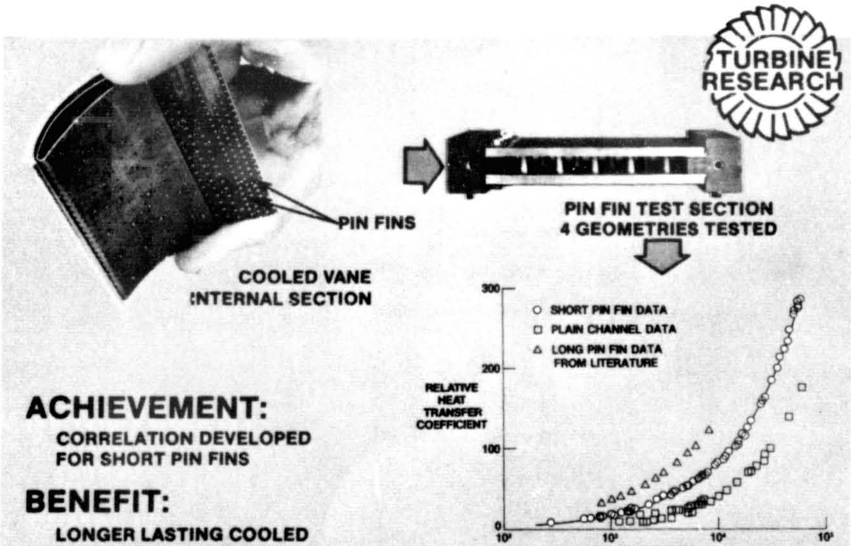
CD-81-12597

Fig. 2 Fan and compressor research areas.



12-17-81 Ⓐ

Fig. 3 Technique for using ink dots to visualize end-wall flow.



TURBINE RESEARCH

PIN FINS

COOLED VANE
INTERNAL SECTION

PIN FIN TEST SECTION
4 GEOMETRIES TESTED

ACHIEVEMENT:

CORRELATION DEVELOPED
FOR SHORT PIN FINS

BENEFIT:

LONGER LASTING COOLED
BLADE TRAILING EDGES

△ C-81-496
5000 11-80

Fig. 4 Short-pin-fin heat transfer.

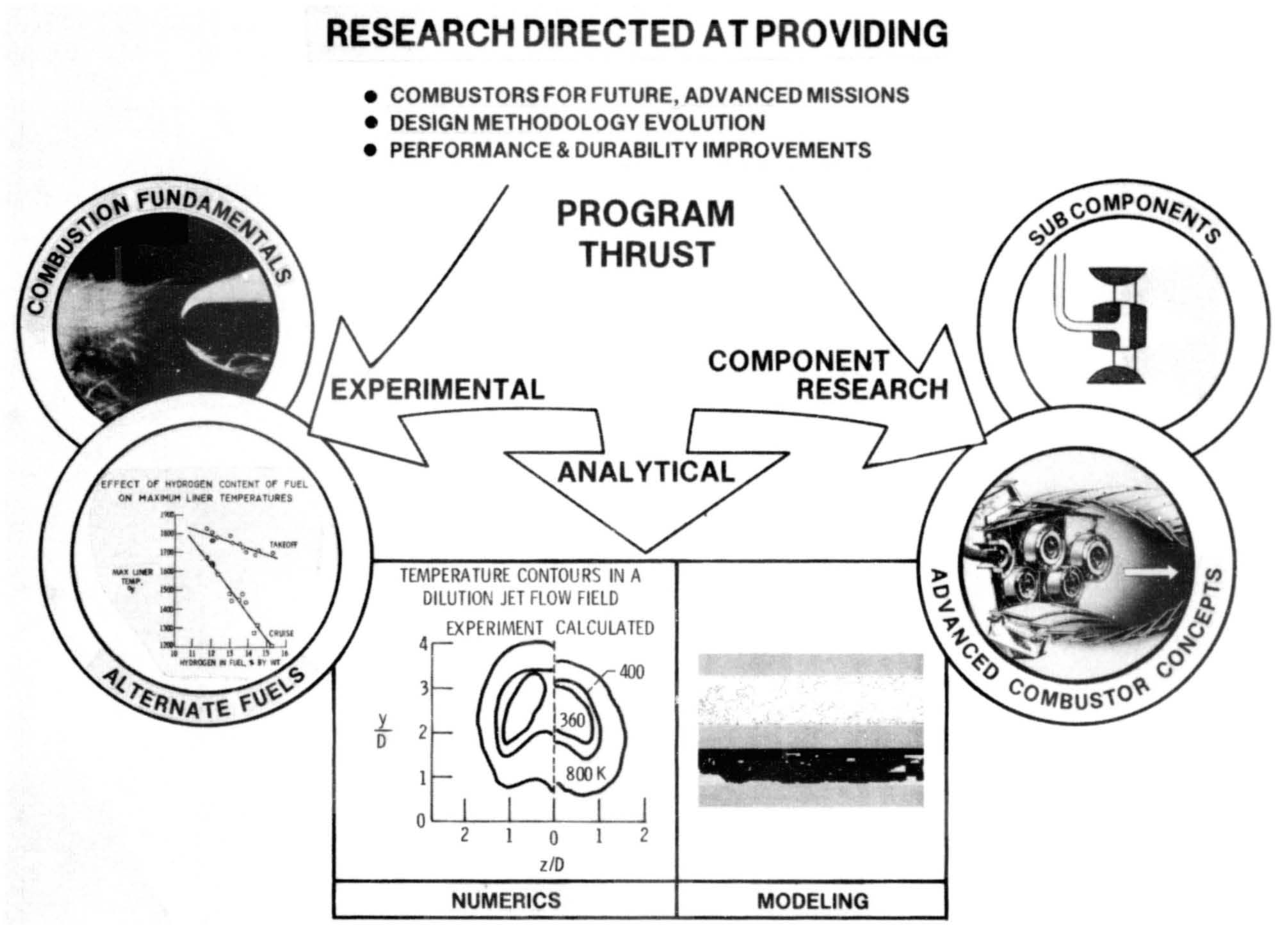
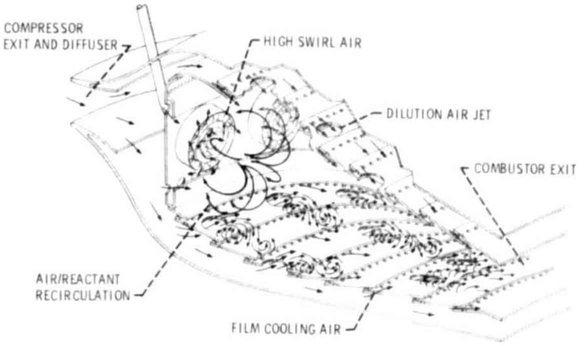
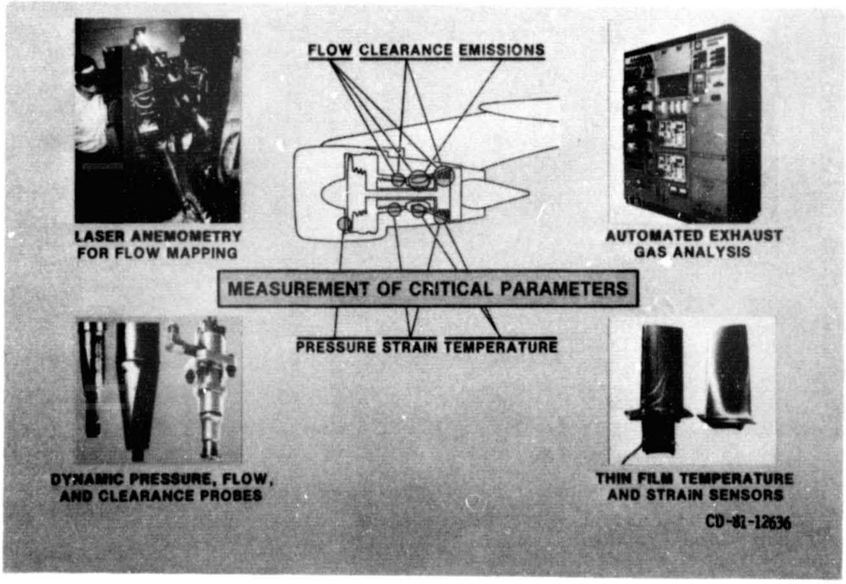


Fig. 5 Combustion research.



- FULLY 3-DIMENSIONAL FLOW
- HIGH TURBULENCE LEVELS
- CHEMICAL REACTION/HEAT RELEASE
- 2 PHASE WITH VAPORIZATION

Fig. 6 Combustor flow phenomena.



FLOW CLEARANCE EMISSIONS

LASER ANEMOMETRY
FOR FLOW MAPPING

AUTOMATED EXHAUST
GAS ANALYSIS

MEASUREMENT OF CRITICAL PARAMETERS

PRESSURE STRAIN TEMPERATURE

DYNAMIC PRESSURE, FLOW,
AND CLEARANCE PROBES

THIN FILM TEMPERATURE
AND STRAIN SENSORS

CD-81-12636

Fig. 7 Advanced instrumentation for propulsion research.

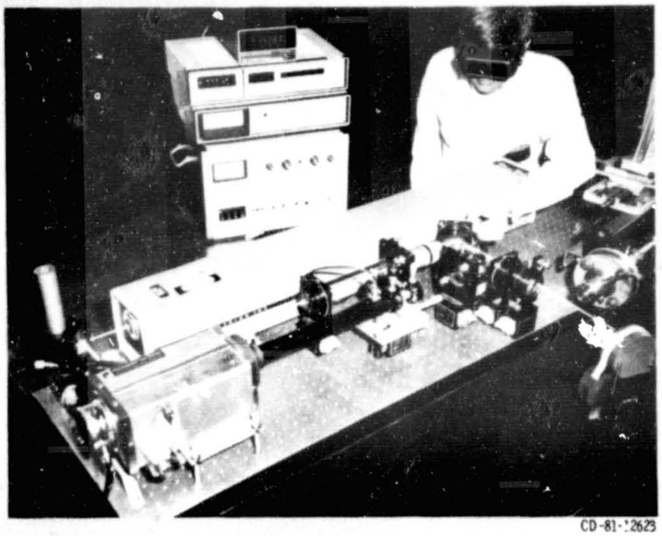


Fig. 8 Line-of-sight laser anemometer for measuring radial component of flow in an axial-flow machine.

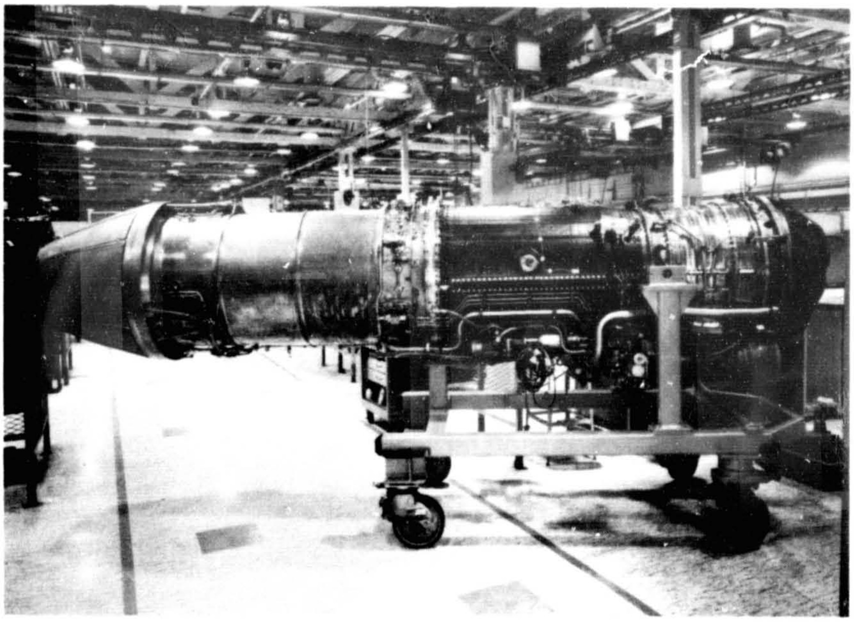
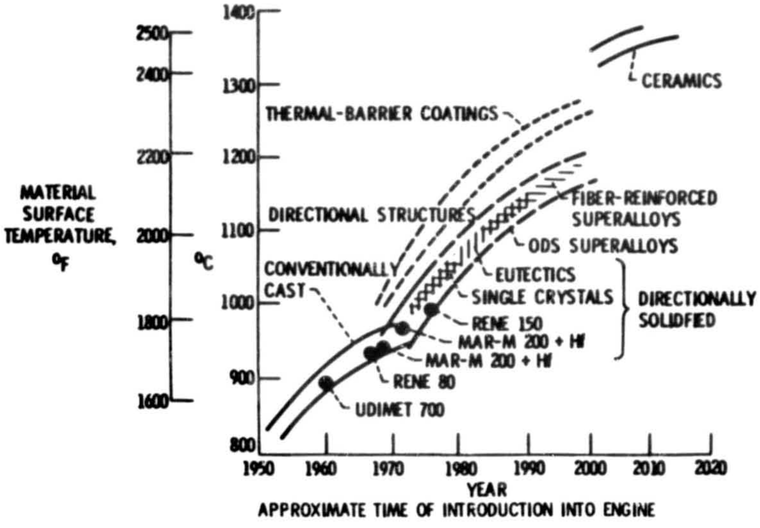


Fig. 9 T300 graphite fiber - PMR-15 outer duct installed in F-104 engine. (Composite duct located directly above carriage.)



CS-81-3571

Fig. 10 Temperature capabilities of turbine blade materials.

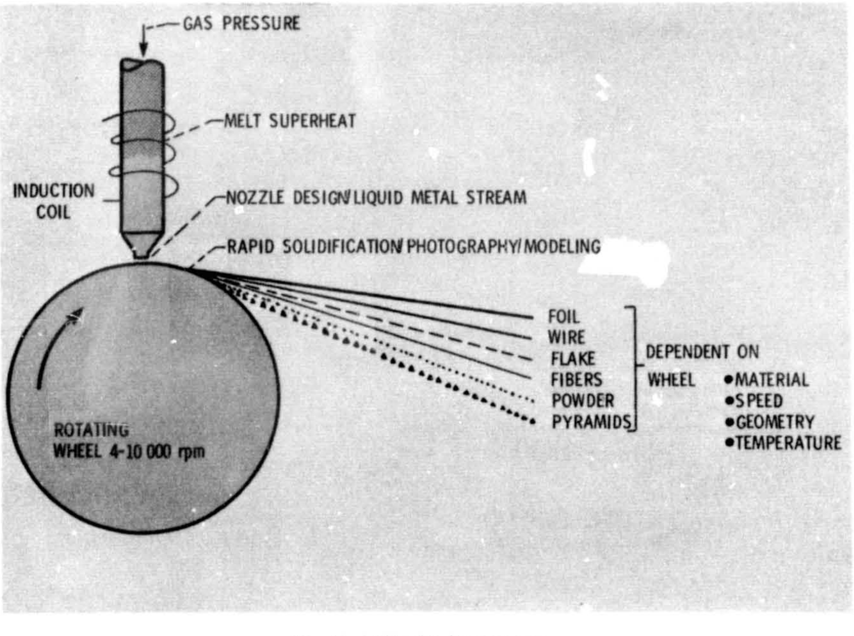
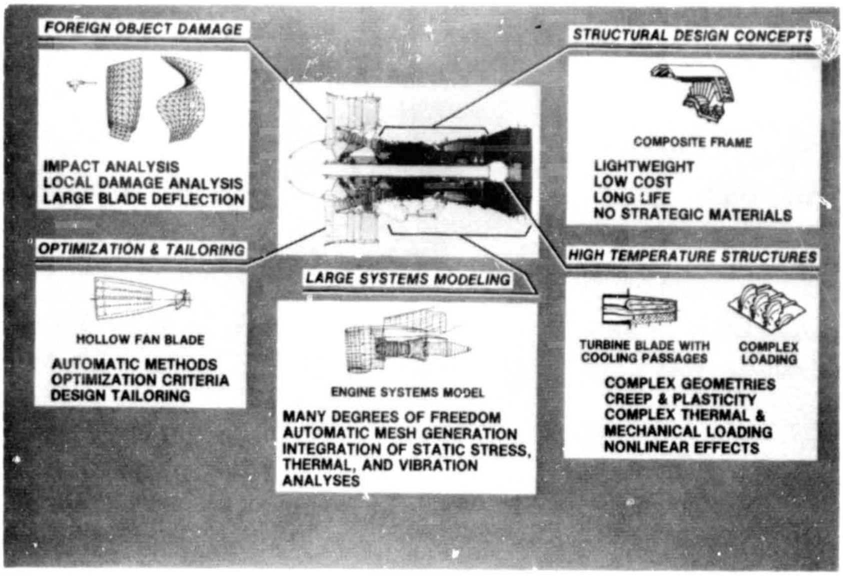


Fig. 11 Melt spinning process.



FOREIGN OBJECT DAMAGE

IMPACT ANALYSIS
LOCAL DAMAGE ANALYSIS
LARGE BLADE DEFLECTION

OPTIMIZATION & TAILORING

HOLLOW FAN BLADE

AUTOMATIC METHODS
OPTIMIZATION CRITERIA
DESIGN TAILORING

LARGE SYSTEMS MODELING

ENGINE SYSTEMS MODEL

MANY DEGREES OF FREEDOM
AUTOMATIC MESH GENERATION
INTEGRATION OF STATIC STRESS, THERMAL, AND VIBRATION ANALYSES

STRUCTURAL DESIGN CONCEPTS

COMPOSITE FRAME

LIGHTWEIGHT
LOW COST
LONG LIFE
NO STRATEGIC MATERIALS

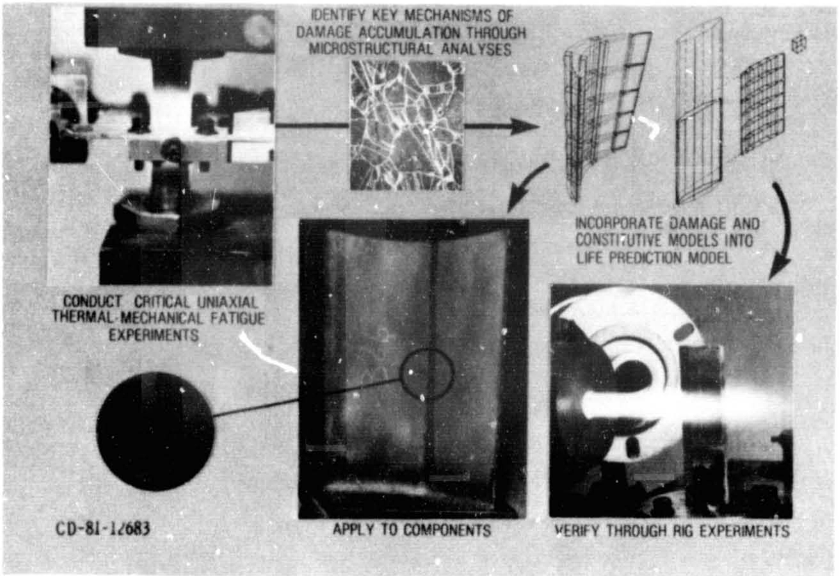
HIGH TEMPERATURE STRUCTURES

TURBINE BLADE WITH COOLING PASSAGES

COMPLEX LOADING

COMPLEX GEOMETRIES
CREEP & PLASTICITY
COMPLEX THERMAL & MECHANICAL LOADING
NONLINEAR EFFECTS

Fig. 12 Structural mechanics.



CONDUCT CRITICAL UNIAXIAL THERMAL-MECHANICAL FATIGUE EXPERIMENTS

IDENTIFY KEY MECHANISMS OF DAMAGE ACCUMULATION THROUGH MICROSTRUCTURAL ANALYSES

INCORPORATE DAMAGE AND CONSTITUTIVE MODELS INTO LIFE PREDICTION MODEL

APPLY TO COMPONENTS

VERIFY THROUGH RIG EXPERIMENTS

CD-81-12683

Fig. 13 Development of life prediction methodology.

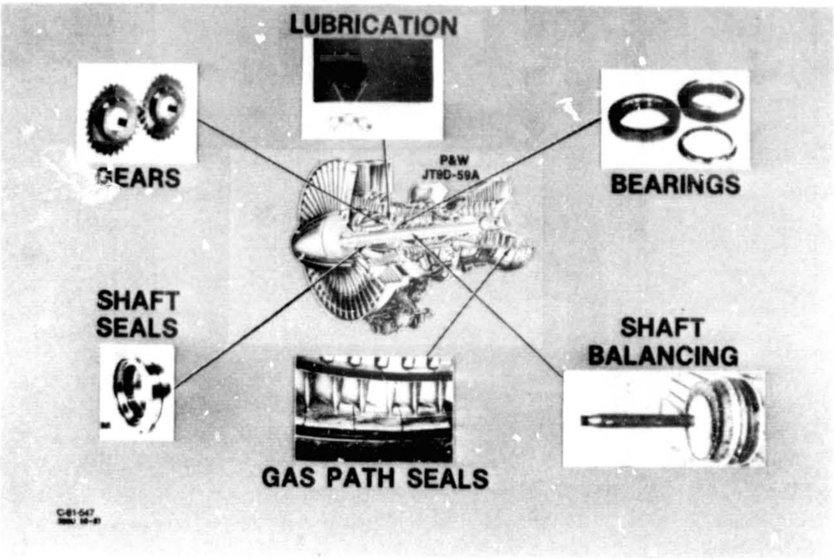


Fig. 14 Power transfer component research.

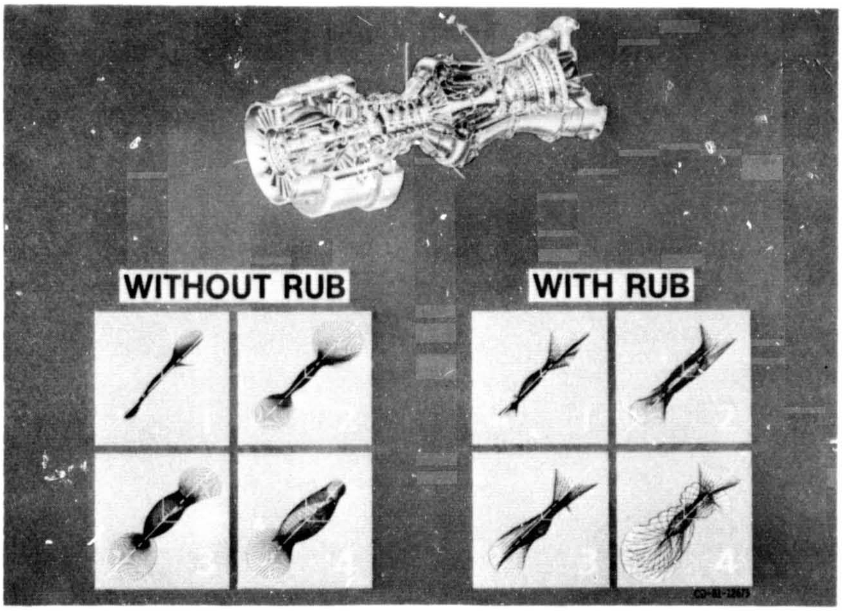


Fig. 15 Effects of turbine blade loss.

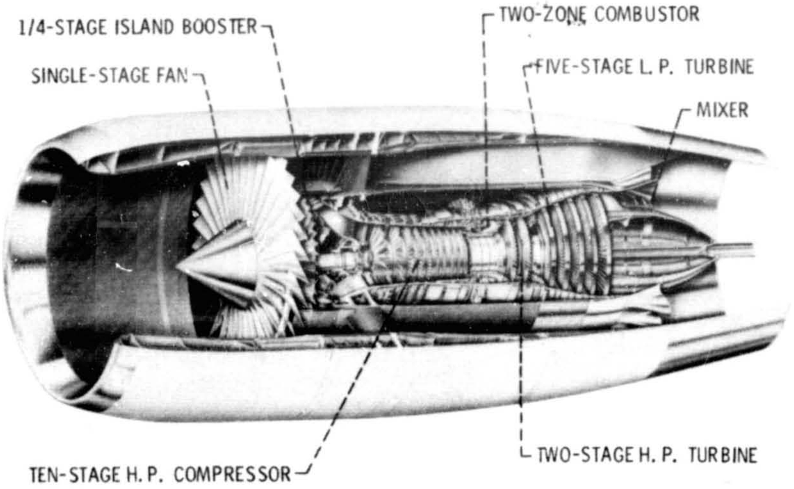


Fig. 16 Energy efficient engine - General Electric configuration.

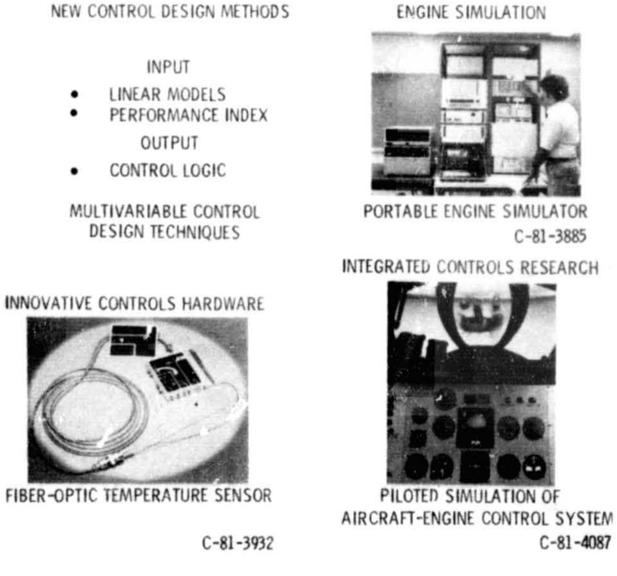
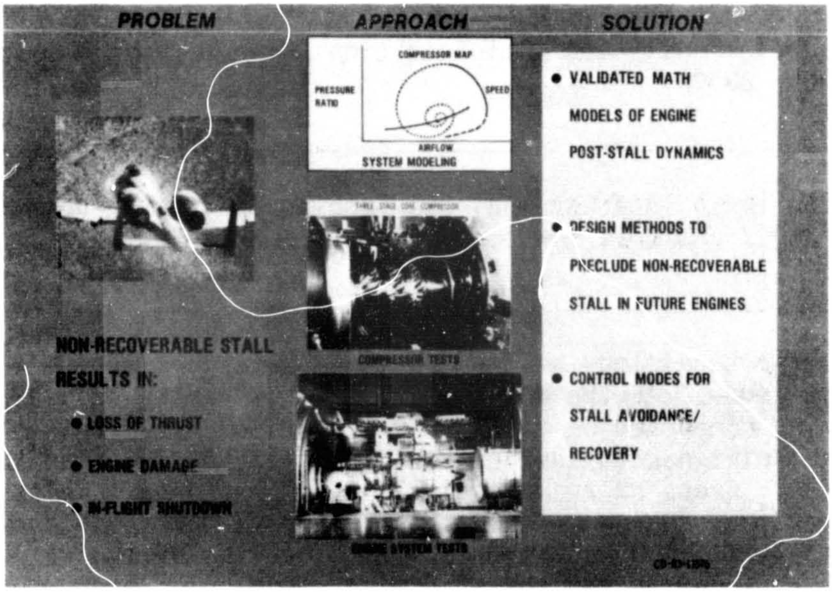


Fig. 17 Propulsion controls research.



PROBLEM

NON-RECOVERABLE STALL RESULTS IN:

- LOSS OF THRUST
- ENGINE DAMAGE
- IN-FLIGHT SHUTDOWN

APPROACH

SOLUTION

- VALIDATED MATH MODELS OF ENGINE POST-STALL DYNAMICS
- DESIGN METHODS TO PRECLUDE NON-RECOVERABLE STALL IN FUTURE ENGINES
- CONTROL MODES FOR STALL AVOIDANCE/ RECOVERY

Fig. 18 Stall recovery research.