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Aeronautical Propulsion–Present Status and Future Directions

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AERONAUTICAL PROPULSION - PRESENT STATUS AND FUTURE DIRECTIONS

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SUMMARY

The advancement of aeropropulsion systems continues to provide technology to various portions of the gas turbine field. It is recognized that this area is undergoing considerable change, which will result in substantially improved gas turbine components and systems. These changes are occurring in a number of technical areas including advanced analytical and physical measurement methods, the application of large scientific computers, the dynamic modeling of components and systems, the application of integrated control systems that optimize and improve performance and system condition monitoring, and the development of new and unique materials and structures. As these areas evolve, the ways in which technology will advance, and factors affecting the design and development of new systems, will probably be considerably different than those of today. It is also anticipated that the necessary skilled work force will be different. Certainly there will be changes, but the nature, extent, and rate of those changes can only be surmised at this time.

INTRODUCTION

Gas turbine performance has been substantially improved over the past 30 years. This has resulted in a continued increase in the application of gas turbines, and thus a substantial market exists to support an extensive research and development program. The research and development program has resulted in an extensive technology base and a unique methodology for the development of gas turbines at the leading edge of technology. It can be observed that advances have been achieved in a number of directions, including performance improvements, increased range of stable operation, increased durability, and, in some cases, cost reductions. The very success of the gas turbine technology program has raised some concerns that future gains may be modest and require a great deal of effort and cost. It has been suggested that research efforts should be applied to other areas that may provide a greater return. Further considerations have indicated, however, that a number of numerical and physical analysis methods that have advanced, along with technical advances in related areas, provide the opportunity for considerable advances in future gas turbines. To fully achieve these advances, however, it may be necessary to modify the ways in which gas turbine research activities are carried out.

The purpose of this paper is to review some of the approaches and methods now involved in the research and development process and the effect these may have on future gas turbines and future research programs. One may infer from this some of the skills and requirements for the development of advanced gas turbines, as well as those required for the continuous advancement of the technology base. Since the author's experience has been totally in the field of gas turbines for aeropropulsion systems, this review will deal primarily with aeropropulsion technology. However, aeropropulsion systems 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 applicability to other gas turbine application areas.

THE DESIGN AND DEVELOPMENT PROCESS

The development of an advanced aeropropulsion system involves some 5 or 6 years of design, component testing, and system testing, followed by 2 or 3 years of improvement through flight testing and operation. In the design process, it is necessary to specify performance levels beyond those achievable from the existing technology base. The designers must gamble that the required performance and durability can be achieved in the development process without excessive cost or delays for redesign or rebuilding of components. Conservative design performance levels could easily be achieved in the development process, but the aeropropulsion system would not be competitive when it reached the operational status. A successful venture could not be expected.

The competitive nature of the aeropropulsion gas turbine industry has been a major driving force in the advancement of gas turbine technology. Industry competition and the high cost of development have also been the major reasons for the involvement of industrial organizations, government organizations, universities, and a wide variety of research organizations in the advancement of the gas turbine technology base.

The research and development process has resulted in an extensive experimental data base for gas turbine components. This data base has been a major factor in the design of current gas turbine components and systems. Advanced levels of performance have been achieved, with a high degree of confidence, by the process of continued extrapolation from the existing empirical data base. Considerable progress has been achieved by this evolutionary process over the past 30 years. The usable stage pressure ratio of axial flow compressors has been increased from less than 1.1:1 to over 2:1 by this process. Besides this evolutionary process, concepts have been developed to operate compressor rotor blades efficiently with transonic and supersonic flows. Analytical approaches have continued to add to the understanding and provide guidance for systematically removing or overcoming limiting conditions. Thus, the overall development of gas turbine technology has involved the usual type of activities, but it has depended extensively on the experimental data base. Presently, considerable effort is underway to reduce this empirical dependence.

The objectives of gas turbine technology programs have varied over the past years. For example, in the area of combustor research, increasing combustor efficiency was a major concern at one time, whereas the reduction of pollutants was a major objective at another. Recently, combustor durability, especially with fuels of high carbon content, has been considered to be of major concern. Analytical methods now being developed may contribute to improved combustor exit temperature distributions and pattern factors. Thus, the major objectives of combustor research have varied depending on the prevailing concerns. This has been typical of gas turbine research in general.

Advances in gas turbine systems have reached a level where further gains may require concurrent advances in a number of related disciplines or technical areas. For example, advances in turbine technology will depend strongly on a number of discipline areas, including fluid mechanics, heat transfer, structural dynamics, high temperature materials, and manufacturing techniques. In addition, advances in turbine technology may well require similar advances in combustor, compressor, and other component or systems capability.

In summary, the following key points can be made about gas turbine design and development:

(1) The competitive nature of the aeropropulsion gas turbine industry has required the maintenance of an extensive technology development program and a continually expanding technology base.

(2) The technology base contains considerable empirical information, and advances have been evolutionary extrapolations from the known base.

(3) As the level of technology has increased, it has become increasingly necessary to advance capability in a number of related discipline and component areas.

(4) Design and development objectives have changed depending on the need for performance gains, improved durability, adaptability or the current environmental or economic concerns.

COMPONENT RESEARCH

There has been increasing activity to develop analytical methods to achieve better understanding of the phenomena limiting advances in gas turbine performance. These methods are presently aimed primarily at improving the gas turbine components. It is anticipated that they will provide the capability to continue the advancement of gas turbine components and systems. To provide a major impact, it is necessary that these methods be sufficiently advanced to extend the performance beyond the level achieved by existing analysis and design methods.

Continued advances in gas turbine technology have required improved compressors, combustors, and turbine components. Present research efforts to improve these components involve the development of computational fluid mechanics and computational structural mechanics to assist the technologist to improve component design. Three-dimensional numerical solutions can be expected to be practical in the not-too-distant future when sufficient computational capability is available. An important problem is that of learning how to use these new analytical methods to design improved components that do not require an extensive number of rebuilds to achieve the desired performance level.

A portion of this research involves verification through detailed experiments, that the controlling physical phenomena are properly modeled by the analytical solutions. Progress has been achieved in providing physical measurements of similar detail to that computed by the advanced numerical analysis methods. Figure 1 illustrates the use of the laser velocimeter to measure the Mach number distribution between the blades of a high speed fan rotor in operation. These measurements can be compared with computed results at the same level of detail. Comparison of the calculated and measured results over the stable operating range can be utilized to modify the blading to achieve the desired results. Considerable confidence in the numerical results can also thus be established. Of course, the experimentalist can use the measured results directly to determine a useful modification to the blading. With either the computer-based numerical analysis or the advanced flow measurement approach, future gas turbine components can be optimized on the basis of detailed flow phenomena rather than overall performance considerations as has been done in the past.

Gas turbine components optimized on the basis of detailed flow phenomena can be expected to achieve performance levels higher than those achieved in today's systems. It can also be expected that components could be designed to meet the unique requirements of each application rather than being minor modifications or adaptations of existing systems. This new capability, which is developing also in the structures area, could be utilized to substantially shorten the required development time, thus making it possible to respond quickly to new or changing requirements.

Compressor advancements that are considered important for future aeropropulsion systems are indicated in figure 2. Some of these gains are primarily aerodynamic in nature, whereas others are structural or system related. The improved analytical methods will make it possible, and, in fact, are necessary, to achieve these gains.

Computational analytical methods are also becoming useful in the turbine area. Of major concern in the turbine is heat transfer and control of metal temperature. Detailed studies have revealed the problem of the horseshoe vortex, which tends to scrub cooling air away from the annulus wall. This flow has been observed through the use of ink dots on a cold cascade wall as shown in figure 3. In this case, calculated results confirm the observed results. However, in the case of a real turbine operating at high temperature, it is not yet possible to make such measurements, and numerical analysis is the only source of information.

Some current areas of combustor research are shown in figure 4. Simplified combusting flows have been modeled numerically with a considerable degree of success. The numerical modeling of jet crossflow in a zone of combusted like-flow has produced temperature distributions similar to those measured. The overall flow and combustion field in the modern combustor is highly complex and obviously beyond current modeling or measurement capability. However, the detailed modeling of the crossflows can be used to understand and control the cooling airflow distribution and thus the temperature profile to the turbine inlet.

A wide variety of advanced instrumentation systems are necessary to continue the advancement of gas turbine components. Some of the instrumentation systems are shown in figure 5. To obtain detailed aerothermal and structural dynamic data, instrumentation must provide minimal interference to the phenomena being measured. These systems depend extensively on laser technology, as well as on unique signal processing capabilities now available through microprocessor technology. These so-called "smart" instruments can provide the researcher with the required data, free of excessive information, and can avoid conditions that may destroy the sensor or give false information. The line-of-sight laser anemometer, shown in figure 6, can measure all velocity components in a single survey of a turbine . A holographic cinematography system has also been developed to examine shock motion effects. Similar classes of instrumentation and measurement systems are available for the study and development of improved dynamic performance and structural characteristics of advanced gas turbine components.

MATERIALS AND STRUCTURES

Gas turbines have been optimized based on the characteristics of metals available for low temperature and high temperature regions. The continuous advances in materials capabilities and structural analysis and design methods have contributed substantially to gas turbine advances. In the future, a wide variety of advanced materials and structural analysis methods will be available to advance gas turbines still further.

The ability to fabricate parts of fiber-reinforced PMR polyimides for higher temperatures has been considerably improved. Graphite fiber/PMR-15 composite has been used in the outer duct for the F-104 engine as shown in figure 7. The reduced weight and increased stiffness of components made of this type of composite is important to improved gas turbine structures and will assure the increased use of such materials.

High temperature materials research has resulted in increased usable metal temperatures of about 10° per year. Figure 8 indicates that additional concepts exist for superalloys such that usable metal temperatures may be increased at this rate for some 15 to 20 years. Even higher gas temperatures can be achieved by the use of thermal-barrier coatings or structural ceramics. Continued improvement in ceramic materials and processing makes this a very attractive area for future high-temperature applications. Ceramic components could offer performance gains in those applications where the use of cooling air would result in substantial losses of cycle or component efficiency.

Expensive strategic alloying materials may be conserved and improved properties may be available through new processing methods. Melt spinning, as illustrated in figure 9, may produce unique composites and microstructures due to the very rapid solidification process. Unique processes, coatings, and composite systems provide the capability for parts of various materials or compositions to be optimized for the given application. Such optimization requires a complete knowledge of the aerothermal environment as well as the structural and structural dynamic requirements.

Analytical methods required for the structural analysis of aeropropulsion systems are indicated in figure 10. These methods provide the opportunity to evaluate the dynamic interaction of the various engine components. Optimization techniques can be applied to tailor blade designs for unique requirements of a given application.

Uniaxial creep-fatigue data provide first-order information on cyclic stress-strain response. Life prediction requirements are indicated in figure 11. Damage accumulation from various loading mechanisms must be incorporated in life prediction methodology and must include the detailed propagation of microcracks through the material structure.

SYSTEMS TECHNOLOGY

Advanced gas turbine components must be integrated suitably to achieve an optimum system. The energy efficient engine, shown in figure 12, integrated advanced components 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 to achieve a high overall cycle pressure. A very short, low-polluting combustion chamber and a substantial number of efficient turbine stages were incorporated. The successful operation of the engine with these advanced components indicates that a high performance propulsion system with suitable operating conditions can be achieved.

An indication of the advanced methods and technology available for engine controls is given in figure 13. Aircraft and engine controls must be suitably integrated to enable the pilot to properly manage the system. Aeropropulsion systems require extensive control capability, sensing elements, and actuation systems to achieve a high level of performance over a wide range of flight and operating conditions. Besides achieving proper control, systems of the future may be expected to detect and accommodate faults, to monitor and optimize performance, and to assess or monitor the condition of the system. Performance improvements will be available as a result of the application of these advanced control systems. Aeropropulsion systems that control and minimize clearances and thus leakages, or reset elements to achieve optimum performance, will be feasible. Control systems to more closely approach or recover from adverse operating conditions may be able to provide a higher level of system performance. The recovery of a propulsion system from stall, as illustrated in figure 14, may require a control system with additional capability. This control system may be required to function with components uniquely selected for their dynamic operating characteristics. Certainly the optimization of components and controls for future systems will require the capability of extensive dynamic modeling of gas turbine components and systems.

FUTURE TECHNOLOGY

The previous sections indicate potential advances in a number of related areas that will result in improved aeropropulsion systems. Some of these technical areas can materialize in the relatively near future whereas others may require 15 or 20 years to provide a major impact on the methods used and the manner in which gas turbine technology is advanced. Likewise the timing and changes in the skills of the technologists involved will have a considerable effect on how the technology is applied to advanced systems. The following general remarks can only be partial indications of potential directions that may evolve:

(1) Advanced computational methods in fluid mechanics, structural mechanics, and closely related areas of detailed structural and fluid measurements are already contributing to some advanced propulsion systems. The utilization of these in multistage gas turbines, and unsteady component and system phenomena will require considerable effort.

(2) Future gas turbines may be optimized on the basis of detailed flow and structural phenomena rather than overall performance correlations. The technologists must learn to deal with and optimize gas turbines based on these detailed phenomena.

(3) Analytical methods using large scientific computers will provide some of the detailed phenomena that cannot be obtained in any other manner.

(4) Most gains will require increased capability in a number of related areas, such as aerodynamics, structural dynamics, materials, heat transfer, and manufacturing methods. The application of interrelated disciplines will be of increasing importance.

(5) Integrated control systems and microprocessor technology will provide an opportunity to improve system and component performance in a wide variety of ways.

(6) The introduction into gas turbines of new materials with substantially different characteristics than existing metals will require a reoptimization of aerothermal and structural parameters. Some of the analytical methods for these reoptimizations are now available.

(7) Some of the areas that may be advanced could result in substantial reductions in the cost and time required for the development of a new gas turbine system.

(8) The capability of going directly from computations to application could result in improved systems optimized for a given application. This would avoid providing margins for adaptations to new applications.

The above illustrate only a few of the directions in which the aeropropulsion and gas turbine technology may advance. A number of external factors including economics, perceived requirements, the relative advances in the various areas, as well as the skill makeup of the technologists involved, will determine how and in what time frame advanced gas turbine technology will evolve. Additional gas turbine history is yet to be made and written.

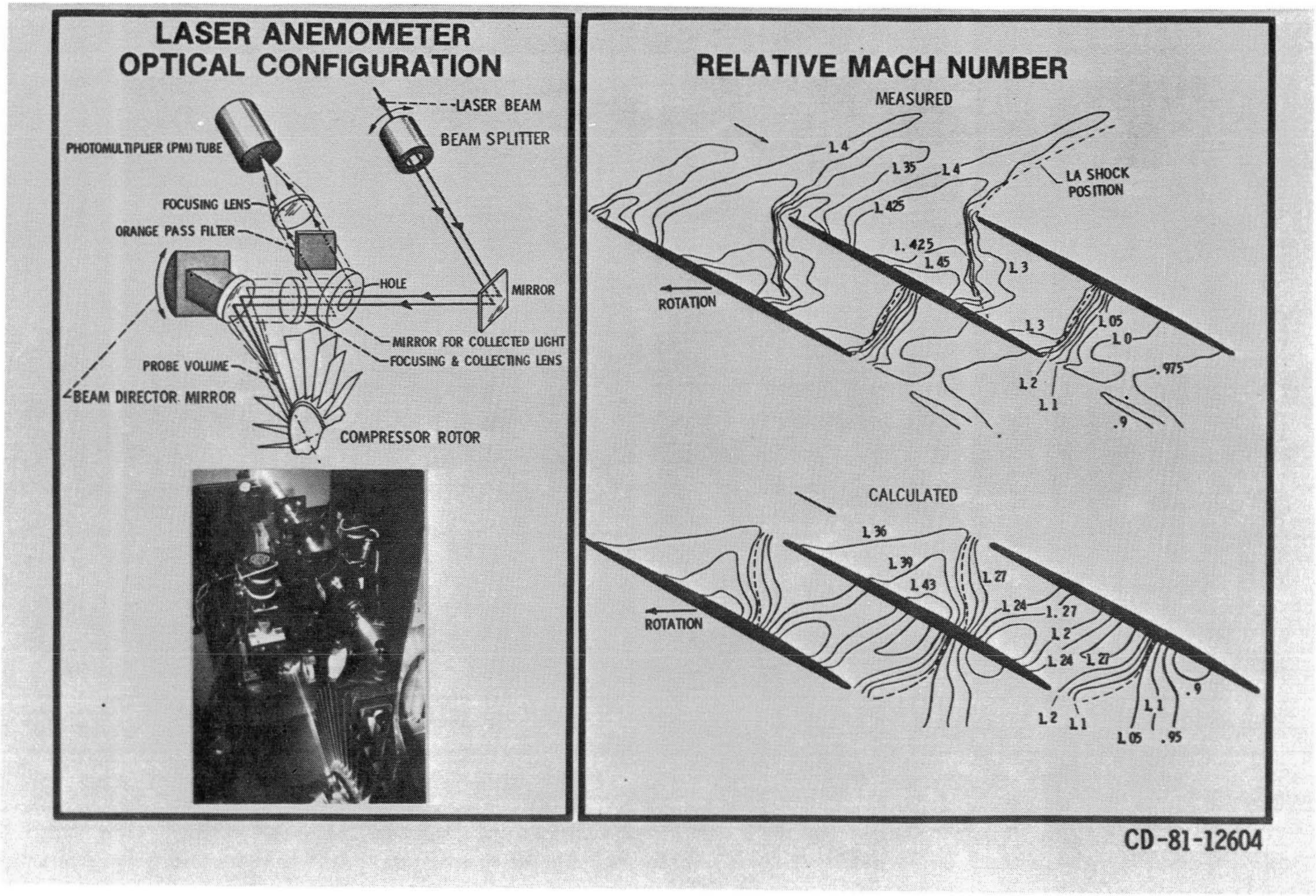

Fig. 1 Advanced methods for compressor flow research.

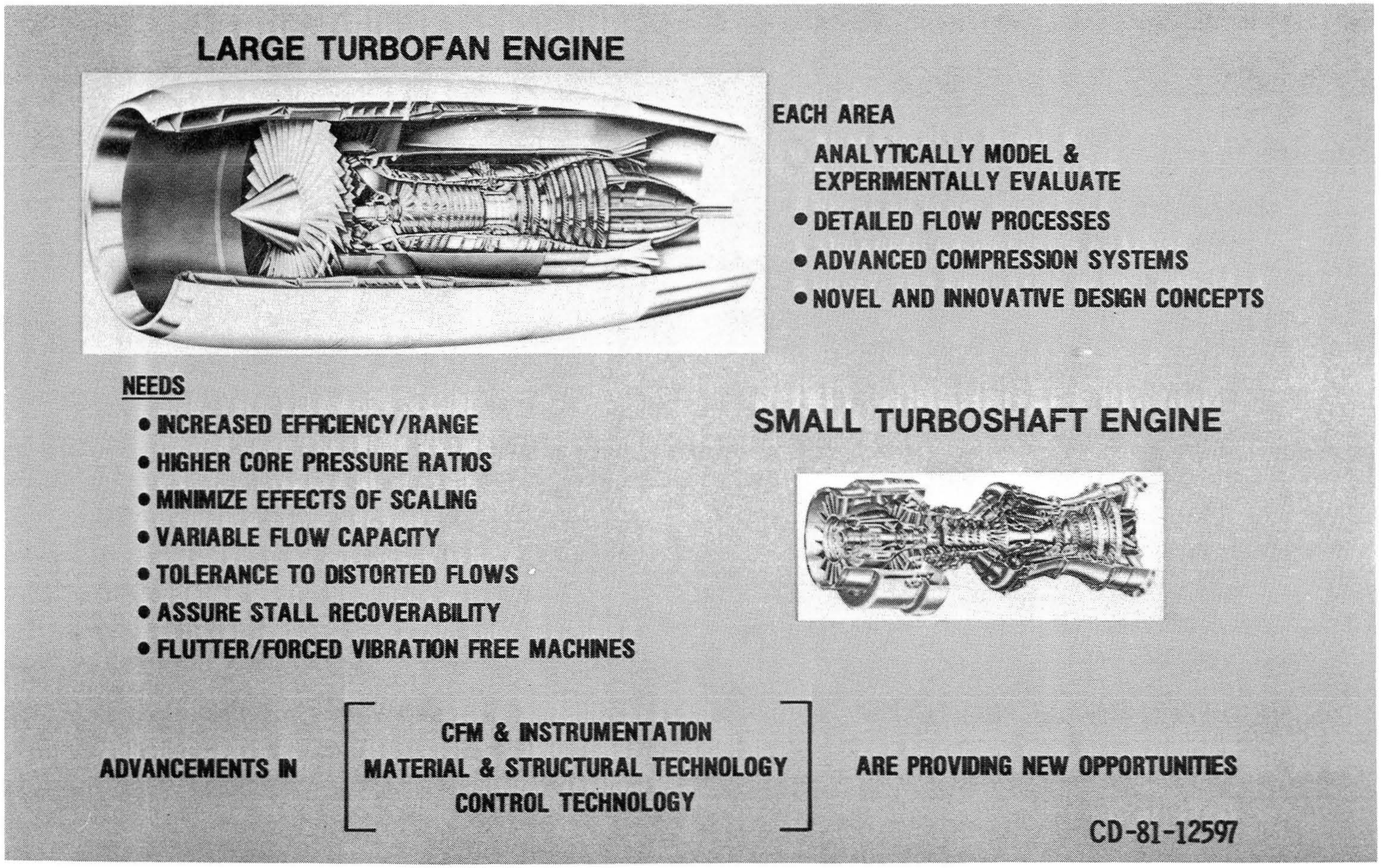

Fig. 2 Fan and compressor research areas.

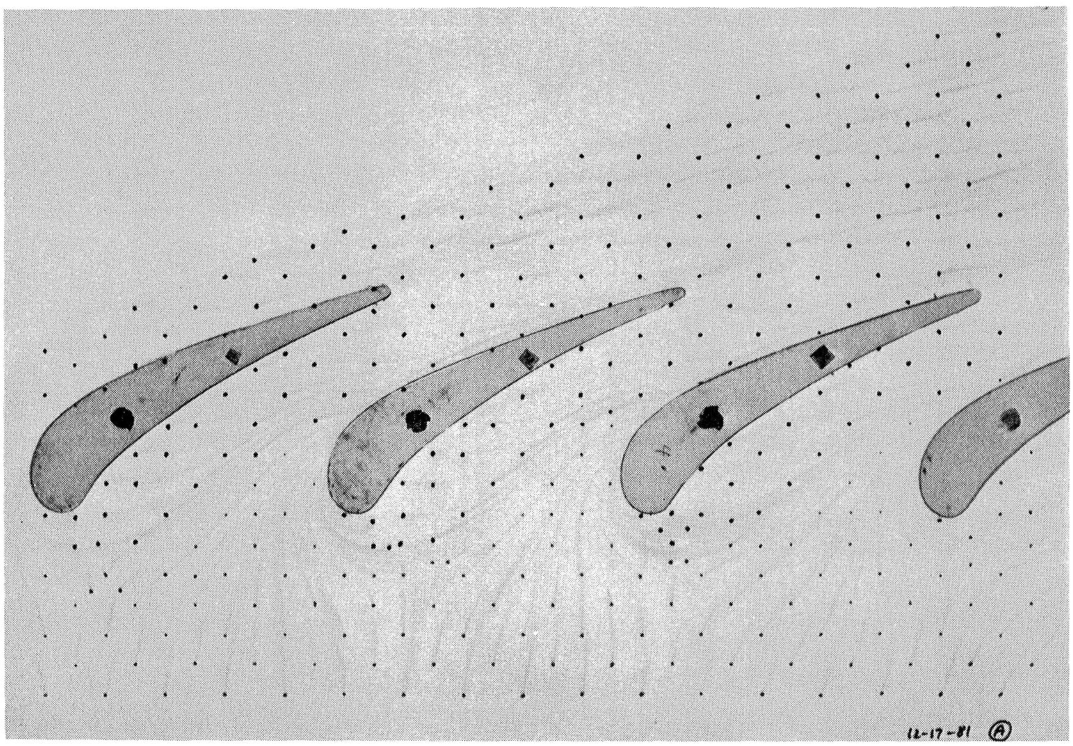

Fig. 3 Technique for using ink dots to visualize end-wall flow.

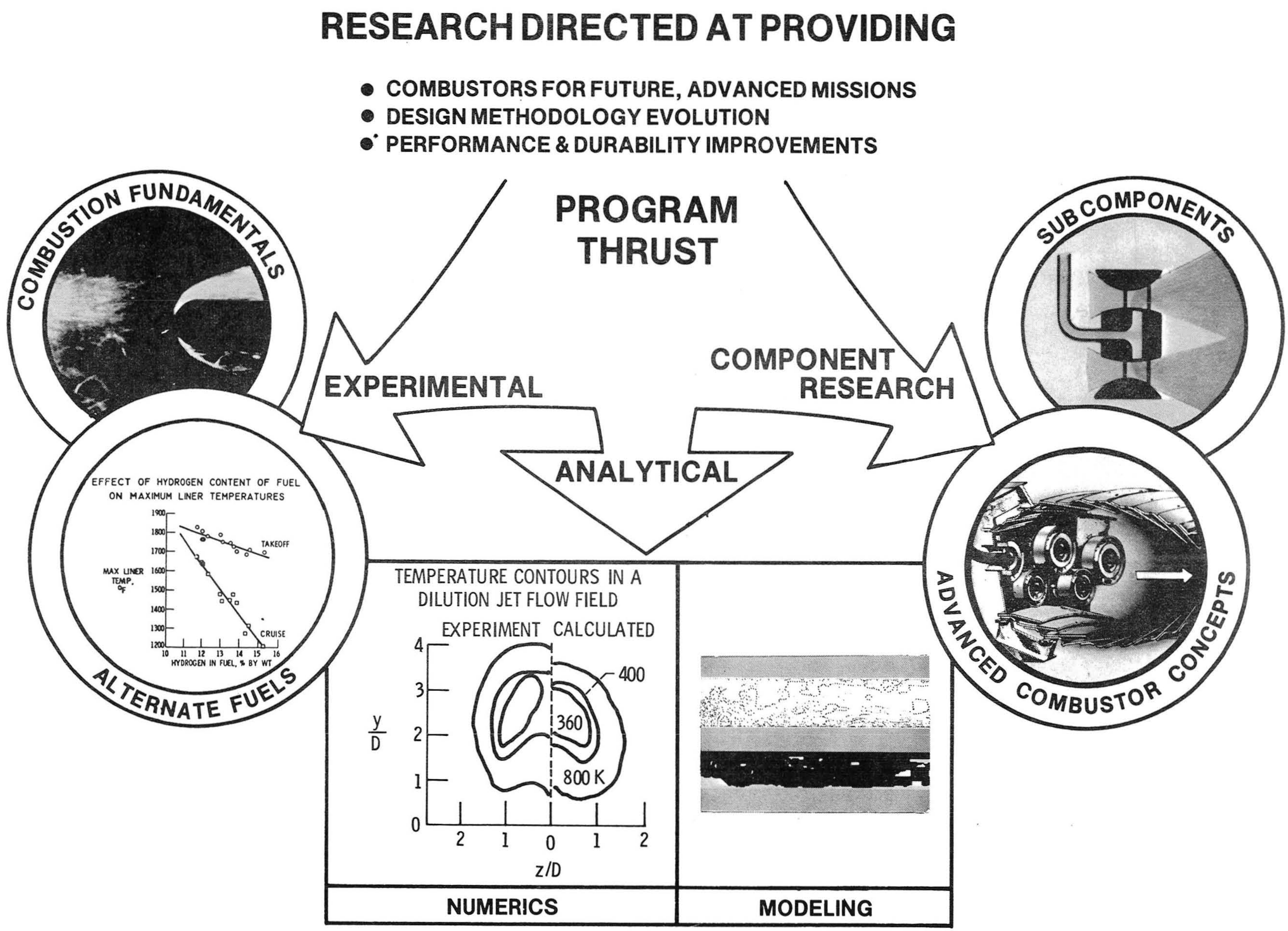

Fig. 4 Combustion research.

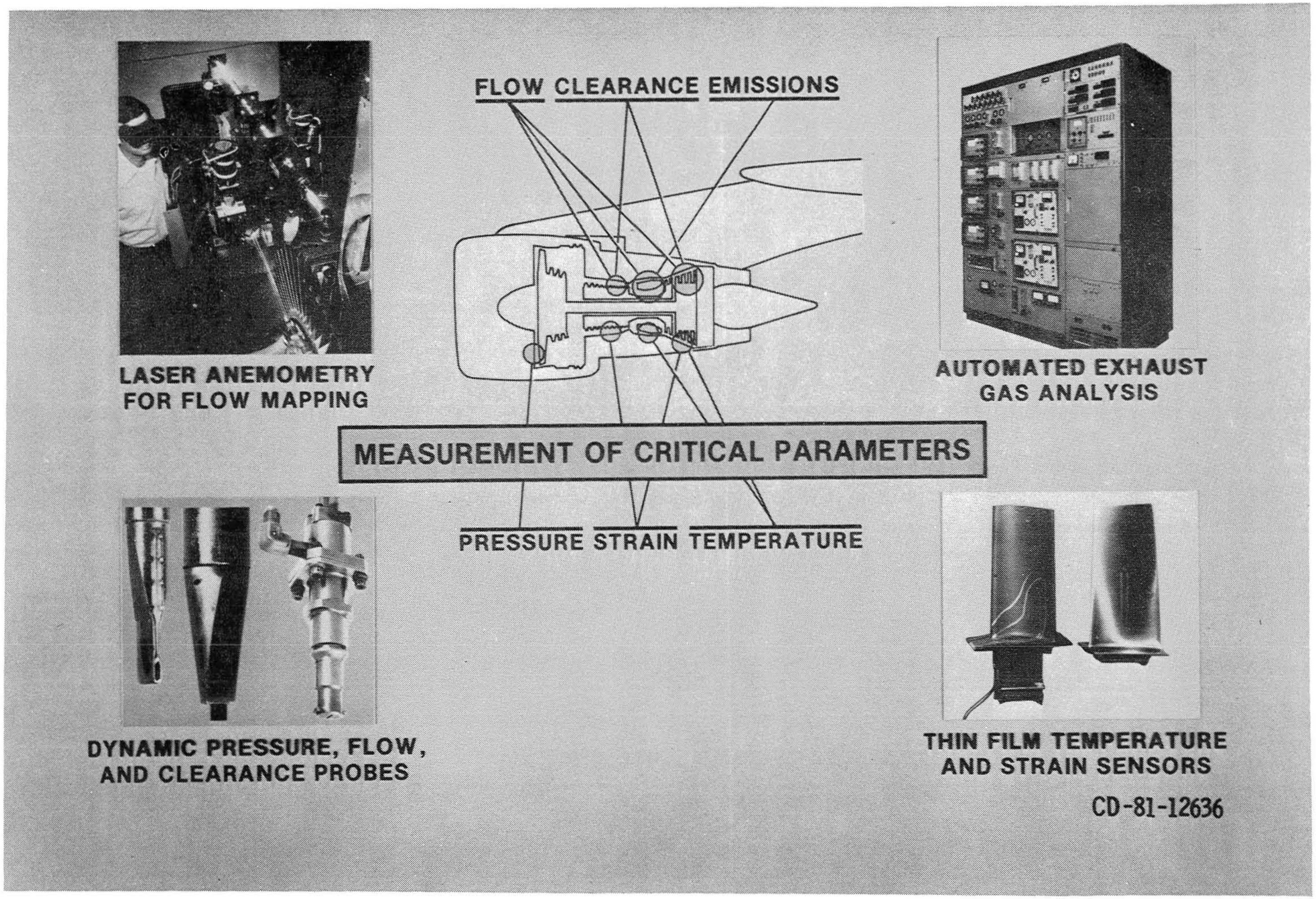

Fig. 5 Advanced instrumentation for propulsion research.

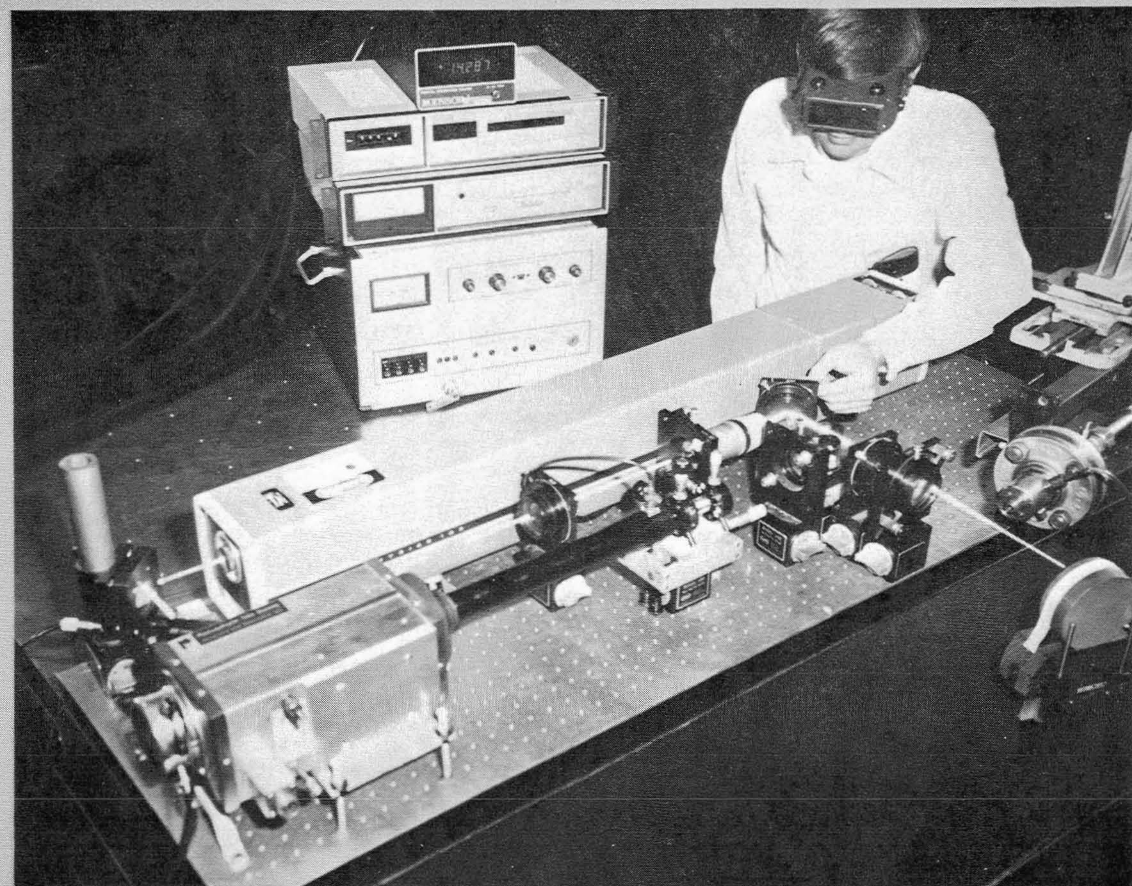

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Fig. 6 Line-of-sight laser anemometer for measuring radial component of flow in an axial-flow machine.

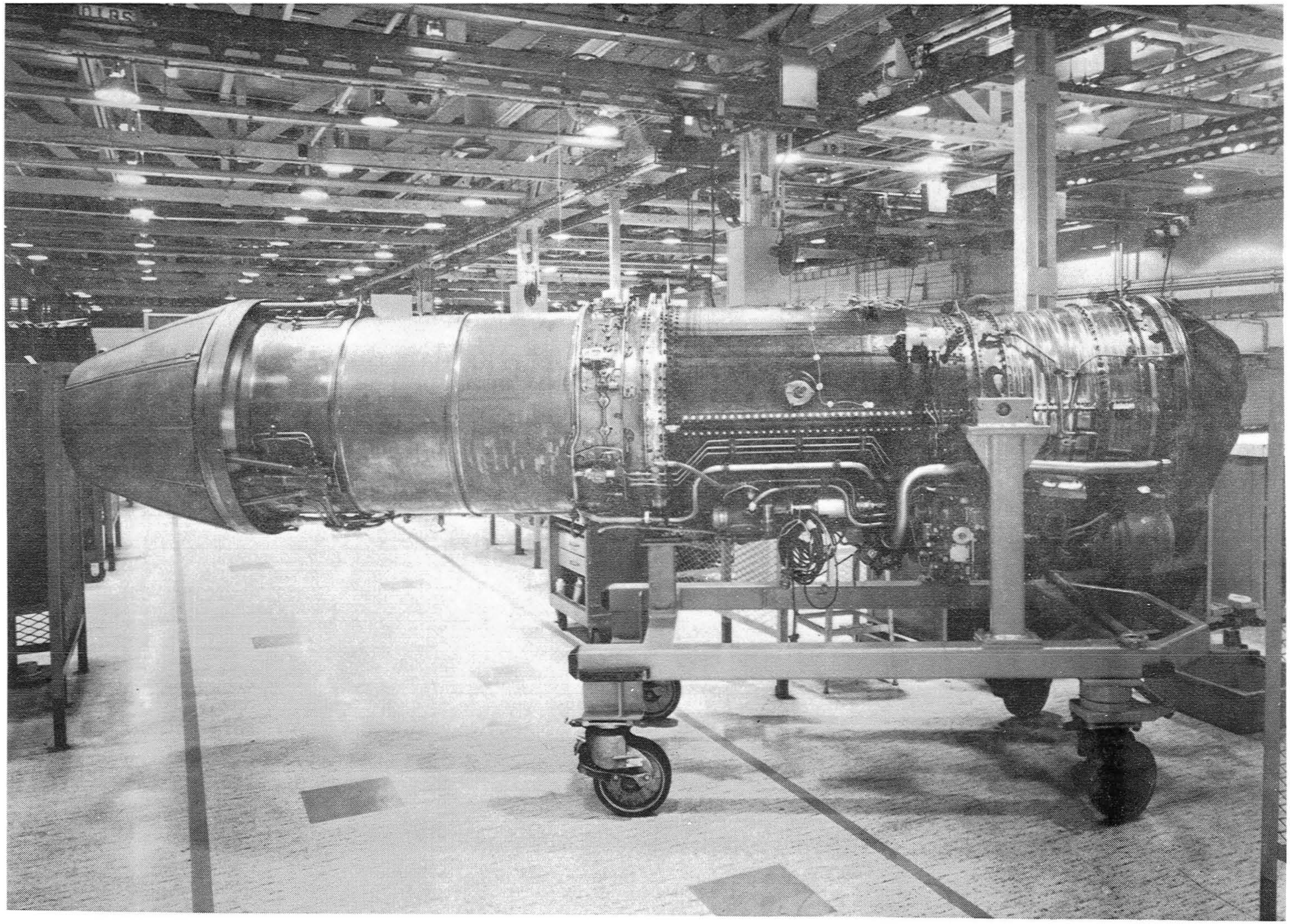


Fig. 7 T300 graphite fiber - PMR-15 outer duct installed in F-104 engine. (Composite duct located directly above carriage.)

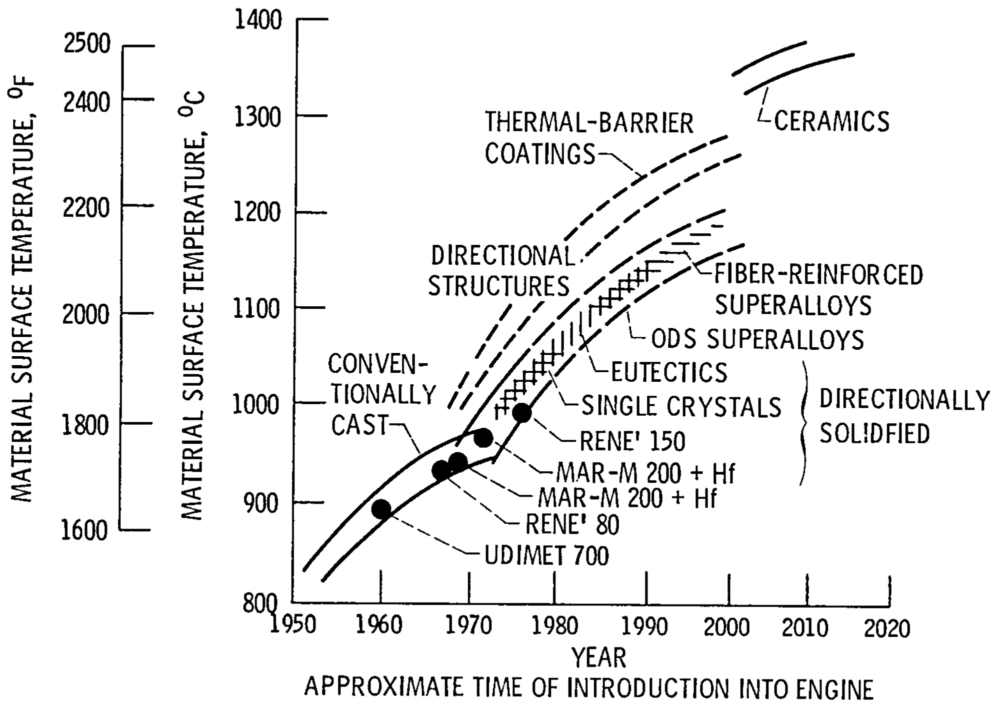


Fig. 8 Temperature capabilities of turbine blade materials.

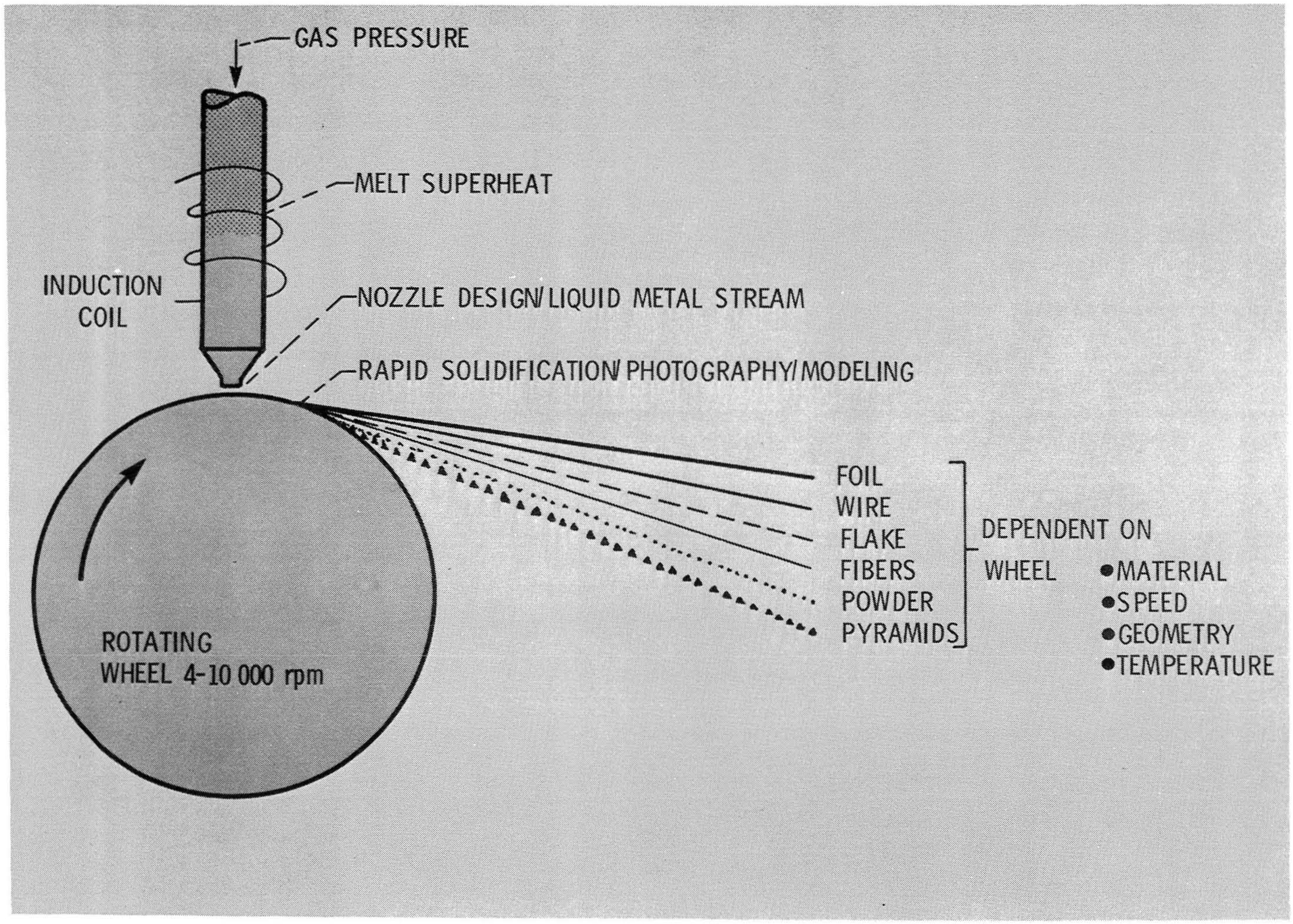


Fig. 9 Melt spinning process.

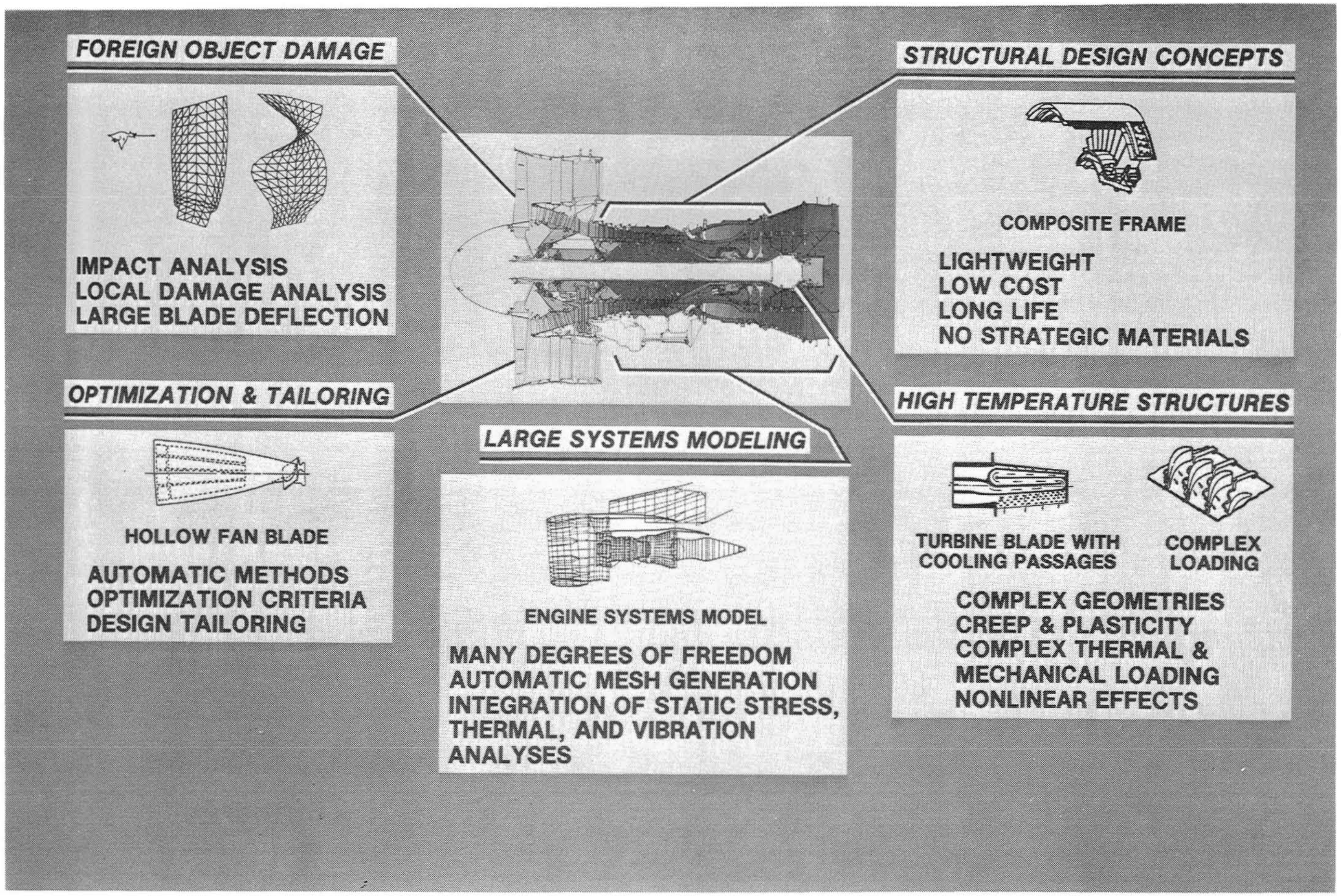


Fig. 10 Structural mechanics.

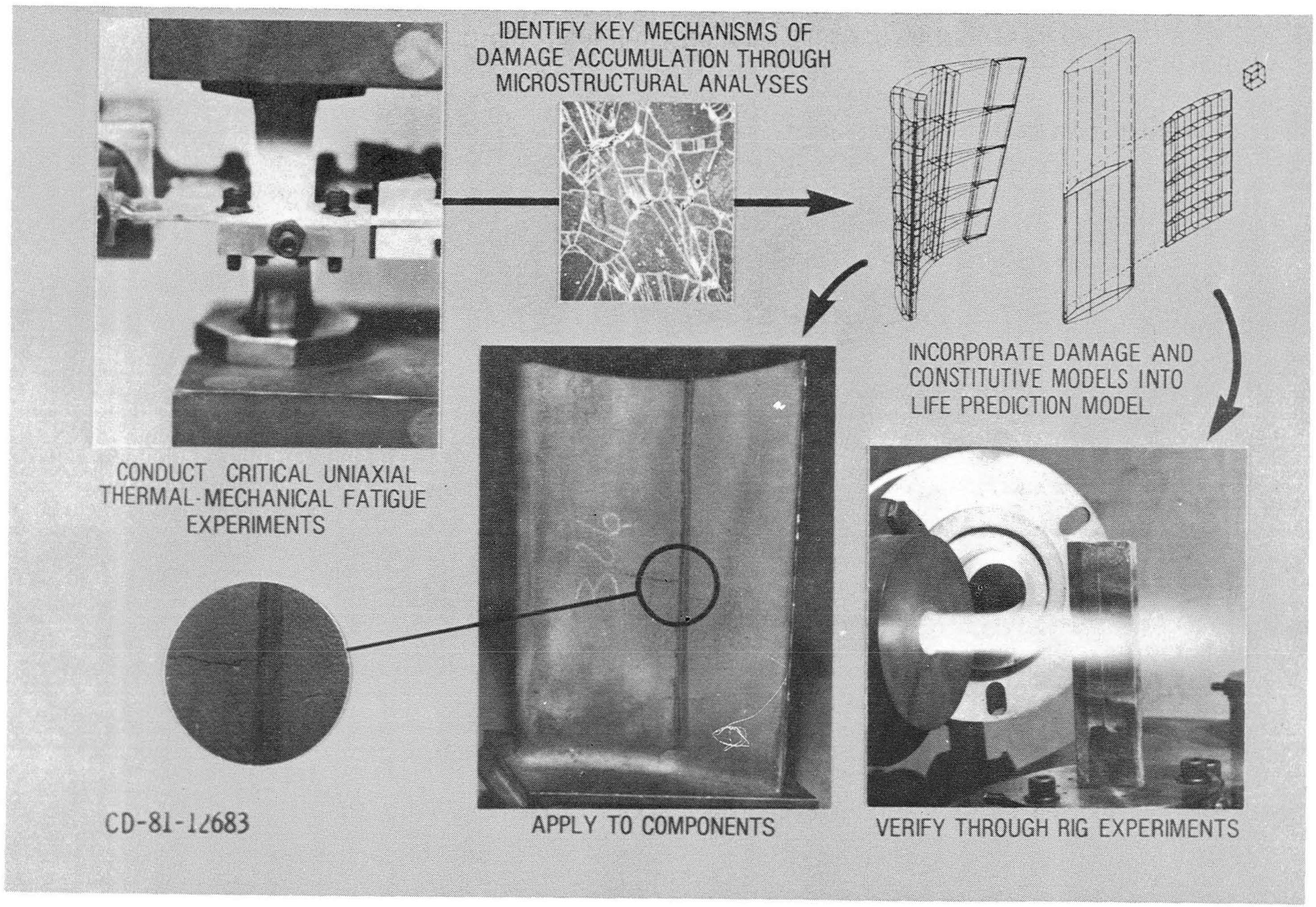


Fig. 11 Development of life prediction methodology.

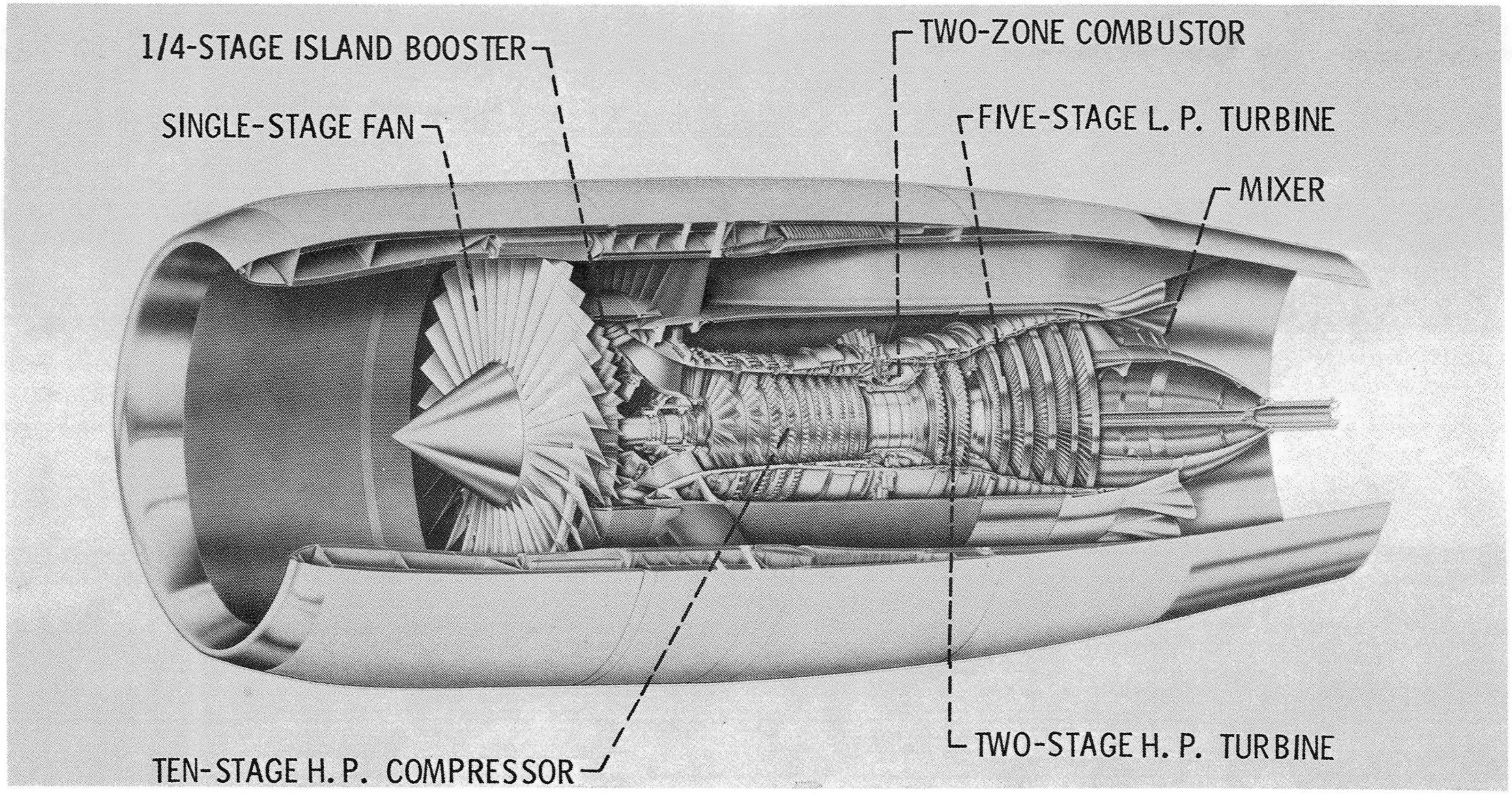


Fig. 12 Energy efficient engine - General Electric configuration.

NEW CONTROL DESIGN METHODS

INPUT

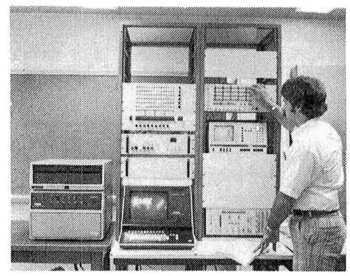
- LINEAR MODELS
- PERFORMANCE INDEX

OUTPUT

- CONTROL LOGIC

MULTIVARIABLE CONTROL
DESIGN TECHNIQUES

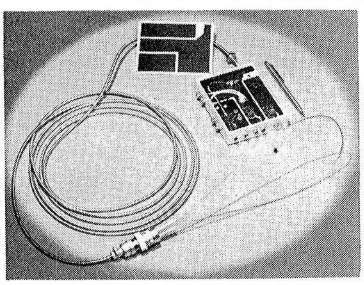
ENGINE SIMULATION



PORTABLE ENGINE SIMULATOR

C-81-3885

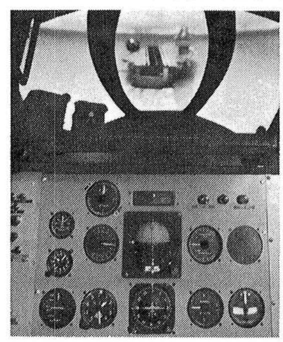
INNOVATIVE CONTROLS HARDWARE



FIBER-OPTIC TEMPERATURE SENSOR

C-81-3932

INTEGRATED CONTROLS RESEARCH



PILOTED SIMULATION OF
AIRCRAFT-ENGINE CONTROL SYSTEM

C-81-4087

Fig. 13 Propulsion controls research.

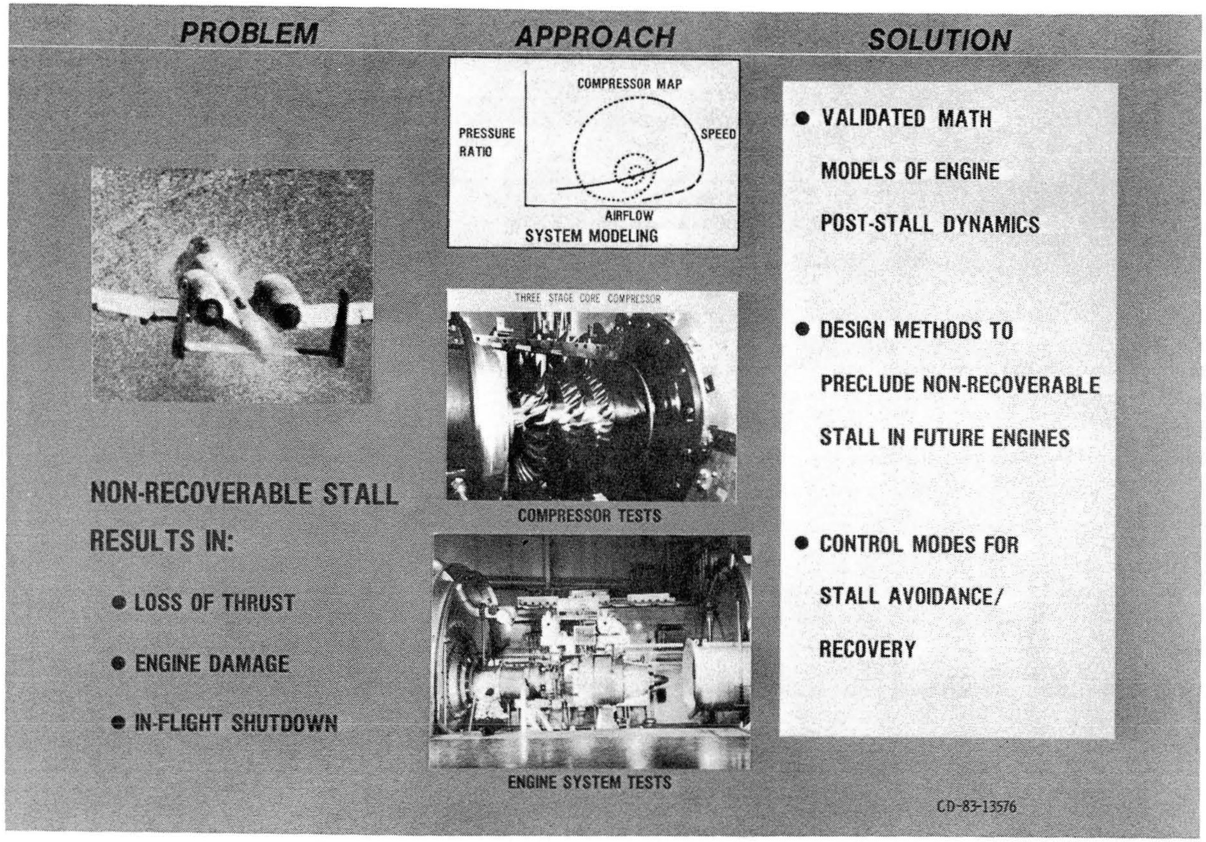


Fig. 14 Stall recovery research.

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