AN INTRODUCTION TO NASA'S TURBINE ENGINE HOT SECTION TECHNOLOGY (HOST) PROJECT

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INTRODUCTION

Today's modern gas turbine engines with their high thrust to weight ratio and low specific fuel consumption are comprised of many sophisticated components utilizing the latest high strength materials and technology. This is especially true in the hot section components of the combustor and turbine where high temperature superalloys and protective coatings are necessary in an environment where gas temperatures are well above the melting point of the materials. Current hot section components must endure higher temperatures, higher stresses, and more severe thermal transients than ever before. The durability and efficiency goals of the hot section components operating in this adverse environment will be difficult to achieve. Any shortfalls in achieving these goals could have significant effects on the overall operating cost of the modern gas turbine engine. Early in 1978, NASA began to plan a major project of turbine engine hot section research. Plans called for in-house and contract research to develop and improve the accuracy of current analysis methods so that increased durability could be designed into future engines. This paper is an overview of the new NASA Turbine Engine Hot Section Technology (HOST) project that began officially in January, 1981.

The HOST project was formulated around a simple, yet basic premise. Specifically, present analysis methods for designing combustor and turbine components need improvements in accuracy and applicability before increases in life can be attained during the initial design process of advanced turbine engines. The improved accuracy in life prediction can be attained by conducting focused and directed research efforts in each of the areas involved in component design, including description of the thermal and aerodynamic environments, the material's mechanical response, and the interactions between environmental and structural response. Verification of the more accurate predictions will be a necessary element of the HOST project and it will require high temperature instrumentation capable of measuring near-engine environment effects. The achievement of these improvements will require a rigorous and systematic research effort, beginning with evaluations of current predictive methods by comparing their predictions to benchmark data from special component tests, followed by supporting research to improve the modeling of the physical phenomena, and concluding with tests to verify the improved models in each of the pertinent discipline areas. These areas include structural analysis, surface protection, combustion, turbine heat transfer, and instrumentation.

TURBINE ENGINE HOT SECTION

The hot section components of an advanced turbine engine include the combustor and the turbine. A schematic of a typical turbine engine hot section is shown in figure 1. The contoured shaded areas represent an annular flow combustor connected to an axial flow turbine. The combustor liner and turbine airfoil outlines are represented in the figure. The arrows on the schematic represent the flow of the hot section cooling air around the components and through the turbine disk cavities. Because the liner of the combustor and the airfoils of the turbine are the hot section parts exposed to the highest temperatures and consequently suffer a large degree of damage, the research efforts in HOST will be concentrated on improving the analysis methods used to design these three parts. Typically the hot section has twenty percent of the engine weight but accounts for almost sixty percent of the maintenance costs. The consequences of combustor liner failures are generally more economic than operational and result only in a slow, general deterioration of the engine. It is included with the turbine airfoils as part of the HOST project primarily because of the combustor's close coupling and direct effect on the turbine durability.

A knowledge of the basic functions of the combustor and the turbine is necessary if the impact and importance of hot section durability problems is to be understood. In the combustor, the basic release of energy to the core airflow takes place with the burning of the turbine engine fuel. Involved in this energy release are many phenomena, including flow mixing, combustion kinetics, turbulence, flame radiation, soot formation and consumption, liner heat transfer, and gradual acceleration of the high temperature combustor airflow into the turbine. The control of these phenomena by suitable design factors will determine the temperature distribution in the combustor liner and the exit temperature profiles of the airflow leaving the combustor and entering the turbine. In the turbine, this entering airflow is channeled through a set of inlet guide vanes to properly align the flow vectors for optimum and efficient transfer of momentum and energy to the rotating blades of the turbine. The efficiency of the turbine, which contributes greatly to the overall performance and fuel efficiency of the engine, is directly related to the gas flow and temperature distributions. Besides the gas temperature distribution, the gas flow behavior is also needed. Any flow disturbance that inhibits uniform circumferential temperatures or proper radial temperature distribution imposes a penalty on engine performance. This is particularly true near a turbine hub, where large secondary flow vortices are often generated. The extent of these vortices depends upon the quality of the flow entering the turbine. They can be partially controlled by the radial gradients of the energy extracted from a turbine. The temperature and flow phenomena must be better understood and predicted with greater accuracy if life prediction methods are to be improved.

HOT SECTION DURABILITY PROBLEMS

The durability of hot section components is highly dependent on such factors as the type of aircraft mission flown, the geographical location of the operating base, and pilot operation. All of these factors affect the temperature and pressure environment and the cyclic load history of the parts in the hot section. During a typical turbine engine design, the type of aircraft mission expected to be flown is expressed in terms of engine cycle information. Design life predictions are made for accumulating levels of repetitive, and somewhat simplified engine cycles. The engine's hot section temperatures and pressures from the engine cycle information are used in these predictions. Variation in conditions due to geographical locations and weather conditions are accounted for in non-standard day test conditions. Variations due to individual pilots, however, can not be treated deterministically. The design assumes that the engine operates along a worse case cycle.

The incorporation of these real-life variants is beyond the scope of the HOST project. What is possible is to look at factors which affect the durability of the individual components in the gas path of the hot section. Other programs have gathered experimental and field service data regarding the actual and probable modes of failure for combustor liners and turbine airfoils. Examples of durability problems in components are shown in figure 2. Typically, air-cooled combustion chambers experience large, thermally induced strains that exceed elastic limits of materials at points of maximum stress and/or temperature. Creep-low cycle fatigue interactions and louver lip collapse have been established as primary burner liner failure modes. Oxidation/erosion modes tend to be secondary failures, usually caused by some other damage mechanism. For turbine airfoils (vanes and blades) creep-fatigue cracking and oxidation/corrosion tend to be dominant failure modes. But for the airfoils, these modes are of more importance and usually necessitate engine removal when detected to prevent further damage such as blade or vane rupture. These modes of failure for the combustor liner and the turbine airfoils have been selected as pertinent examples, but they are not all inclusive.

RESEARCH EFFORTS

Approach

The HOST project will support research to improve the accuracy of analysis methods, which can be used during engine design to increase component durability levels, thereby reducing maintenance and operating costs of the turbine engines. Research will be funded in the areas of structural analysis, surface protection, combustion, turbine heat transfer, and instrumentation. The overall approach of HOST in each of these areas will be to: (1) evaluate existing models; (2) quantify their strengths and weaknesses; (3) conduct new experimental and analytical research to more accurately model the physical phenomena; (4) use the new models in predictive analyses and verify their improvements in accuracy; and, (5) conduct a sensitivity study to assess the improvements in overall hot section durability to be achieved by use of a combination of these new methods.

The HOST project emphasizes the coordination of the research activities (fig. 3) to provide a system of more accurate analysis methods. The use of these improved methods will lead not only to enhanced durability, but also to lower maintenance costs for the hot section, freedom for more innovative design and checkout of new ideas, the ability to perform more accurate trade-off studies between performance and durability plus high reliability in future engines.

The specific elements of research that will be supported and coordinated in HOST are shown in the work breakdown structure in figure 4. The technical aspects of the activities in the six columns of figure 4 will be managed by staff members from four different divisions at the Lewis Research Center. This delegation of technical responsibility is illustrative of the matrix management concept that will be used for the HOST project. Descriptions of the planned research are presented in the following paragraphs.

Structural Analysis

Some typical damage observed on one component from the hot section of a turbine engine is shown in figure 5. This section of a combustor liner shows thermal fatigue cracking. To approach such a problem, the structural analyst must have sophisticated tools for accurate analysis. These include a knowledge of the thermal and mechanical loads, inelastic methods of analysis such as nonlinear finite element computer codes, cyclic constitutive (stress-strain) relationships, and the capability to determine the effects of the creep-fatigue interactions on crack initiation.

The structural analysis efforts under HOST will pursue areas such as thermal loading prediction methods, specialized vane and liner geometric and structural analysis models, methods and procedures to determine time and temperature structural response characteristics, and improved methods to describe time dependent and time independent inelastic material behavior. In addition, material constitutive relationships will be improved for predicting material behavior response to cyclic variations in stress, strain, and temperature with time. Also, life prediction methods will be developed for crack initiation models. The existing methods for such problems will be improved and automated to reduce the required manpower and computer time. For instance, the thermal analysis methods will be integrated with the structural analysis codes, so that the relatively coarse thermal map of a component becomes the input to the more detailed finite element program. Also, the methods will include self-adaptive solution strategies that use substructuring to examine the inelastic regions of a component with an overall elastic behavior.

The specific elements under HOST in the area of structural analysis are listed in figures 6(a) and 6(b) along with the expected results. The bars show the expected starting times and durations of each effort, in terms of fiscal years, which run from October through September.

The first element listed under structural analysis in figure 6(a) represents a planned effort to develop a computerized method to transfer the thermal loads that a burner liner might experience to a structural analysis model. The method will automatically integrate information from a thermal analysis computer code with an advanced nonlinear structural analysis code. The next element, shown by the bar extending from FY82 to 86, extends the application of the first method to prediction of loads that are component related, and time dependent for other hot section components for various engine mission cycles. It also will include effects of local hot streaks, cooling holes, and thermal anisotropy, as found in turbine blades and vanes. The structural analysis methods of the future will require improved versions of today's computer capabilities such as 3-D nonlinear finite element methods that can handle plasticity, creep, strain concentration, and unsymmetrical thermal effects found in hot section components. For effective structural analysis of the hot section, the codes will handle all these interacting inelastic effects. HOST will develop these capabilities and determine strategies and self-adaptive algorithms for solution of such complex analysis problems. After these automated modeling and solution strategies are completed, they will be verified by comparison with data from tests of specific engine components subjected to typical thermal and mechanical forces from appropriate mission cycles. The final program element in figure 6(a) will include component specific models and verification of the above efforts.

Within the computerized structural analysis methods are equations which model the behavior of the material when it is subjected to various loads and temperatures. These equations represent different theories and engineering models that attempt to describe the physical phenomena taking place. The theories, and hence these constitutive equations, must describe the response of a material subjected to both mechanical and thermally induced stresses and strains. For low temperatures, when the material is in the elastic range, the theories are quite adequate. But in the hot section of the turbine, most parts are well into inelastic behavior, and the modeling becomes very complex. Many theories have been proposed to describe this behavior. Several elements of HOST in figure 6(b) will evaluate the various theories and models to understand and improve upon the constitutive equations.

The first of these elements in figure 6(b) will determine the best model to represent the cyclic behavior of isotropic materials. The model will include the complexities of creep-plasticity, multi-axial stress and strain, plus the effects of long-time exposure of surfaces. The second element will develop and verify similar constitutive models for anisotropic materials, such as those used in the manufacturing of directionally solidified vanes or blades. The final product of these efforts will be sets of equations that represent the inelastic response of hot section components with greater accuracy than today's methods.

The second aspect of the HOST project in figure 6(b) is the prediction of the life of hot section component parts using an understanding of the synergistic effects of creep, fatigue, and environment on crack initiation behavior. Existing models that are explicit in the primary variables of stress, strain, temperature, environment, and time will be screened. The first element under Life Prediction Methods will select and develop a model for a specific isotropic material/coating combination that is typical for a liner or vane. The effects of mission loading, multi-axial stress and thermal cycling will be included. A second and parallel program element of HOST will develop a similar life prediction method for an anisotropic material/coating combination for a liner or blade. Both of these efforts will consist of a concentrated effort of laboratory testing resulting in modifications to life prediction methods. After sufficient validation, a second material/component combination will be examined in each of these efforts.

Surface Protection

Significant work has been done to further the science and technology of coatings. Figure 7 shows micrographs of a NiCrAlY coating before and after soaking for a long time at 1366 K. The coating is degraded not only by the hostile environment, but also by its diffusion at the substrate boundary. HOST will concentrate on analytical methods to account for each of the effects of environment, corrosion/erosion, oxidation/diffusion, and metallic coatings to be able to predict the time to crack initiation of coatings and coated hot section parts.

The HOST effort will concentrate on modeling the effects of environmental attack and coatings on crack initiation, the location and rate of erosive particle impact and corrosive salt depositions on airfoils, and also the coating degradation on blades, vanes, and combustors to provide coating life predictions. The various surface protection elements under HOST will study the phenomenological effects and interactions, and will produce analytical models for different types of components (i.e., turbine blades, vanes, and combustor liners). All of these models will be evaluated and verified using either real data from engine field failure experience or laboratory data from erosion/corrosion burner rigs.

The first surface protection element of HOST in figure 8(a) will model the effects of environment and coatings on the creep-fatigue crack initiation of isotropic materials used for liners and vanes. Later, another element will produce similar models, but for anisotropic materials such as directionally solidified vanes and blades. These two elements will be combined with the Life Prediction Methods of figure 6(b), as represented by the dashed lines of figure 8(a). As another element, the behavior of sheet materials coated for use as combustor liners will also be obtained during cyclic testing in a suitable test rig.

Other research efforts in the area of Surface Protection are shown in figure 8(b). The effects of corrosion and erosion, and their interaction, will be modeled and then used as part of a more comprehensive coating life model. To assist in developing a corrosion/erosion model, research elements investigating mass deposition on airfoils and the location and rates of erosion on airfoils will be conducted. The third element of the corrosion/erosion model effort will include rig burner tests of the combined corrosion/erosion mode to verify the deposition and erosion models.

Under the coating life model of figure 8(b), the first research element will collect engine field failure experience data for coatings to provide a real environment data base. The effects of oxidation and corrosion will be investigated and then modeled in inhouse tests to verify the effects of this dual cycle mode of attack. Next, the corrosion/erosion and dual cycle models will be combined. Life predictions will be verified in test rigs. Finally, a test program will obtain correlations of rig test effects and engine test effects on coating life.

Combustion

Present turbine engine combustors exhibit very complex flow conditions and high levels of heat transfer by radiation (fig. 9). These conditions make the prediction of gas and metal temperatures very difficult. To aid in this task, the combustion research will be conducted in the areas of aerothermal modeling and liner cyclic testing. To support this analytical work, a test program will be developed to study gas flow and mixing phenomena and flame radiation effects. Also, plans call for the design of a test rig that can obtain accelerated low life data for liner segments subjected to thermal cycling. The design will be difficult to obtain, since the thermal loads on the liner segment must simulate the real loads on a full circular liner, if the accelerated life data is to be useful.

The first combustion element in figure 10 will assess the existing aerodynamic and thermodynamic models to determine their capabilities, deficiencies, and the priority of areas requiring improvement. Research and model refinements will then be made in areas such as internal flow and exit temperature pattern factor, as well as in the mathematical routines used in computer solutions (e.g., faster solutions of the Navier Stokes equations). An experimental study of the penetration and thermal mixing characteristics that result when secondary (dilution) jets are used in combustors will be conducted. This work will add the empirical relations to explain the effect of dilution jet parameters on the exit temperature profile. Another experimental program will provide comprehensive luminous flame radiation and liner heat flux data for varying gas flow conditions. The effects of pressures up to 40 atmospheres on the luminous flame radiation will be included in the test program, and the results modeled.

The final aspect of the aerothermal modeling activities under HOST will begin in 1984. This "integration" phase will put together all of the submodels and routines that will be developed in the model refinement and testing activities. It will also include an assessment of the improvements made.

The low cycle fatigue life of combustor liners will be studied by running thermal cyclic tests on segments of liners. This data will be used with the life prediction methods described earlier under structural analysis. The effects of hot streaking on the life of combustor liners will also be investigated.

Turbine Heat Transfer

The turbine heat transfer research to be conducted in this area includes research into gas path analysis, gas side heat transfer, coolant side heat transfer, and metal temperature prediction. Advanced turbine engine design requires accurate predictions or knowledge of the local metal temperatures of the various static and rotating parts. For the turbine, as exemplified by the schematic cutaway in figure 11, these analyses must consider the characteristics of the gas flow at the entry, including its temperature, pressure and turbulence levels. The extremely complex flow field around the blades and along the walls must be understood and modeled, before the temperature of static and dynamic airfoils can be calculated. If the gas temperature and heat flux conditions for each row through the turbine are known, the heat transfer coefficients for blades, vanes and endwalls can be calculated. The coefficients can then be used to calculate the operating temperatures of these parts for transient as well as steady-state conditions. Finally, the information can be used to analytically optimize the design (and durability) of the components for various materials and geometries.

The efforts under HOST will be both experimental and analytical. They will establish benchmark quality data, model the complex heat transfer mechanisms, and, finally, provide the methodology for determining temperatures and heat transfer coefficients, which can then be input to structural analyses routines. The first two turbine elements in figure 12 will evaluate the effect on flow transition of variables such as Reynold's number, turbulence, geometry, and temperature ratios for vanes with and without the effects of film cooling. Viscous 3-D analyses to predict heat transfer and gas flow for stator and rotor cascades, including side and endwall effects, will be undertaken as part of HOST. In the next element, the heat transfer and flow characteristics will be determined for various geometries of multiple jet impingement arrays. The influence of rotational (Coriolis) forces and entrance geometry on the prediction of coolant-side heat transfer coefficients will be studied in another element of HOST. Steady-state and transient metal temperature prediction codes will be improved, and interfaced with structural analysis codes, by using the improved flow and heat transfer models above.

Research to measure local heat transfer coefficients over a stator vane, and a rotating blade will be included to verify the development of the above models. Measurements using improved instrumentation will be made to help evaluate the accuracy of codes for predicting gas-side heat transfer coefficients, metal temperatures and static strains in the materials.

Instrumentation Development

Crucial to the experimental effort of HOST are accurate measurements of the temperature, pressure, strain, and heat flux in the hot gas flow stream of the turbine engine. These measurements will be made to provide the benchmark quality data required for verification of the models developed in the other areas. Many of the measurements will require instruments that extend the present state-of-the-art. Fortunately, new techniques and computerized instrumentation (fig. 13) offer promising solutions and exciting extensions of current technology.

The first element in figure 14 will make use of new thin film sputtering techniques to develop a miniature heat flux sensor that is applied directly on blades and vanes. Also to be developed is a method for measuring the radiation portion of the total heat flux to sections of the combustor. Current static strain gages can operate at temperatures of 650 K (or 920 K for a few hours). By using thin film or powder metallurgy techniques, HOST will develop new static strain gages and installation methods for temperatures up to 1250 K. The third element of figure 14 will be the development of a viewing system that is needed for observation of the hot section components during operation at near engine condition temperatures and pressures. For instance, inside the combustor, the edges of the liner could be viewed to see if they are buckling or closing. Also, the interactions of the swirling flow of gases and fuel spray could be carefully studied. The increasing of the clarity of the view of these phenomena within the hot section will be a major part of this effort.

An automated laser anemometer system to measure the three components of average and fluctuating velocities will be developed. The final effort in instrumentation under HOST will produce a probe to measure dynamic gas temperatures up to 1000 Hz. Present temperature probes with fine wire thermocouples having electronic compensation are limited to a frequency response of about 30 Hz. The compensation depends on the gas stream flow properties (Mach number, density, etc.) but these vary during a test, so the compensation must also be dynamic, following these parameters in real time.

CONCLUDING REMARKS

The Turbine Engine Hot Section Technology (HOST) project, discussed above, will utilize current models and conduct new research to develop improved and more accurate analysis methods for the design of advanced turbine engine components. The research in the five areas of structural analysis, surface protection, combustion, turbine heat transfer, and instrumentation will be focused so that problems in hot section component durability can be understood and overcome. Current plans for the research call for eighty percent of the work to be done by engine manufacturers and other competent research institutions. The remaining twenty percent of the HOST effort will be accomplished inhouse by NASA Lewis Research Center technical personnel.

Although the HOST project includes research efforts in a number of separate technical disciplines, its organization is that of a systems technology project. As such, it has identifiable schedules with intermediate milestones and project end dates. The specific project products, as defined above in the text and in figures 6 to 14, are the key part of a systems technology project. While current plans and thinking are presented, it must be recognized that a certain amount of risk exists that some of the project's products may prove to be too far beyond the state of the art or not achievable by the end of the HOST project in fiscal year 1986. Individual research efforts will be monitored and appropriate plan changes made, if required, to ensure that the HOST project attains its objective.

The products of all of the HOST-supported research, excluding the instrumentation development, will be presented in the form of individual models, or in some cases, as computer modules, that can be acquired separately and utilized by engine manufacturers in analyzing designs of advanced turbine engine components. No attempt will be made during the HOST project to integrate the individual models into one overall model. All improved models, benchmark data bases, and any programmed computer modules will be disseminated to the U.S. domestic aerospace industry through formal reports and at suitable workshops and meetings. Thus, the U.S. engine manufacturers will be able to improve the durability of hot section components in their advanced turbine engine designs. This enhanced ability will enable the U.S. aerospace industry to maintain its favorable position in an increasingly competitive world aerospace market.

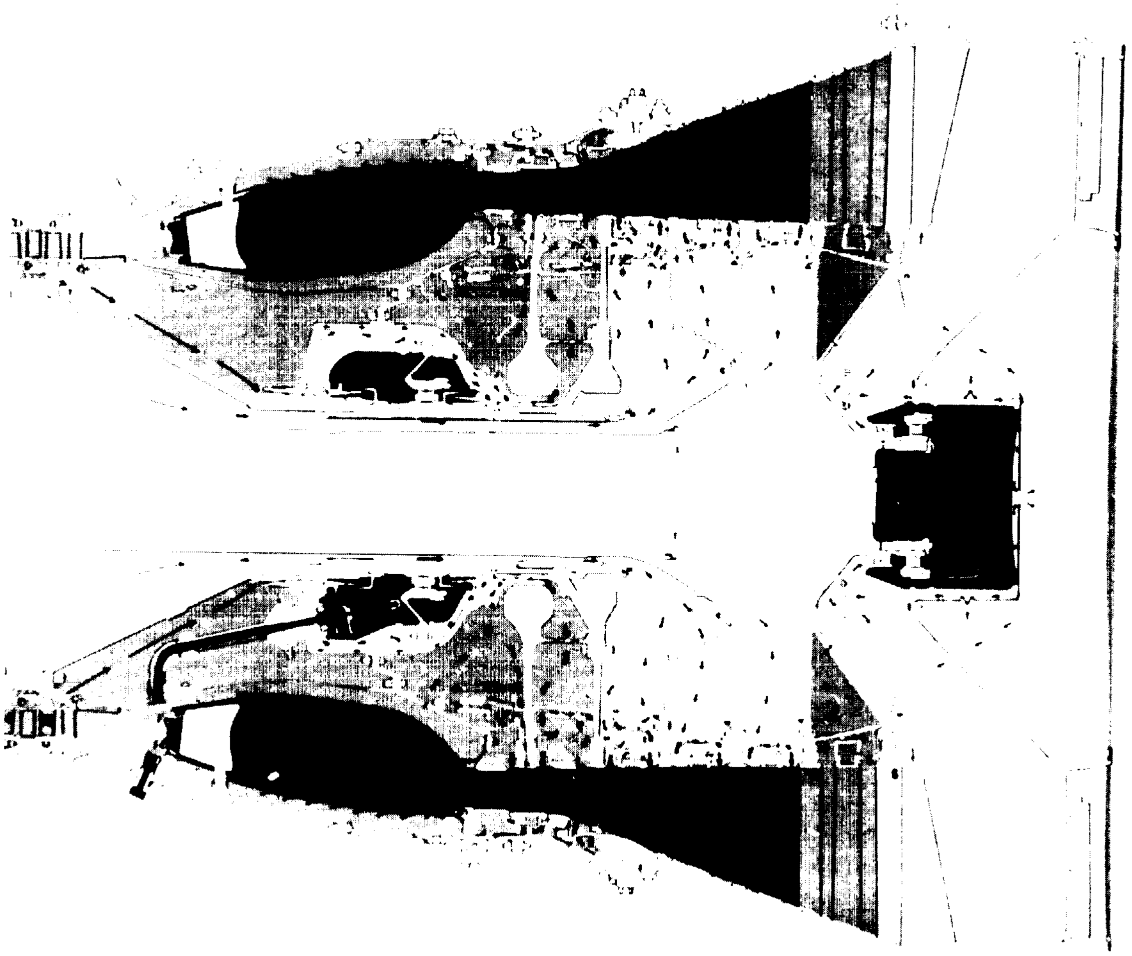


Figure 1. - Turbine engine hot section.

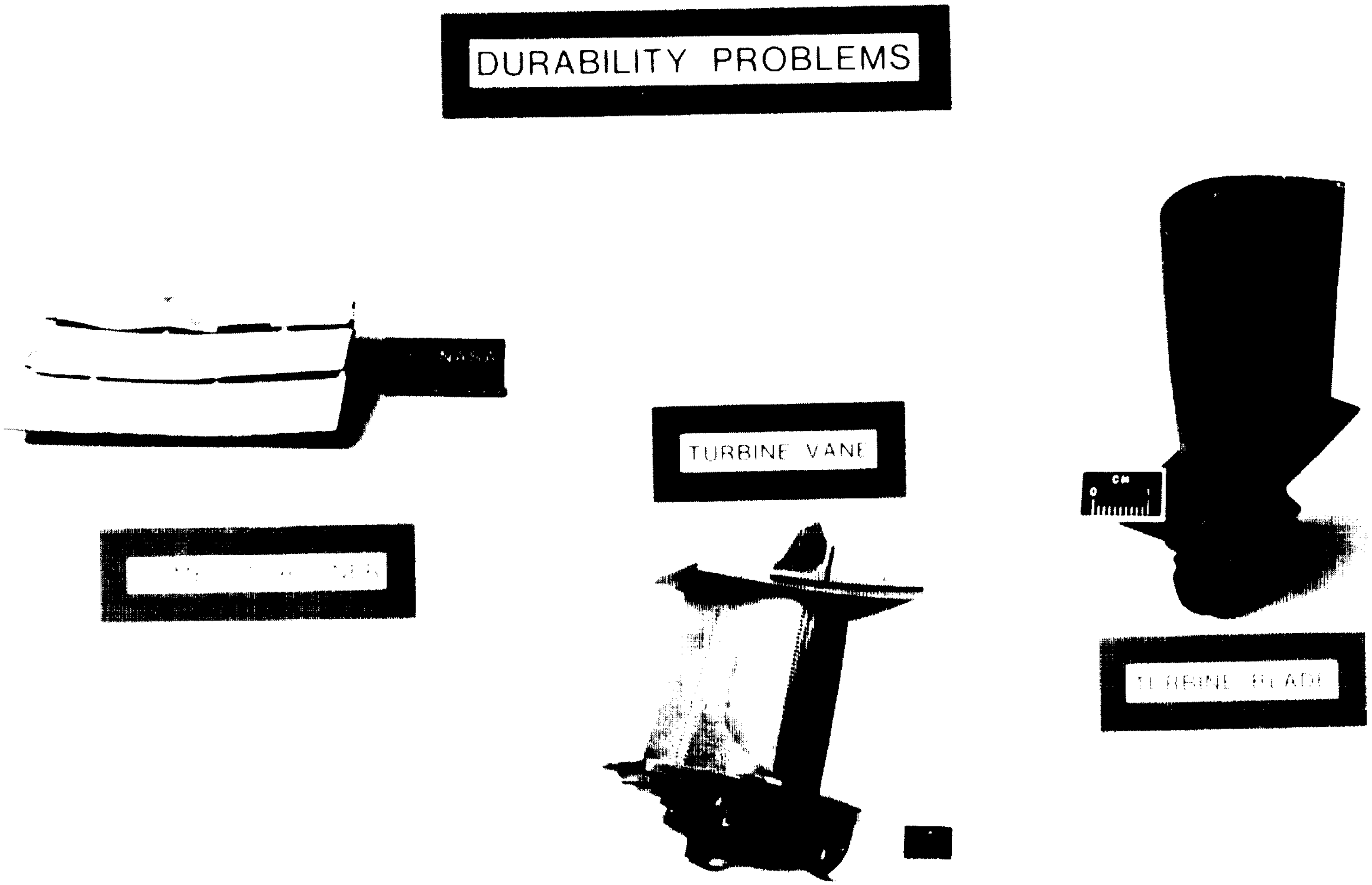


Figure 2. - Hot section components.

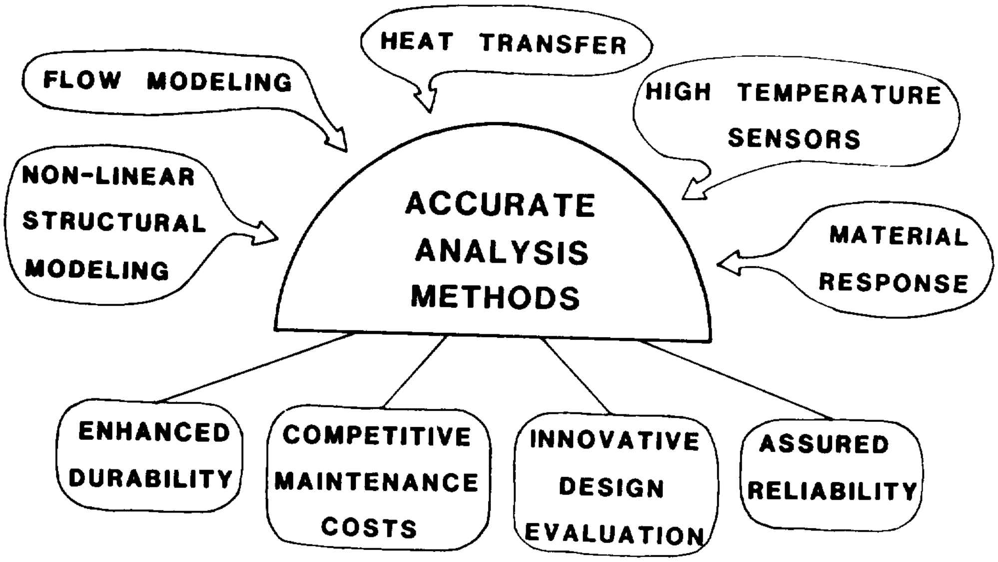


Figure 3. - Coordinated research activities.

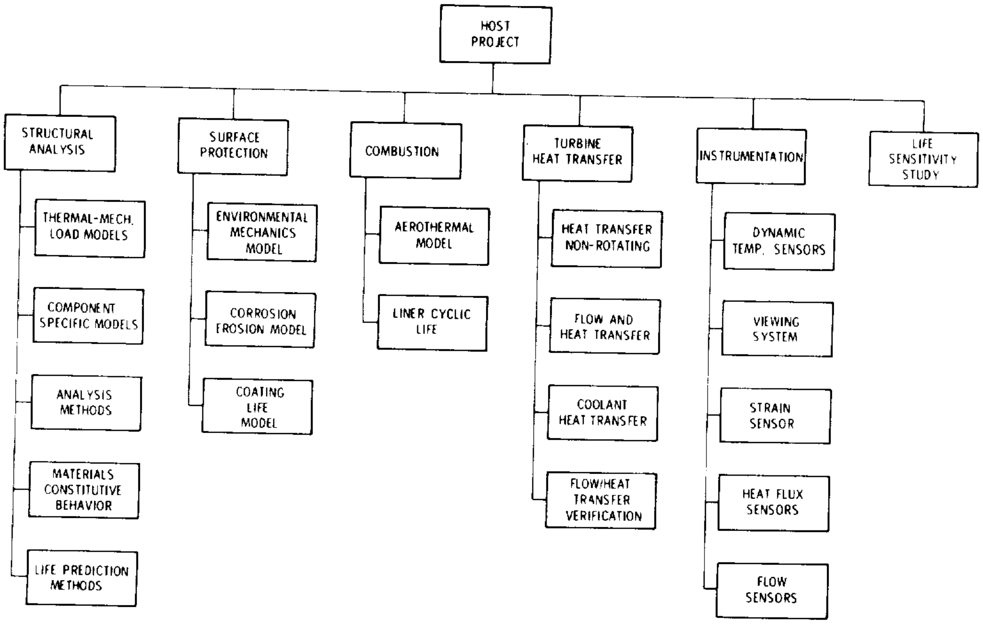


Figure 4. - Work breakdown structure.

STRUCTURAL ANALYSIS

THERMO–MECHANICAL LOADS

INELASTIC METHODS

σ - ϵ RELATIONS

CREEP FATIGUE INTERACTIONS

THERMAL FATIGUE CRACKS IN COMBUSTOR LINER

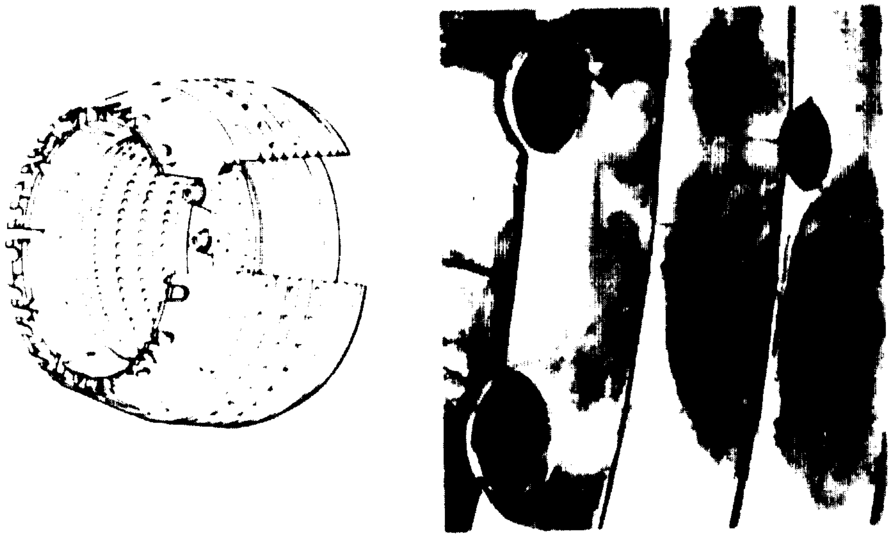
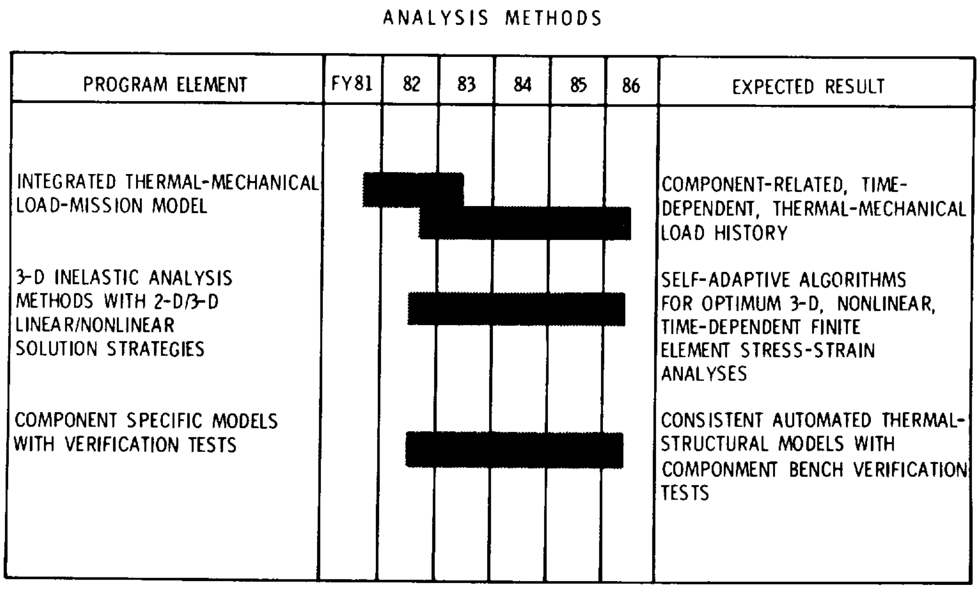


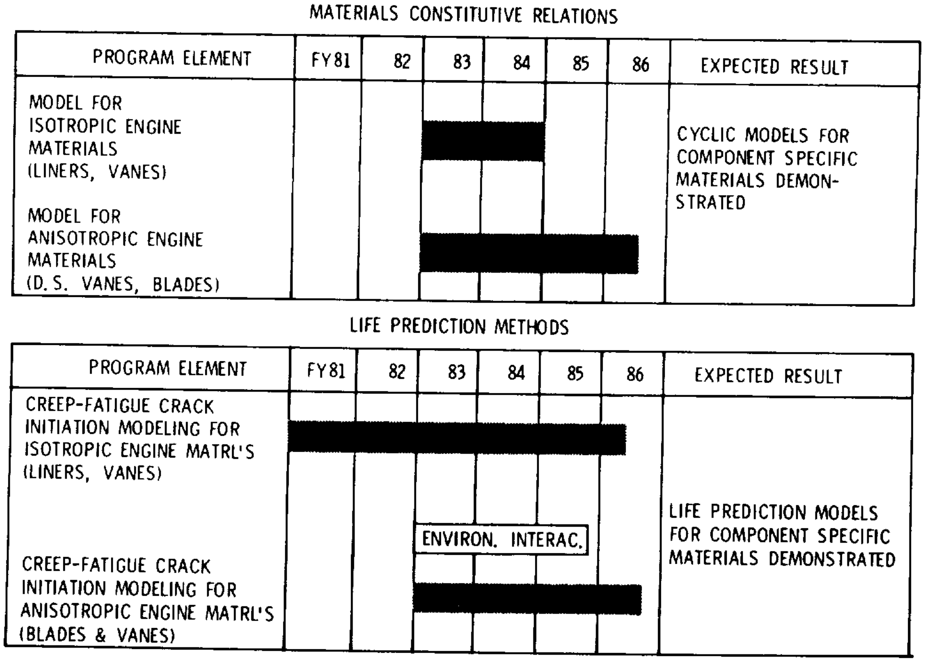
Figure 5. - Structural analysis research.



ANALYSIS METHODS

PROGRAM ELEMENT	FY81	82	83	84	85	86	EXPECTED RESULT
INTEGRATED THERMAL-MECHANICAL LOAD-MISSION MODEL	■	■	■	■	■	■	COMPONENT-RELATED, TIME-DEPENDENT, THERMAL-MECHANICAL LOAD HISTORY
3-D INELASTIC ANALYSIS METHODS WITH 2-D/3-D LINEAR/NONLINEAR SOLUTION STRATEGIES		■	■	■	■	■	SELF-ADAPTIVE ALGORITHMS FOR OPTIMUM 3-D, NONLINEAR, TIME-DEPENDENT FINITE ELEMENT STRESS-STRAIN ANALYSES
COMPONENT SPECIFIC MODELS WITH VERIFICATION TESTS		■	■	■	■	■	CONSISTENT AUTOMATED THERMAL-STRUCTURAL MODELS WITH COMPONMENT BENCH VERIFICATION TESTS

(a) Analysis methods.



MATERIALS CONSTITUTIVE RELATIONS

PROGRAM ELEMENT	FY81	82	83	84	85	86	EXPECTED RESULT
MODEL FOR ISOTROPIC ENGINE MATERIALS (LINERS, VANES)			■	■			CYCLIC MODELS FOR COMPONENT SPECIFIC MATERIALS DEMONSTRATED
MODEL FOR ANISOTROPIC ENGINE MATERIALS (D.S. VANES, BLADES)			■	■	■	■	

LIFE PREDICTION METHODS

PROGRAM ELEMENT	FY81	82	83	84	85	86	EXPECTED RESULT
CREEP-FATIGUE CRACK INITIATION MODELING FOR ISOTROPIC ENGINE MATRL'S (LINERS, VANES)	■	■	■	■	■	■	LIFE PREDICTION MODELS FOR COMPONENT SPECIFIC MATERIALS DEMONSTRATED
			ENVIRON. INTERAC.	ENVIRON. INTERAC.	ENVIRON. INTERAC.		
CREEP-FATIGUE CRACK INITIATION MODELING FOR ANISOTROPIC ENGINE MATRL'S (BLADES & VANES)			■	■	■	■	

(b) Materials constitutive relations and life prediction methods.

Figure 6. - Structural analysis.

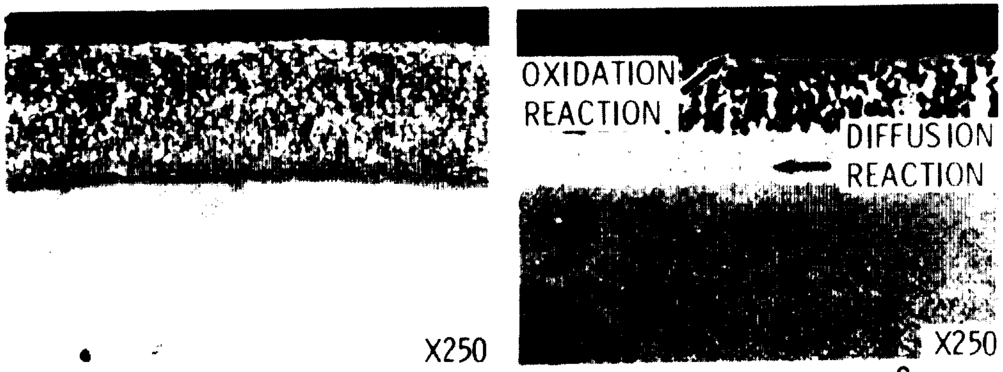
SURFACE PROTECTION

CORROSION EROSION

METALLIC COATINGS

ENVIRONMENT

ENVIRONMENTAL AND SUBSTRATE REACTIONS
DEGRADE COATINGS



AS-DEPOSITED NiCrAlY COATING

AFTER 200 hr AT 2000° F

Figure 7. - Surface protection research.

ENVIRONMENTAL/MECHANICAL PROPERTY INTERACTIONS

PROGRAM ELEMENT	FY81	82	83	84	85	86	EXPECTED RESULT
C/F INITIATION							
ISOTROPIC (LINERS, VANES)	- -	- -	- -	- -	- -	- -	
ENV./COATING EFFECTS TASKS			■	■	■	■	MODELS FOR EFFECTS OF ENVIRONMENTAL ATTACK & COATINGS ON CRACK INITIATION
C/F INITIATION							
ANISOTROPIC (D. S. VANES, BLADES)			- -	- -	- -	- -	
ENV./COATING EFFECTS TASKS			■	■	■	■	
SHEET MATERIALS IH			■	■	■		EFFECTS OF ENV. ATTACK & COATINGS ON CRACK INITIATION IN COMBUSTOR LINERS

(a) Environmental/mechanical property interactions.

- CORROSION/EROSION MODEL -

PROGRAM ELEMENT	FY81	82	83	84	85	86	EXPECTED RESULT
AIRFOIL DEPOSITION MODEL - G	■	■	■				MODEL TO PREDICT CORRODANT DEPOSITION ON TURBINE AIRFOILS
AIRFOIL EROSION MODEL			■	■			MODEL TO PREDICT LOCATION AND SEVERITY OF EROSION ATTACK OF TURBINE AIRFOILS
CORROSION/EROSION MODEL - IH			■	■	■	■	VERIFICATION OF MODELS IN RBT

- COATING LIFE MODEL -

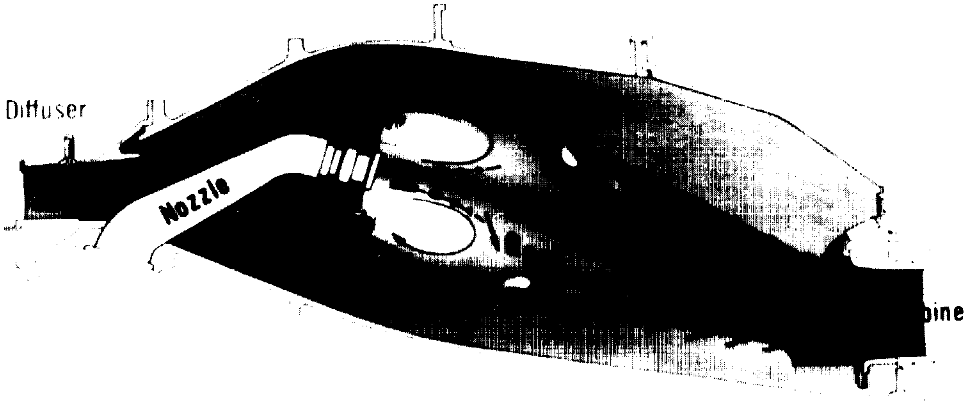
PROGRAM ELEMENT	FY81	82	83	84	85	86	EXPECTED RESULT
ENGINE DATA BASE			■	■			CAPABILITY TO PREDICT COATING DEGRADATION ON BLADES, VANES, COMBUSTORS
OXIDATION LIFE PREDICTION - IH	■	■	■				
CORROSION LIFE PREDICTION			■	■			
DUAL CYCLE ATTACK - IH			■	■	■		
HOST-CORROSION/EROSION MODEL			■	■	■		
LIFE PREDICTION VERIFICATION				■	■		
RIG/ENGINE CORR - IH					■	■	

(b) Corrosion/erosion and coating life models.

Figure 8. - Surface protection.

COMBUSTION

AEROTHERMAL MODELING



LINER PANEL SEGMENT

THERMAL CYCLIC DATA

Figure 9. - Combustion research.

PROGRAM ELEMENT	FY 81	82	83	84	85	86	EXPECTED RESULT
A. AEROTHERMAL MODELING							
1. ASSESSMENT		■					MODEL AND DATA DEFICIENCIES IDENTIFIED
2. MODEL REFINEMENT & SUPPORTING RESEARCH			■	■	■		NEW PHYSICAL MODELS, IMPROVED COMPUTING METHODS
a. DILUTION-JET MIXING	■	■	■	■	■		EXIT TEMPERATURE PROFILES PREDICTED
b. FLAME RADIATION (I-H)		■	■	■	■		HIGH PRESSURE FLAME RADIATION AND HEAT FLUX DATA
3. INTEGRATION				■	■	■	VERIFIED MODEL IMPROVEMENTS
B. LINER CYCLIC LIFE							
1. LINER PANEL DESIGN	■	■					LINER TEST PANELS DESIGNED
2. CYCLIC TESTING (I-H)	■	■	■	■	■		IMPROVED ABILITY TO ACCURATELY PREDICT LINER CYCLIC LIFE

Figure 10. - Combustion analysis.

- ENTRY GAS FLOW CONDITIONS
  - -TEMPERATURE, PRESSURE, & TURBULENCE CHARACTERISTICS
- GAS CONDITIONS FOR EACH ROW
- HEAT TRANSFER COEFFICIENTS
  - -BLADES, VANES, END WALLS
- TEMPERATURE OF COMPONENTS
  - -STEADY STATE & TRANSIENT
- OPTIMIZATION TO IMPROVE DURABILITY
  - -METAL TEMPERATURES & GEOMETRY

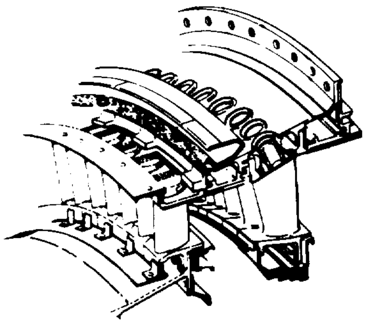


Figure 11. - Turbine heat transfer research.

PROGRAM ELEMENT	FY81	82	83	84	85	86	EXPECTED RESULT
GAS-SIDE HEAT TRANSFER, NON-ROTATING, 2-D	■	■					DETERMINE INFLUENCE OF VARIABLES ON FLOW TRANSITION & DURATION & IMPROVED MODELS
GAS-SIDE HEAT TRANSFER, NON-ROTATING, FILM		■	■				
GAS FLOW ENVIRONMENT AND HEAT TRANSFER, NON-ROTATING	■	■	■	■			IMPROVE PREDICTION CODES FOR ENVIRONMENT & GAS-SIDE HEAT TRANSFER, NO ROTATION
GAS FLOW ENVIRONMENT AND HEAT TRANSFER, ROTATING, 3-D		■	■	■	■		SAME AS ABOVE WITH ROTATION
MULTIPLE JET ARRAY IMPINGEMENT	■						IMPROVED HEAT TRANSFER CORRELATION FOR IMPINGEMENT COOLING
COOLANT SIDE HEAT TRANSFER WITH ROTATION AND ENTRANCE GEOMETRY			■	■	■		HEAT TRANSFER CORRELATIONS, INCLUDING EFFECTS OF ROTATIONS AND ENTRANCE GEOMETRY
METAL TEMPERATURE PREDICTION CODES			■	■	■		METAL TEMPERATURE PREDICTION CODES WITH IMPROVED HEAT TRANSFER MODELS/ CORRELATIONS
IN-HOUSE RESEARCH AND VERIFICATIONS		■	■	■	■	■	VERIFICATIONS OF FLOW, HEAT TRANSFER, AND STRAIN PREDICTION AT NEAR REAL TURBINE ENVIRONMENT

Figure 12. - Turbine heat transfer.

- SENSORS: HEAT FLUX, STRAIN & TEMPERATURE
- LASER ANEMOMETER

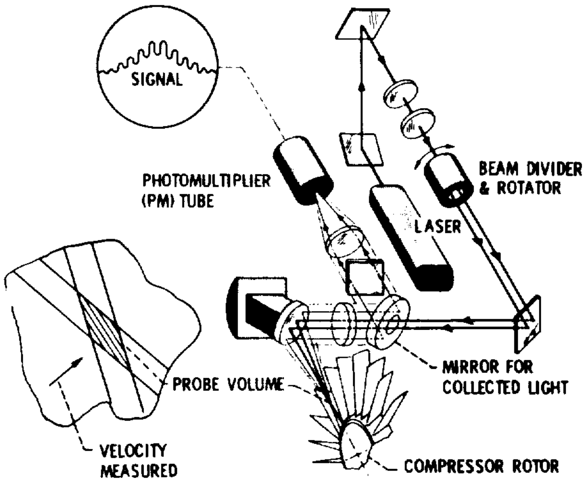


Figure 13. - Instrumentation development.

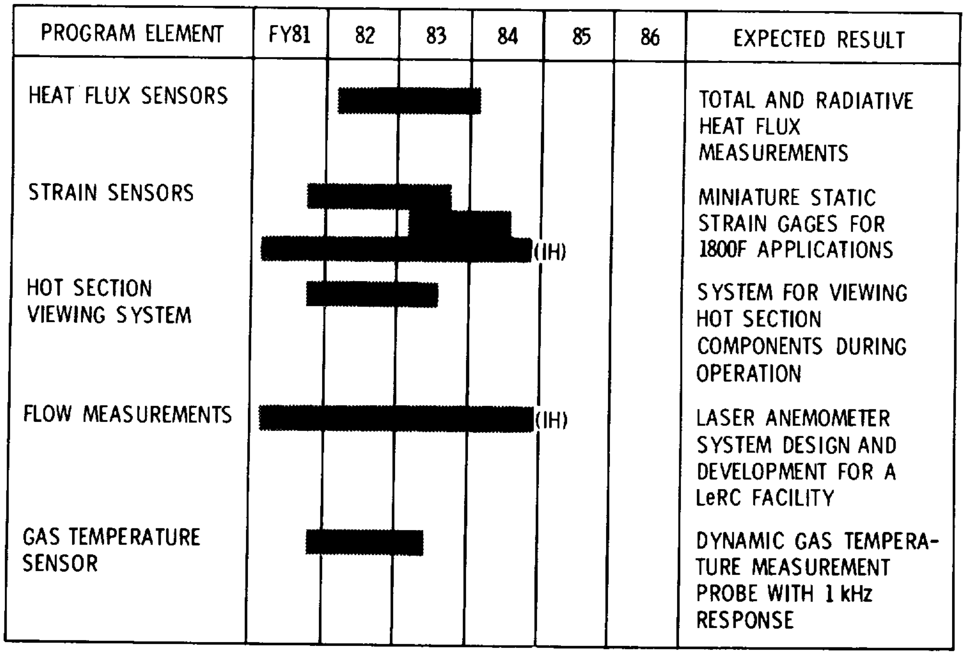


Figure 14. - Instrumentation.