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AIRCRAFT ENGINE HOT SECTION TECHNOLOGY - AN OVERVIEW OF THE HOST PROJECT

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NASA sponsored the Turbine Engine Hot Section Technology (HOST) Project to address the need for improved durability in advanced aircraft engine combustors and turbines. Analytical and experimental activities aimed at more accurate prediction of the aerothermal environment, the thermomechanical loads, the material behavior and structural responses to loads, and life predictions for cyclic high-temperature operation have been underway for the last 7 years. The project has involved representatives from six engineering disciplines who are spread across three work sectors - industry, academia, and NASA. The HOST Project not only initiated and sponsored 70 major activities, but also was the keystone in joining the multiple disciplines and work sectors to focus on critical research needs. A broad overview of the project is given along with initial indications of the project's impact.

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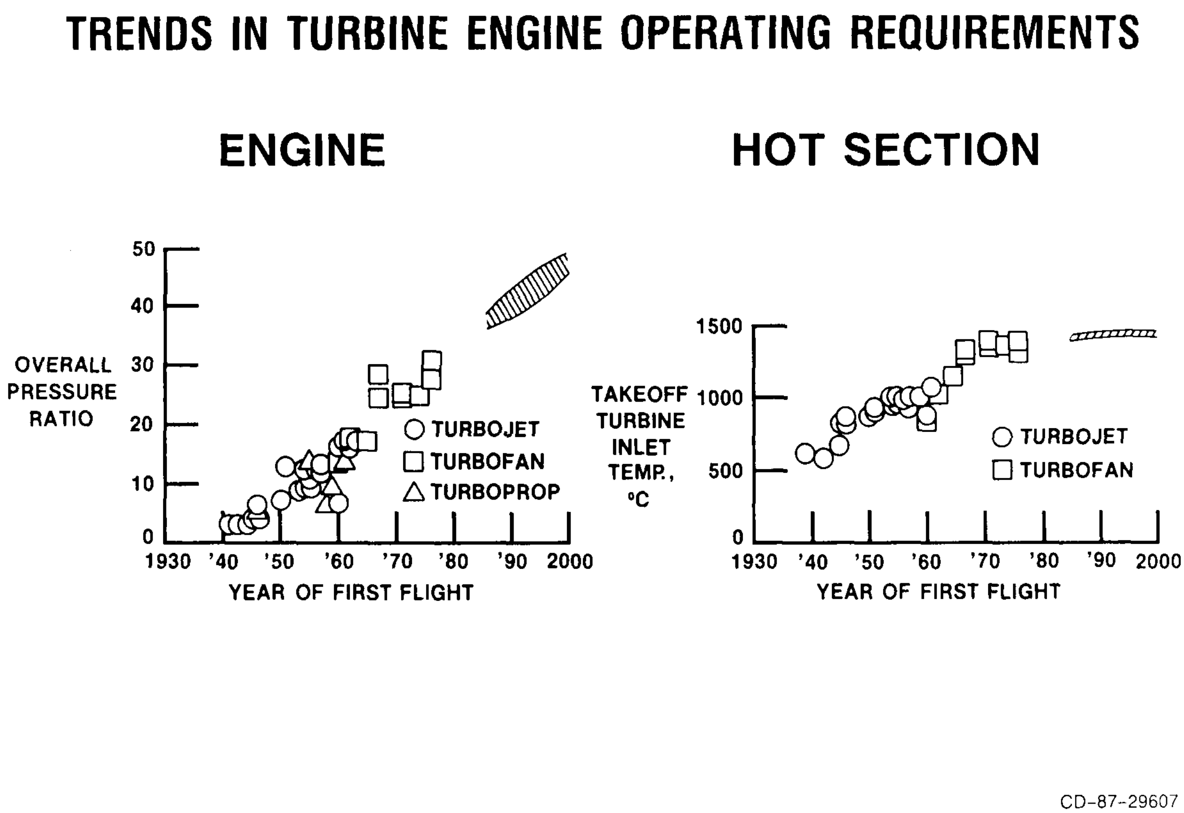
TRENDS IN TURBINE ENGINE OPERATING REQUIREMENTS

Since introduction of the gas-turbine engine to aircraft propulsion, the quest for greater performance has resulted in a continuing upward trend in overall pressure ratio for the engine core. Associated with this trend are increasing temperatures of gases flowing from the compressor and combustor and through the turbine. For commercial aircraft engines in the foreseeable future, compressor discharge temperature will exceed 922 K (1200 °F), while turbine inlet temperature will be approximately 1755 K (2700 °F). Military aircraft engines will significantly exceed these values.



IMPACT OF MORE SEVERE OPERATING CONDITIONS ON COMBUSTOR LINERS

Since 1973 increasing fuel prices have created the demand for energy conservation and more fuel efficient aircraft engines. In response to this demand engine manufacturers continually increased the performance of current generation gas-turbine engines. Soon afterward, the airline industry began to experience a notable decrease in the durability or useful life of critical parts in the engine hot section - the combustor and turbine. This was due primarily to cracking in the combustor liners, turbine vanes, and turbine blades. Spalling of thermal barrier coatings that protect combustor liners also occurred.

IMPACT OF MORE SEVERE OPERATING CONDITIONS ON COMBUSTOR LINERS

- AXIAL AND CIRCUMFERENTIAL CRACKS
- EXTENSIVE SPALLING OF THERMAL BARRIER COATING

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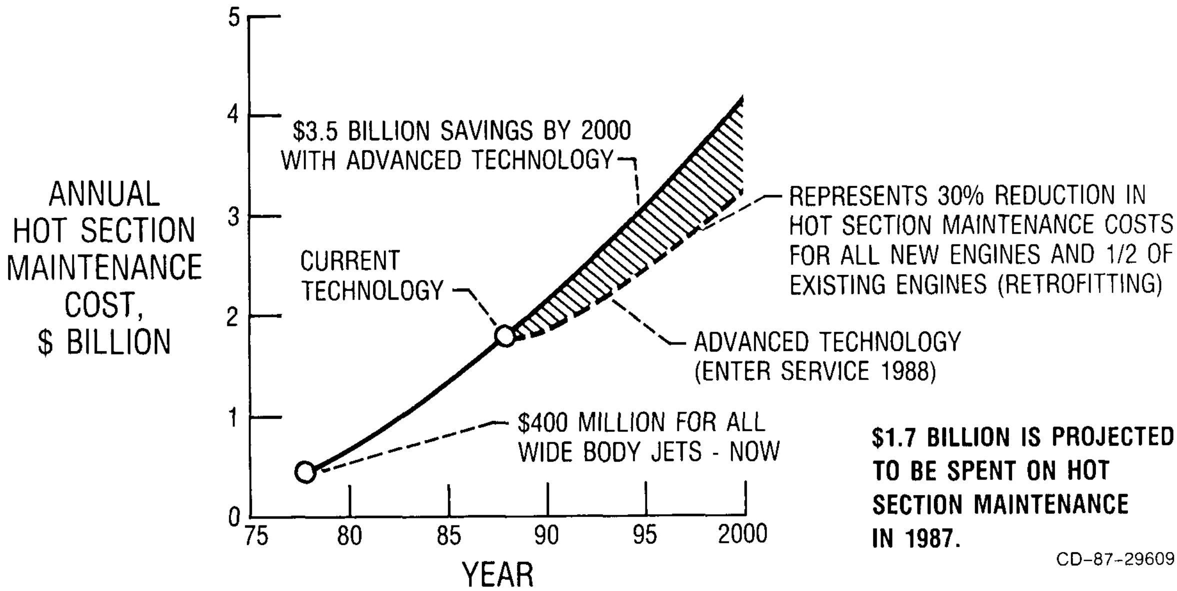
EFFECT OF MORE SEVERE OPERATING CONDITIONS ON ENGINE MAINTENANCE

For the airlines reduced durability for in-service engines was measured by a dramatic increase in maintenance costs, primarily for high bypass ratio engines. Higher maintenance costs were especially evident in the hot section. Hot section maintenance costs account for almost 60 percent of the engine total.

EFFECT OF MORE SEVERE OPERATING CONDITIONS ON ENGINE MAINTENANCE

"HOT SECTION PARTS ACCOUNT FOR 60 PERCENT OF ENGINE MAINTENANCE COSTS. IN 1978, APPROXIMATELY $400 MILLION WAS SPENT..."

A.J. DENNIS, PRATT & WHITNEY (AIAA 79-1154)



$1.7 BILLION IS PROJECTED TO BE SPENT ON HOT SECTION MAINTENANCE IN 1987.

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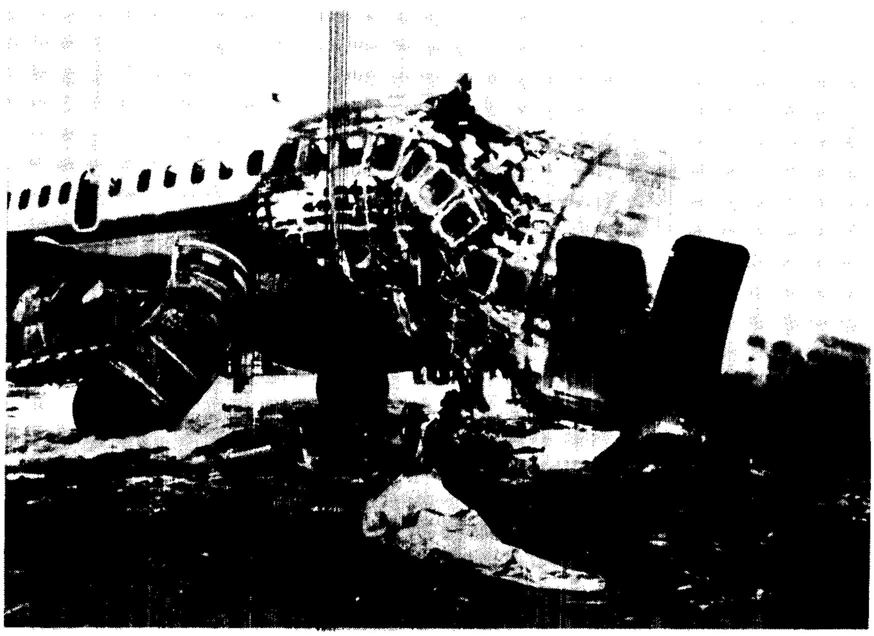
IMPACT OF MORE SEVERE OPERATING CONDITIONS ON FLIGHT SAFETY

Besides having an effect on maintenance costs, failure of hot section parts can affect flight safety. An example is a Boeing 737 accident in Manchester, England, in August 1985, with the loss of 55 lives. The accident was a direct result of failure due to cracking in a combustor liner and subsequent puncture of a wing fuel tank.

IMPACT OF MORE SEVERE OPERATING CONDITIONS ON FLIGHT SAFETY



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APPROACHES TO IMPROVING HOT SECTION DURABILITY

Durability can be improved in hot section components by using a single approach or a combination of the four approaches described below.

(1) High-Temperature Materials

High-temperature metallic materials currently include nickel- and cobalt-based superalloys. Certain elements of these alloys, such as cobalt, are in short supply and are expensive. Recently, researchers completed a study of ways to reduce their usage. Advanced high-temperature superalloy components also include directionally solidified, single-crystal, and oxide-dispersion-strengthened materials. For such materials, the development time is lengthy, fabrication is sometimes difficult, and, again, costs are high. Thus, successful use of these materials requires a balance among design requirements, fabrication possibilities, and total costs.

(2) More Effective Cooling Techniques

Current cooling techniques tend to be sophisticated; fabrication is moderately difficult. In higher performance engines cooling capability may be improved by increasing the amount of coolant. But the penalty for doing this is a reduction of thermodynamic cycle performance of the engine system. In addition, the coolant temperature of such advanced engines is higher than that for current in-service engines. Consequently, more effective cooling techniques are being investigated. Generally, they are more complex in design, demand new fabrication methods, and may require a multitude of small cooling holes, each of which introduces potential life-limiting high stress concentrations. Acceptable use of the advanced cooling techniques will require accurate models for design analysis.

(3) Advanced Structural Design Concepts

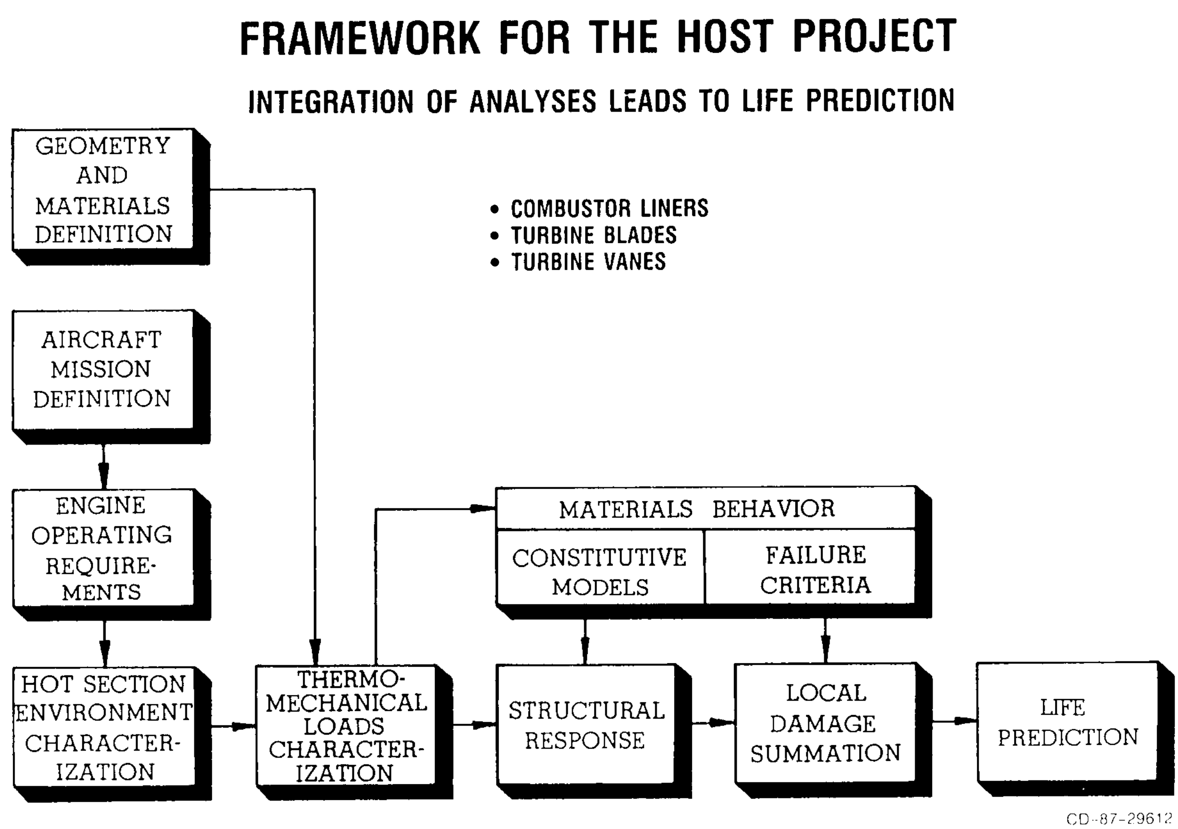
The introduction of advanced structural design concepts usually begins with a preliminary concept that then must be proven, must be developed, and -- most critically -- must be far superior to entrenched standard designs. Acceptance certainly is time consuming, and benefits must be significant. For improved durability in high performance combustors, an excellent example of an advanced structural design concept is the segmented liner. The life-limiting problems associated with high hoop stresses were eliminated by dividing the standard full-hoop liners into segments. At the same time, designers realized increased flexibility in the choice of advanced cooling techniques and materials, including ceramic composites.

(4) More Accurate Design Analysis Tools

Finally, the design analysis of hot section component parts, such as the combustor liners or turbine vanes and blades, involves the use of analytical or empirical models. Such models often involve computer codes for analyzing the aerothermal environment, the thermomechanical loads, heat transfer, and material and structural responses to such loading. When the parts are exposed to high-temperature cyclic operation as in a turbine engine, the repetitive straining of the materials invariably leads to crack initiation and propagation until failure or break-away occurs. The useful life of a part is usually defined as the number of mission cycles that can be accumulated before initiation of significant cracks. Thus, designers need to predict useful life accurately so they can design a part to meet requirements.

FRAMEWORK FOR THE HOST PROJECT

Efforts to predict the life of a part generally follow the flow of analytical models shown in the figure. Thus, designing a part such as a turbine blade to meet a specified life goal may require several iterations through the life prediction system, varying the blade geometry, material, or cooling effectiveness in each pass, until a satisfactory life goal is predicted.



THE HOST PROJECT

To meet the needs for improved analytical design and life prediction tools, especially those used for high-temperature cyclic operation in advanced combustors and turbines, NASA has sponsored the Turbine Engine Hot Section Technology (HOST) Project. The project was conducted from fiscal year 1981 through 1987.

The HOST Project has developed improved analytical models for the aerothermal environment, the thermomechanical loads, material behavior, structural response, and life prediction, along with more sophisticated computer codes, which can be used in design analyses of critical parts in advanced turbine engine combustors and turbines. Use of these more accurate analytical tools during the design process will ensure improved durability of future hot section engines components.

The complex durability problem in high-temperature, cyclically operated turbine engine components requires the involvement of numerous research disciplines. This involvement must include, not only focused research, but also interdisciplinary and integrated efforts. The disciplines included in HOST were instrumentation, combustion, turbine heat transfer, structural analysis, fatigue and fracture, and surface protection.

Most disciplines in the HOST Project followed a common approach. First, phenomena related to durability were investigated, often using benchmark experiments. With known boundary conditions and proper instrumentation, these experiments resulted in a better characterization and understanding of such phenomena as the aerothermal environment, the material and structural behavior during thermomechanical loading, and crack initiation and propagation. Second, state-of-the-art analytical models were identified, evaluated, and then improved upon through use of more inclusive physical considerations and/or more advanced computer code development. When no state-of-the-art models existed, researchers developed new models. Finally, predictions using the improved analytical tools were validated by comparison with experimental results, especially the benchmark data.

THE HOST PROJECT

OBJECTIVE

- PROVIDE MORE ACCURATE DESIGN ANALYSIS TOOLS WHICH WILL BETTER ENSURE, DURING THE DESIGN PROCESS, IMPROVED DURABILITY OF HOT SECTION COMPONENTS.

APPROACH

- FOCUS MULTIDISCIPLINARY RESEARCH TOWARD
  - —BENCHMARK QUALITY EXPERIMENTS
  - —ADVANCED ANALYTICAL MODELS
  - —IMPROVED COMPUTER CODES

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HOST PROJECT ACTIVITIES

The HOST Project initiated and sponsored 70 major research activities across six technical disciplines. Research results from some of these activities are reported throughout this publication.

Instrumentation

Activity	Contract (C), grant (G), or NASA organization (N)	number
Hot Section Viewing System	C	NAS3-23156
Dynamic Gas Temperature Measurement System - A	C	NAS3-23154
Dynamic Gas Temperature Measurement System - B	C	NAS3-24228
Turbine Static Strain Gage - A	C	NAS3-23169
Turbine Static Strain Gage - B	C	NAS3-23722
Turbine Heat Flux Sensors	C	NAS3-23529
Laser Speckle Strain Measurement	C	NAS3-26615
High Temperature Strain Gage Materials	G	NAG3-501
Hot Section Sensors	N	2510
Laser Anemometry for Hot Section Applications	N	2520/2530
HOST Instrument Applications	N	2510

Combustion

Activity	Contract (C), grant (G), or NASA organization (N)	number
Assessment of Combustor Aerothermal Models - I	C	NAS3-23523
Assessment of Combustor Aerothermal Models - II	C	NAS3-23524
Assessment of Combustor Aerothermal Models - III	C	NAS3-23525
Improved Numerical Methods - I	C	NAS3-24351
Improved Numerical Methods - II	C	NAS3-24350
Improved Numerical Methods - III	G	NAG3-596
Flow Interaction Experiment	C	NAS3-24350
Fuel Swirl Characterization - I	C	NAS3-24350
Fuel Swirl Characterization - II	C	NAS3-24352
Mass and Momenta Transfer	C	NAS3-22771
Diffuser/Combustor Interaction	C	F33615-84-C-2427
Dilution Jet Mixing Studies	C	NAS3-22110
Lateral Jet Injection into Typical Combustor Flowfields	G	NAG3-549
Flame Radiation Studies	N	2780

Turbine Heat Transfer

Activity	Contract (C), grant (G), or NASA organization (N)	number
Mainstream Turbulence Influence on Flow in a Turning Duct - A	C	NAS3-23278
Mainstream Turbulence Influence on Flow in a Turning Duct - B	G	NAG3-617
2-D Heat Transfer without Film Cooling	C	NAS3-22761
2-D Heat Transfer with Leading-Edge Film Cooling	C	NAS3-23695
2-D Heat Transfer with Downstream Film Cooling	C	NAS3-24619
Measurement of Blade and Vane Heat Transfer Coefficient in a Turbine Rotor	C	NAS3-23717
Assessment of 3-D Boundary Layer Code	C	NAS3-23716
Coolant Side Heat Transfer with Rotation	C	NAS3-23691
Analytic Flow and Heat Transfer	C	NAS3-24358
Effects of Turbulence on Heat Transfer	G	NAG3-522
Tip Region Heat Transfer	G	NAG3-623
Impingement Cooling	G	NSG3-075
Computation of Turbine Blade Heat Transfer	G	NAG3-579

Notes: A, B — Activities in series

I, II, III — Activities in parallel

Turbine Heat Transfer

Activity	Contract (C), grant (G), or NASA organization (N)	number
Advanced Instrumentation Development	N	2640
Warm Turbine Flow Mapping with Laser Anemometry	N	2620
Real Engine-Type Turbine Aerothermal Testing	N	2640

Structural Analysis

Activity	Contract (C), grant (G), or NASA organization (N)	number
Thermal/Structural Load Transfer Code	C	NAS3-23272
3D Inelastic Analysis Methods - I	C	NAS3-23697
3D Inelastic Analysis Methods - II	C	NAS3-23698
Component Specific Modeling	C	NAS3-23687
Liner Cyclic Life Determination	N	5210
Structural Components Response Program	N	5210
High Temperature Structures Research Laboratory	N	5210
Constitutive Model Development	N	5210
Constitutive Modeling for Isotropic Materials - I	C	NAS3-23925
Constitutive Modeling for Isotropic Materials - II	C	NAS3-23927
Theoretical Constitutive Models for Single Crystal Alloys	G	NAG3-511
Biaxial Constitutive Equation Development for Single Crystals and Directionally Solidified Alloys	G	NAG3-512

Fatigue and Fracture

Activity	Contract (C), grant (G), or NASA organization (N)	number
Creep-Fatigue Life Prediction for Isotropic Materials	C	NAS3-23288
Elevated Temperature Crack Propagation	C	NAS3-23940
Life Prediction and Material Constitutive Behavior for Anisotropic Materials	C	NAS3-23939
Analysis of Fatigue Crack Growth Mechanism	G	NAG3-348
Vitalization of High Temperature Fatigue and Structures Laboratory	N	5220

Surface Protection

Activity	Contract (C), grant (G), or NASA organization (N)	number
Effects of Surface Chemistry on Hot Corrosion	C	NAS3-23926
Thermal Barrier Coating Life Prediction - I	C	NAS3-23943
Thermal Barrier Coating Life Prediction - II	C	NAS3-23944
Thermal Barrier Coating Life Prediction - III	C	NAS3-23945
Airfoil Deposition Model	G	NAG3-201
Mechanical Behavior of Thermal Barrier Coatings	G	NCC3-27
Coating Oxidation/Diffusion Prediction	N	5120
Deposition Model Verification	N	5140
Dual Cycle Attack	N	5120
Rig/Engine Correlation	N	5120
Burner Rig Modernization	N	5160

BROAD IMPACT OF HOST PROJECT

The HOST Project met all the objectives in the NASA long-range aeronautics plan, including

(1) Recognition of the importance of NASA Aeronautics to both civil and military aviation. Ivan Bush stated before his recent retirement from the AFAPL "The Air Force looks to the HOST Project for the technology required in advanced fighters."

(2) Providing the U.S. with improved capability for R&T. State-of-the-art test facilities have been built at Lewis and at certain universities. Lewis has established an international leadership in constitutive modeling of materials behavior under complex thermomechanical loading.

(3) Restoring a balanced aeropropulsion program between performance improvement and durability; that is EEE, ATP, QCSEE Programs versus HOST.

(4) Strengthening the NASA-university partnership in aeronautics R&T. The HOST Project initiated 13 direct grants and approximately 26 indirect grants through industry. Also, Robert Henderson from the AFAPL stated "HOST improved the relationship between the government - NASA and the Air Force - and universities."

(5) Strengthening user interfaces to promote technology transfer. The HOST Project was responsible for 250 technical publications including six NASA Conference Publications, six major workshops and numerous miniworkshops, and dedicated HOST sessions at AIAA and ASME society meetings.

The HOST Project spearheaded a change from the traditional "build 'em and bust 'em" approach to turbine engine development to analytical predictions made <u>before</u> building hardware. These predictions were based on improved and more accurate mathematical models, computer codes, and broad experimental databases. Some results from this change in approach include

(1) Improved durability in advanced hot sections
(2) Reduced development time and costs
(3) More accurate trade-off between performance and durability.

Research supported and focused by HOST improved quantitative accuracy to predict physical behavior of hot section parts under complex cyclic loading. The project efforts

(1) Developed better understanding and modeled more accurately basic physics of durability phenomena;
(2) Emphasized local as well as global conditions and responses;
(3) Accommodated nonlinear and inelastic behavior;
(4) Expanded some models from two to three-dimensions.