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

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SUMMARY

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 were conducted from 1980 to 1987. The project 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.

INTRODUCTION

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.

In 1973 increasing fuel prices 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. In addition, spalling of thermal barrier coatings that protect combustor liners also occurred.

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. As shown by Dennis and Cruse (ref. 1), hot section maintenance costs account for almost 60 percent of the engine total. Widespread concern about such soaring maintenance costs led to a new demand - to improve hot section durability.

Durability can be improved in hot section components by using any combination of the following four approaches. They are the use of (1) materials having higher use temperatures, (2) more effective cooling techniques to reduce material temperatures, (3) advanced structural design concepts to reduce stress, and (4) more accurate analytical models and computer codes in the design analysis process to identify hot spots, high stresses, and so on.

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. Ways for reducing these alloying elements were presented by Stephens (ref. 2). Advanced high-temperature superalloy components also include directionally solidified, single-crystal, and oxide-dispersion-strengthened materials. Development time for new materials 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.

Current cooling techniques tend to be sophisticated, while 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.

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 as discussed by Tanrikut et al. (ref. 3). 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.

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 predicting and 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 an aircraft turbine engine, the repetitive straining of the materials invariably leads to crack initiation and propagation until failure or breakaway occurs. The useful life of a part is usually defined as the number of mission cycles that can be accumulated before initiation and propagation of significant cracks. Thus, designers need to predict useful life accurately so they can design a part to meet requirements.

Efforts to predict the life of a part generally follow the flow of analytical models shown in figure 1. Thus, designing a part such as a turbine blade to meet a specified life goal may require several iterations through the life prediction system of figure 1, varying the blade geometry, material, or cooling effectiveness in each pass, until a satisfactory life goal is predicted.

Fortunately, at the time of demands for improved hot section durability, dramatic increases were occurring in mathematical solution techniques, electronic computer memory, and computer computational speed. The time was ripe for significant improvements in analytical predictive capability.

Analysis models and codes have frequently predicted physical behavior qualitatively but have exhibited unacceptable quantitative accuracy. To improve predictive capability, researchers generally need (1) to understand and model more accurately the basic physics of the phenomena related to durability, (2) to emphasize local as well as global conditions and responses, (3) to accommodate nonlinear and inelastic behavior, and (4) to expand some models from two to three dimensions.

REVIEW OF 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 Lewis Research Center sponsored the Turbine Engine Hot Section Technology (HOST) Project. The project was initiated in October 1980 and completed in late 1987.

Objective

The HOST Project 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 aircraft 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.

Approach

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 quality 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.

Programs

In fulfillment of its objective, the HOST Project initiated and sponsored 70 major research and technology programs. HOST management issued contracts for 40 separate activities with private industry, most of which were multiyear and multiphased. In several activities, more than one contractor was involved because of the nature of the research and each contractor's unique qualifications. Thirteen more separate activities were conducted through grants with universities. Finally, at the NASA Lewis Research Center, 17 major efforts were supported by the project.

TECHNOLOGY TRANSFER

This report summarizes research needs and results for the HOST Project. The HOST Project research activities were usually organized, conducted, and reported along the discipline lines noted above. This report does the same.

Numerous publications provide further details about research results from the HOST Project. Six annual workshops were conducted, with conference proceedings being provided for each one (refs. 4 to 9). Each of the proceedings generally covers research results for the preceding year. The last two proceedings (refs. 8 and 9) also include a bibliography of definitive research reports. A comprehensive bibliography of the HOST Project is given in reference 10, and a comprehensive final review of the HOST Project's research accomplishments and their impact is provided in reference 11.

INSTRUMENTATION

The instrumentation work entailed five programs, covering a combustor viewing system, a dynamic gas temperature system, laser anemometry, heat flux sensors, and high-temperature strain measurement.

Combustor Viewing System

To allow visual diagnoses of abnormal operation of combustors, fuel injectors, liners, and nozzle guide vanes, HOST researchers developed a combustor viewing system that provides qualitative images during component operation. The viewing system consists of a water-cooled optical probe, a probe actuator, an optical interface unit that couples the probe to cameras and to an illumination source, and system controls. This system has been used in both combustor component and full-scale engine tests, for combustor liner durability studies, and for flowpath diagnostics. It has been used to examine light-off and blowout characteristics and appears to have considerable potential for other time-dependent phenomena and for flame radiometry.

Dynamic Gas Temperature System

Prior to HOST, researchers had no techniques to accurately measure fluctuating hot gas temperatures at frequencies above 10 Hz. Through HOST we developed a dynamic gas temperature measurement system and tested it in an F-100 engine facility and a high-pressure component test facility. Accurate gas temperature measurements are now possible up to 1-KHz and 3000 °F peaks. This helps with modeling combustor flows and better defines the environment imposed on turbine airfoils.

Laser Anemometry

The laser anemometer (LA) has become a valuable tool for nonintrusive gas velocity measurements in turbine engine work. Under HOST, we developed technology needed to apply LA to high-temperature turbines. Specific work areas included seeding, data acquisition, system optimization, and optical design.

Seeding. - Seed materials and high-volume seed generators were evaluated in a small combustor facility. We examined various refractory materials dispersed with a fluidized bed and titanium dioxide seed produced by the chemical reaction of titanium tetrachloride and water vapor.

Data acquisition. - Efficient data acquisition requires minimum operator intervention during test runs. To accomplish this, we developed a computer-controlled signal preprocessor for counterprocessors. This preprocessor controls filter settings, photomultiplier tube (PMT) voltage, and radiofrequency (RF) gain, as well as monitoring the PMT current.

System optimization. - A computer model was developed to determine optimal designs for fringe-type LA's. Prediction analysis methods were used to determine optical designs that provide minimum measurement uncertainties for given particle size, proximity to surfaces, and signal processor parameters. Experiments were conducted to measure surface reflectance properties - data needed for system optimization. A study of filter-induced errors was conducted to determine the best filter designs for use with counterprocessors.

Optical design. - The conventional fringe-type LA is not necessarily optimal for measurements within turbomachines. It has the required large acceptance angle, but its relatively large probe volume precludes accurate measurements close to flow passage walls. Under HOST, a unique four-spot time-of-flight LA was developed and tested. The four-spot LA has both a large acceptance angle and the capability to measure close to walls. In testing, we obtained successful measurements as close as 75 μm from a surface normal to the viewing direction. Another optical design project conducted under HOST was the development of an optical corrector for use with the cylindrical windows used in turbine facilities. This corrector eliminates the aberrations caused by the window.

Heat Flux Sensors

Heat flux sensors were developed and tested in both combustor liner and turbine airfoil applications. Tests in combustor liners provided useful heat flux data. However, the sensors proved to be too sensitive to transverse temperature heat flux gradients for most applications to turbine airfoils. This was particularly true for the Gardon gage sensor because of its lack of symmetry. Sensor configurations with lower transverse sensitivity have been considered but not tested.

High-Temperature Strain Measurements

The program's goal was to improve the capability for static strain measurement from the pre-HOST temperature limits of roughly 700 to 1800 °F. This was the most ambitious research effort of HOST's instrumentation subproject. We used three approaches in this work: (1) to develop improved resistance strain gage alloys, (2) to learn how to use available strain gages more effectively, and (3) to evaluate alternative optical strain measuring systems.

Improved strain gage alloys. - Improved strain gage alloys in the FeCrAl and PdCr systems were developed, but neither has been demonstrated as a successful high-temperature strain gage. Work continues on developing wire and thin film strain gages of PdCr.

More effective use of available strain gages. - Evaluation tests of strain gages mainly from the FeCrAl system (including wire gages from China) have provided a better understanding of FeCrAl gage characteristics. As a result, an experiment to measure combustor liner strain in which strain gage cooling rates were carefully controlled to match those used in pre- and post-test calibrations provided useful strain data at temperatures up to 1250 °F.

Alternative strain measuring systems. - Optical systems appear to have potential for high-temperature noncontact strain measurements. One such system, a laser speckle photogrammetric system, was tested and shown to be capable of measuring thermal expansion of a Hastelloy-X plate at temperatures up to 1600 °F. However, problems related to index refraction gradients in the gas within the viewing path must be solved (or at least controlled) to permit this technology to be applied widely.

Thin-Film Sensors

In addition to the work described above, we have been working on technology to put thin-film sensors on turbine engine hot section components. Thin-film thermocouple technology has been developed and such sensors are in use in engine testing. Current work in this area is focused on three goals: basic improvements in sensor processing technology, extension to other sensors such as strain gages and heat flux sensors, and accommodating changes in substrate materials. This work was partially supported by the HOST Project.

COMBUSTION

The HOST Project combustion work emphasized aerothermal modeling. The original plan called for three work phases. During phase 1, researchers assessed existing gas turbine combustion models. They then made suggestions for improving existing models, particularly for numerical accuracy. In phase 2 they improved models for interacting and nonreacting fluid flows. Phase 3 was to improve models for interacting and reacting fluid flows. Phase 3 work was not performed (because HOST Project funding was curtailed), but it is still important work that substantially affects our understanding and the predictive accuracy of combustion fluid flow models.

A separate work element involved dilution jet mixing. This work started before the HOST Project, but was subsequently funded by HOST. While the dilution jet mixing work had an independent existence, it became an integral part of the HOST research environment. This work was less ambitious in scope than the three-phase aerothermal modeling task, but it contributed significantly to the aerothermal phase 1 modeling assessment.

Assess Combustor Aerothermal Modeling - Phase 1

Gas turbine combustor models include submodels of turbulence, chemical kinetics, turbulence/chemistry interaction, spray dynamics, evaporation/combustion radiation, and soot formation/oxidation. During phase 1 model assessment work, three HOST contractors made extensive assessments of numerics, physical submodels, and the suitability of available data. They tested several models: K-E turbulence, algebraic stress and its modifications, scalar transport, and turbulence/chemistry interaction. Their major conclusion was that available computational fluid dynamics codes provided a useful combustor design tool, but the codes were only qualitatively accurate. Further study was needed to improve the numerical scheme and specified experimental data before various emerging physical submodels (for turbulence, chemistry, sprays, turbulence/chemistry interactions, soot formation/oxidation, radiation, and heat transfer) could be properly assessed.

The assessment identified a serious deficiency in numerical accuracy for data on flows, particularly where the false diffusion is of the same order of magnitude as the turbulent diffusion. This masked differences between turbulence models such that very different models gave essentially the same result and sometimes caused undeservedly good agreement between data and predictions.

Improved Spatial Property Variations and Quantitative Accuracy - Phase 2

During the second phase of the aerothermal modeling work, HOST researchers undertook three tasks: improved numerical methods, a flow interaction experiment, and fuel injector/air swirl characterization. We improved the resolution of spatial property variations and quantitative accuracy of aerothermal codes through three-dimensional numerical schemes, improved turbulence and chemistry models, and relevant benchmark data. We concentrated on nonreacting single- and two-phase swirling and nonswirling flows.

Improved numerical methods. - Here we found CONDIF and fluxspline useful. For improved computational efficiency, modifications such as SIMPLER and PISO have proven beneficial.

Flow interaction experiments. - Here researchers (1) studied the interactions between the combustor and diffuser systems and (2) obtained comprehensive mean and turbulence measurements for velocity and species concentration in a three-dimensional flow model of the primary zone of combustion chambers. These experiments were conducted with both air and water multiple-swirler rigs, as well as single swirler and swirling jet rigs. A key feature of this program provided a comparison of model calculations against data obtained, to ensure that data are complete and consistent and that they satisfy the boundary condition input requirements of current three-dimensional codes.

Fuel injector/air swirl characterization. - Here we sought to obtain fully specified mean and turbulence measurements of both gas and droplet phases downstream from a fuel injector and air swirler typical of those used in gas turbine combustion chambers. The flowfield of interest is an axisymmetric particle-laden jet flow with and without confinement and coannular swirling air flow. The comprehensive experimental data generated in these programs will be used to validate advanced models for turbulence, flow, stress, and spray.

Interacting-Reacting Flows - Phase 3

Although just as important as phase 2 aerothermal modeling programs that have led to significant improvements in our technical ability to predict nonreacting gas turbine combustor flow fields, work planned for phase 3 was not performed during the HOST Project. This phase 3 work would have collected fully specified reacting flow data, similar to that being gathered for nonreacting flows. Work should continue on the models for reacting sprays and multidimensional heat transfer.

Dilution Jet Mixing

This recently completed NASA work involved our ability to predict combustor exit temperature profiles (limited previously to jet trajectory analyses). The program provided a broad database and developed an empirical model for mixing diluting air jets with combustion gases. It also let us predict combustor exit temperatures accurately within the database's range.

The dilution jet mixing effort identified key flow parameters, collected data on the effect of varying these characteristics, and developed an empirical flow field model.

Conducted jointly by NASA Lewis and Garrett, this work concentrated on mixing of single-sided and opposed rows of jets in a confined duct flow to include effects of noncircular orifices and double rows of jets. The database was extended to include realistic effects of combustion chamber flow area convergence, nonisothermal mainstream flow, opposed (two-sided) in-line and staggered injection, and orifice geometry. Analysis of the mean temperature data obtained in this investigation showed that the effects of orifice shape and double rows are most significant in the region close to the injection plane.

This dilution jet mixing database is also being used to guide development of three-dimensional numerical codes so they provide broader and more accurate predictive capability. The dilution jet mixing work folded in with aerothermal modeling programs because (1) data was used in aerothermal modeling assessment and (2) the empirical model provides an alternative to numerical modeling for flows within the range of the dilution jet mixing experiments.

TURBINE HEAT TRANSFER

The major goal for the heat transfer program was to improve our basic understanding of the physics of aerothermodynamic phenomena in turbine components. Toward this end researchers gathered data for broad databases and, thus, prepared for future research. The development work was of two types: experimental databases and analytical tools. The experimental databases covered both stationary and rotational work. The experimental work is discussed first.

Local Gas-to-Airfoil Heat Transfer Rates

HOST researchers obtained broad databases and modified the STAN5 code to accurately predict heat transfer coefficients, especially at the transition point, for film- and non-film-cooled airfoils.

Allison researchers did initial work on the stator airfoil heat transfer. They checked the effects of several factors such as Reynolds number, turbulence level, and Mach number on heat transfer coefficients for various airfoil geometries at simulated engine conditions. This research was conducted for non-film-cooled airfoils, showerhead film-cooled designs, and showerhead/gill-region film cooling concepts. They obtained an extensive dataset that systematically shows the important effects of film cooling schemes on modern airfoils. The dataset went beyond the traditional effectiveness correlations to provide actual heat transfer data. It should provide a valuable baseline for emerging analysis codes.

Stanford University conducted a systematic study of the physical phenomena affecting heat transfer in turbine airfoil passages. Experimental research dealt with high free-stream turbulence intensity and large turbulence scale that might be representative of combustor exit phenomena. Their results show that heat transfer augmentation can be as high as 5X at a high value of free-stream turbulence intensity, but only 3X if the length scale is changed. These results suggest that the designer must know a great deal more about the aerodynamic behavior of the flow field in order to predict successfully the thermal performance of the turbine components.

The rotation work divided into concentrations on the gas-side airfoil and the coolant effect within passages.

Airfoil Rotation Effects on Heat Transfer

Scientists at United Technologies Research Center worked on determining the effects of airfoil rotation on heat transfer for the blade. This effort produced single-stage turbine data for both high and low inlet turbulence, one and one-half stage turbine data (focusing on the second vane row), and aerodynamic quantities such as interrow time-averaged and rms value of velocity, flow angle, inlet turbulence, and surface pressure distributions. The results varied depending on location and surface. Work in this area indicates that pressure surface heat transfer still requires more study to explain high heat transfer.

Work in the blade's tip region was done at Arizona State University. The group at ASU experimentally modeled a blade tip cavity region and determined heat transfer rates by a mass transfer analogy with naphthalene. The dataset produced an important new addition to a traditionally neglected area and shows that with carefully designed datasets and analyses researchers can obtain an optimal design for tip cavities.

Coolant Rotation in Smooth-Wall Passages

Pratt & Whitney performed heat transfer experiments in a square passage with two 180° flow turns, with and without turbulators, and with and without rotation. Results for the smooth surface configuration show a strong rotational effect. Pratt also modified the three-dimensional Navier-Stokes TEACH code to predict flow and heat transfer in internal passages and rotation. It is adequate for simple geometric cases; however, it requires revision before application to more complex cases. Results for the turbulated passages also show strong rotational effects and significant differences in augmentation between leading and trailing surfaces.

The other half of the heat transfer subproject concentrated on developing analytical tools for boundary layer analysis and viscous flow analysis.

Three-Dimensional Boundary Layer

In this area HOST work concentrated on improving prediction accuracy for three-dimensional effects on heat transfer. This involved assessing three-dimensional boundary layer codes that were not designed for heat transfer work to determine what revisions were needed to make the code useful in heat transfer efforts.

Contracts were let for two efforts. United Technologies Research Center assessed the applicability of its three-dimensional boundary layer code to calculate heat transfer, total pressure loss, and streamline flow patterns in turbine passages. The results indicate a strong three-dimensional effect on a turbine blade, and they agree qualitatively with experimental data. The same code was modified for use as a two-dimensional unsteady code to analyze the rotor-stator interaction phenomena.

The other boundary layer study at the University of Minnesota addressed numerical turbulence modeling, particularly for turbine airfoils. This work extended modeling to apply to transitional flows for both free stream turbulence and pressure gradients. There was a reasonable improvement in predictive ability. This effort is a good start in establishing a methodology for moving away from heavy dependence on empirical constants.

Analytic Flow and Heat Transfer Modeling

Scientific Research Associates (SRA) worked on a fully elliptic, three-dimensional Navier-Stokes code. This group modified the code to handle turbine applications. Comparisons of predictions with analytical experimental data are good when researchers can specify location for the boundary layer transition. Ideally, the code would allow researchers to handle various locations. In this respect, work still remains on improving turbulence and transition modeling.

STRUCTURAL ANALYSIS

Under this heading, there are six major thrusts, involving an interface code between heat transfer and structural analysis, three-dimensional inelastic codes, constitutive models, component-specific modeling, liner cyclic life testing, and substantiated design analysis methods and codes.

Heat Transfer/Structural Analysis Interface Code

With HOST support, General Electric researchers developed an interface code, called TRANSITS, that transfers up to three-dimensional thermal information automatically from heat transfer codes (that generally use coarse finite element grids) to structural analysis codes (that use finer grids). Key features include independent heat transfer and stress model meshes, accurate transfer of thermal data, computationally efficient transfer, steady-state and transient data, user friendly program, flexible system, internal coordinate transformations, automated exterior surfacing techniques, and geometrical and temporal windowing.

Three-Dimensional Inelastic Codes

HOST provided development of three-dimensional inelastic structural analysis codes, involving two contractors, for nonlinear behavior at high thermomechanical loads. At Pratt & Whitney, three developed codes covered different approaches and degrees of complexity: MOMM, MHOST, and BEST3D. These codes provide a tenfold increase in computational efficiency - with improved accuracy. They embody a progression of mathematical models for increasingly comprehensive representation of the geometrical features, loading conditions, and forms of nonlinear material response. MOMM, a mechanics of materials model, is a stiffness method finite element code that uses one-, two-, and three-dimensional arrays of beam elements to simulate hot section component behavior. MHOST employs both shell and solid (brick) elements in a mixed method framework to provide comprehensive capabilities for investigating local (stress/strain) and global (vibration, buckling) behavior of hot section components. BEST3D is a general purpose, three-dimensional, structural analysis program using the boundary element method.

General Electric, the second contractor on the inelastic work, also developed a code that performs three-dimensional, inelastic structural analysis. The objective of this program was to develop analytical methods for evaluating the cyclic time-dependent inelasticity that arises in hot section engine components. Because of the large excursions in temperature associated with hot section engine components, the techniques developed must be able to accommodate large variations in material behavior including plasticity and creep. To meet this objective, General Electric developed a matrix consisting of three constitutive models and three element formulations. A separate program for each combination of constitutive model/element model was written, making a total of nine programs. Each program can stand alone in performing cyclic nonlinear analysis.

The three constitutive models assume distinct forms: a simplified theory (simple model), a classical theory, and a unified theory. The 3-element formulations used an 8-node isoparametric shell element, a 9-node shell element, and a 20-node isoparametric solid element.

For linear structural analysis, the nine codes use a blocked-column skyline, out-of-core equation solver. To analyze structures with nonlinear material behavior, the codes use an initial stress interactive scheme. This code contains a major advance in our ability to handle a dynamic time incrementing strategy.

Constitutive Models

Before HOST, there was no capability to perform combined elastic-plastic creep structural analyses. There were limited high-temperature databases for constitutive model formulations and verifications. Through the HOST Project, researchers developed viscoplastic constitutive models for both isotropic and anisotropic materials, broadened the database capability, and verified models for a range of test conditions. These efforts led to a 30-percent improvement in high-temperature stress-strain prediction. These factors combined to make Lewis an internationally recognized leader in constitutive model development.

Isotropic material modeling. - In efforts aimed at isotropic material modeling, theorists from three organizations provided new models. The first organization, Southwest Research Institute, developed two existing models (Walker and Bodner-Partom) of the unified type for application to isotropic, cast, nickel-base alloys used for air-cooled turbine blades and vanes. Both models demonstrated good correlation with experimental results for two PWA alloys, B1900+Hf and MAR-M247. The program also demonstrated rather conclusively that the unified constitutive model concept is a powerful tool for predicting material response in hot section components under complex, time-varying thermomechanical loadings. At General Electric, researchers evaluated several viscoplastic constitutive theories against a large uniaxial and multi-axial database on René 80 material, which is a cast nickel-base alloy used in turbine blade and vane applications. No available approach for modeling the high-temperature, time-dependent behavior of René 80 was satisfactory, so GE developed a new theory that predicts with good accuracy the 90° out-of-phase tension-torsion experimental results at elevated temperatures. Finally, at a third organization, the University of Akron, researchers developed a time-dependent description potential function based on constitutive theory with stress dependence on J2 and J3 integrals that reduces to a J2 theory as a special case.

Anisotropic material modeling. - Modeling of anisotropic material also had three groups involved, all universities. Turbine manufacturers have been developing nickel-base monocrystal superalloys for years. University of Connecticut theorists successfully modeled the deformation behavior of these materials by using both a macroscopic constitutive model and a micromechanical formulation based on crystallographic slip theory. The University of Cincinnati developed a model for nickel-base single-crystal alloy René N4 using a crystallographic approach. The current equations modified a previous model proposed by Dame and Stouffer, where a Bodner-Partom equation with only the drag stress was used to account for the local inelastic response in each slip system. The University of Akron developed a continuum theory for representing the high-temperature, time-dependent, hereditary deformation behavior of metal composites that can be idealized as pseudohomogeneous continua with locally definable directional characterizations.

Component-Specific Modeling

HOST allowed us to develop a modular code for nonlinear structural analyses that predicts temperatures, deformation, and stress and strain histories. It also gave us an automatic solution strategy for liners, with similar strategies underway for blades and vanes. The package contains five modular elements that are linked by an executive module. The thermodynamic engine model (TDEM) translates a list of mission flight points and time differences into time profiles of major engine performance parameters. The thermodynamic loads model (TDLM) works with the output of the TDEM to produce the mission cycle loading on the individual hot section components. The component specific structural modeling module provides a generic geometry pattern for each component. General Electric also created a software recipe that contains default values for point coordinates, lengths, thicknesses, angles, and radii. Users may modify specific values, but the software has saved them the effort of identifying basic geometry and parameters. Once a researcher defines specific values, the software develops a finite element model of this geometry consisting of 20-noded isoparametric elements. The fourth subsystem performs incremental nonlinear finite element analysis on complex three-dimensional structures under cyclic thermomechanical loading with temperature-dependent material properties and material response behavior. A major advance in the ability to perform time-dependent analyses is a dynamic time incrementing strategy incorporated in this software. The fifth element, COSMO, is an executive module that controls the whole system.

Liner Cyclic Life Testing

Through a cooperative effort, Pratt & Whitney and NASA Lewis Research Center developed a unique vehicle to obtain cyclic thermal and mechanical test data under realistic but controlled test conditions by using annular combustor hardware. Pratt & Whitney provided the test rig, while Lewis supplied the test facility, integrated the rig into the facility, conducted tests, and analyzed the data. The program initially tested a conventional liner of sheet metal, seam welded louver construction from Hastelloy-X material. Later, the program tested an advanced segmented liner made from materials developed by Pratt & Whitney. The tests radiantly heated segments (cylindrical sections) of turbine engine combustor liners. Quartz lamps provided cyclical heating of the test liners. This caused axial and circumferential temperature variations as well as through-the-wall temperature gradients in the test liner. The thermally induced stresses and strains were similar to those of in-service liners. A typical engine mission cycle (i.e., takeoff, cruise, landing, and taxi) of 3 to 4 hr was simulated in 2 to 3 min. On the basis of nonlinear structural analyses of the two liners, researchers determined that the critical stress-strain location in the conventional liner was at the seam weld. For the advanced liner, it was at the retention loop. For the same heat flux, the advanced liner will have a much longer life than the conventional liner, because it has a lower operational temperature (440 °F) and has no structural or hoop constraint in the circumferential direction. The predicted life is greater than one million cycles. There is good agreement between predicted life and measured life.

Substantiated Design Analysis Methods and Codes

An important goal in the structural analysis discipline was concerned with developing user confidence in the models and codes discussed earlier in this section. Confidence comes with experimental validation. HOST allowed scientists to validate many technologies: time-varying thermomechanical load models, component-specific automated geometric modeling and solution strategy capabilities, advanced inelastic analysis methods, inelastic constitutive models, high-temperature experimental techniques and experiments, and nonlinear structural analysis codes. Under HOST, test facilities were upgraded, and codes in two major areas were developed. We also conducted experiments to calibrate and validate the codes. Unique high-temperature cyclic thermomechanical tests on tubular and solid bar specimens were conducted in upgraded structures test laboratories at the Lewis Research Center. Categories for validation activities included (1) new types of multiaxial viscoplastic constitutive models for high-temperature isotropic and anisotropic superalloys and metal matrix composites (2) nonlinear structural analysis methods and codes and (3) uniaxial and multiaxial thermomechanical databases for René N4, René 80, Hastelloy-X, MAR-M247, B1900+Hf, PWA 1480, and Haynes 188.

FATIGUE AND FRACTURE

Prior to HOST work in fatigue and fracture, we had no confidence in life predictions involving complex loading conditions, multiaxial stress states, or thermomechanical loading conditions until components had service experience. Now we have far more confidence in constitutive equations and life models for advanced configurations and materials under complex, multiaxial, and thermomechanical loading circumstances. Five major accomplishments are summarized in the following paragraphs.

Crack-Initiation Life-Prediction Methods

This is the first major fatigue-fracture work element. Two new crack-initiation, life-prediction methods have been developed for application to complex creep-fatigue loading of nominally isotropic superalloys at high temperatures (at Pratt & Whitney and at Lewis). The Pratt work led to a new method, called cyclic damage accumulation (CDA), for predicting high-temperature fatigue life. Under the Lewis program, the strainrange partitioning (SRP) method was advanced to allow researchers to express the approach in terms of total strain range versus cyclic life.

Cyclic Constitutive Models - Protective Coatings and Single-Crystal Alloys

HOST efforts in this second fatigue-fracture concern developed and verified cyclic constitutive models for oxidation protective coatings and for highly anisotropic single-crystal turbine blade alloys. Pratt & Whitney formulated a viscoplastic constitutive model for two fundamentally different coating types: a plasma-sprayed NiCoCrAIY overlay coating and a pack-cementation-applied NiAl diffusion coating. Pratt & Whitney also developed a unified constitutive model for PWA 1480 single-crystal material; it is in the final development stages.

Preliminary Cyclic Crack-Initiation Life-Prediction Model

Pratt & Whitney is also the contractor proposing a model for a preliminary cyclic crack-initiation life-prediction model. It is being evaluated. The model utilizes tensile hysteretic energy and frequency as primary variables.

Two High-Temperature, Cyclic Crack-Growth Life-Prediction Models

Two models have been proposed for the fourth fatigue and fracture work element. Micromechanistic and phenomenological engineering approaches have been taken. The micromechanistic approach, being developed by University of Syracuse scientists, is based on oxidation interactions with mechanical deformation at the crack tip. The engineering approach, at General Electric, has its origins in the path-independent integrals approach, which describes the necessary fracture mechanics parameters.

High-Temperature Fatigue and Structures Laboratory

Lewis Research Center created an advanced high-temperature fatigue and structures research laboratory. Test facilities have been significantly upgraded to allow uniaxial, high cycle/low cycle, and axial torsional fatigue research. Additionally, the laboratory contains a powerful computer facility that is among the best in the world for this kind of effort.

The uniaxial test facility now includes 12 load frame systems. The original eight frames are rated for ±20 000 lb. Lewis added two more frames rated at ±20 000 lb and two at ±50 000 lb. Commercially available servocontrollers control each test system. The test facility provides both diametral and axial extensometers. Computer enhancements have had a major impact on the lab's uniaxial capabilities because each uniaxial system has its own minicomputer for experimental control and data acquisition. To further aid in simulating operating conditions, two machines allow tests to be conducted under two closely controlled environmental conditions, high temperature and vacuum.

To improve our understanding of cumulative cyclic loadings, Lewis bolstered its facility in this area as well. A new system produces arbitrary load or deformation histories corresponding to fatigue lives up to 10 million in less than 10 hr, using state-of-the-art servohydraulic materials test systems.

The third type of test enhancement relates to multiaxial stress. The load frames for each test system are rated for loads of ±50 000 lb axial and

±25 000 in.-lb torsional. These systems allow tests involving rapid thermal transients. A number of experimental projects are currently underway. Thus far the testing has been biaxial; eventually it will be triaxial.

The high-temperature fatigue and structures lab computer offers a versatile system, with a Data General Eclipse MV/4000 connected with 14 satellite computers in a multiprocessor class of computing configuration. This configuration also introduced the first validated ADA language compiler within NASA.

SURFACE PROTECTION

The surface protection subproject involved two programs: thermal barrier coating (TBC) life prediction and an airfoil deposition process/deposition model.

TBC Life Prediction

HOST provided pioneering research on thermal barrier coatings (TBC) involving three approaches to TBC life-prediction modeling. Lewis Research Center, Pratt & Whitney, Garrett, and General Electric worked on this modeling effort. The state-of-the-art coating system consists of about 0.25 mm of zirconia-yttria ceramic over 0.13 mm of an MCrAlY alloy bond coat. Both layers are applied by plasma spraying onto a structural base material. Benefits arise from thermal insulation of the structure that is provided by the ceramic layer.

Following an in-house model development program, Lewis awarded contracts (1) to determine thermomechanical properties, (2) to analyze coating stresses and strains, and (3) to develop life models for thermal barrier coatings.

Thermomechanical properties. - The effort to determine thermomechanical properties achieved general agreement that (1) these coatings fail primarily because of stresses induced by the thermal expansion mismatch between ceramic and metallic base layers and that (2) these stresses are greatly influenced by time-at-temperature processes - oxidation and possibly sintering.

Coating stresses and strains. - Next, researchers developed a laboratory model. This model represented a first step, but it was not in a form useful to engine designers.

Life models. - The model developed by Pratt & Whitney and its subcontractor, Southwest Research, is a fatigue-based coating life model. The model is accurate to plus or minus a factor of three, which is acceptable. The Garrett model considers bond coat oxidation, zirconia toughness reduction, and damage due to molten salt deposits. This model analyzes thermal data for specific elements in terms of mission. The General Electric model employs time-dependent, nonlinear, finite element modeling of stresses and strains present in the thermal barrier coating system, followed by correlation of these stresses and strains with test lives. This model was the only one to check failure induced by edges and, hence, the only one to consider shear strain.

Airfoil Deposition Process/Model

This activity raised fundamental questions about hot corrosion of blades and about deposition of corrosive salts. Scientists needed to identify what corrosive species and deposits were accumulating, how deposits reached the blade, and then what effect they had on the surface protection. Through HOST, researchers identified the corrosive as sodium sulfate, but they also learned from process studies that prior to reaching the blade it was not yet sodium sulfate (it was sodium carriers, sulfate carriers, etc.). People had been performing static studies, but research results in this area indicated that dynamic studies were needed. The reason was that in real-life situations the sodium sulfate supply continually accumulates and then, because of heat, becomes molten, creating a film that flows on the blade surface. The result is that salt deposition and flow rates are variable, prompting the need for a deposition model.

The deposition model that Lewis researchers developed assumes that the sodium-sulfate dissolution rate correlates with corrosion rate. This was the first attempt to correlate the process - initial corrosive species diffusing, moving, depositing, forming, filming, dissolving metal, and starting the corrosive effect. Researchers completed the model; however, funding limitations prevented validation experiments. This model is a significant step toward reality - modeling a real-life, dynamic environment.

CONCLUSIONS

The HOST Project activities encompassed researchers from industry, academia, and government. For a variety of reasons, it drew high-caliber people, including outstanding experts in each discipline. This was perhaps due to the project's difficult technical challenges, its size, and its visibility.

We could have addressed durability issues via several approaches: higher temperature materials, more effective cooling techniques, advanced structural design concepts, and improved design analysis tools. The last option attracted us because of the potential gains given the current breakthoughs in computer hardware technology and software development techniques.

To better understand the physics involved in the development of these design analysis tools for combustors and turbines, researchers developed high-quality experiments. Early project plans called for significant testing in the new High Pressure Facility at NASA Lewis Research Center. Unfortunately, technical problems limited testing to less than full test facility capability. Soon afterwards, Lewis moved away from component testing, with the facility being "mothballed" early in 1986. This change significantly affected HOST, because it greatly reduced model/code verification testing and the use of HOST-developed instrumentation in hot section research.

Most HOST research results were generic. They were applied to both large and small turbine engines. In addition, certain codes were used outside the HOST Project for durability improvements in the space shuttle main engine and for design analysis in an advanced communications technology satellite. There are, however, unique durability challenges in small turbine engines that the

HOST Project could not address because of funding constraints. These challenges include higher turbine blade attachment stresses, faster thermal transients, and different materials. Such challenges in today's small engines are believed to be the challenges in tomorrow's large engines.

Experience has shown that, in general, acceptance of new design analysis tools comes slowly. In some cases this has been true with HOST. Generally, users accept the new tools more quickly during a crisis involving, for example, in-service engine problems.

While a return on the investment in HOST has already been realized, additional returns will become visible as analysts use HOST codes more and as they incorporate these codes within new design analysis systems that are applicable to high-temperature composite and structural ceramic materials, which the HOST Project did not address.

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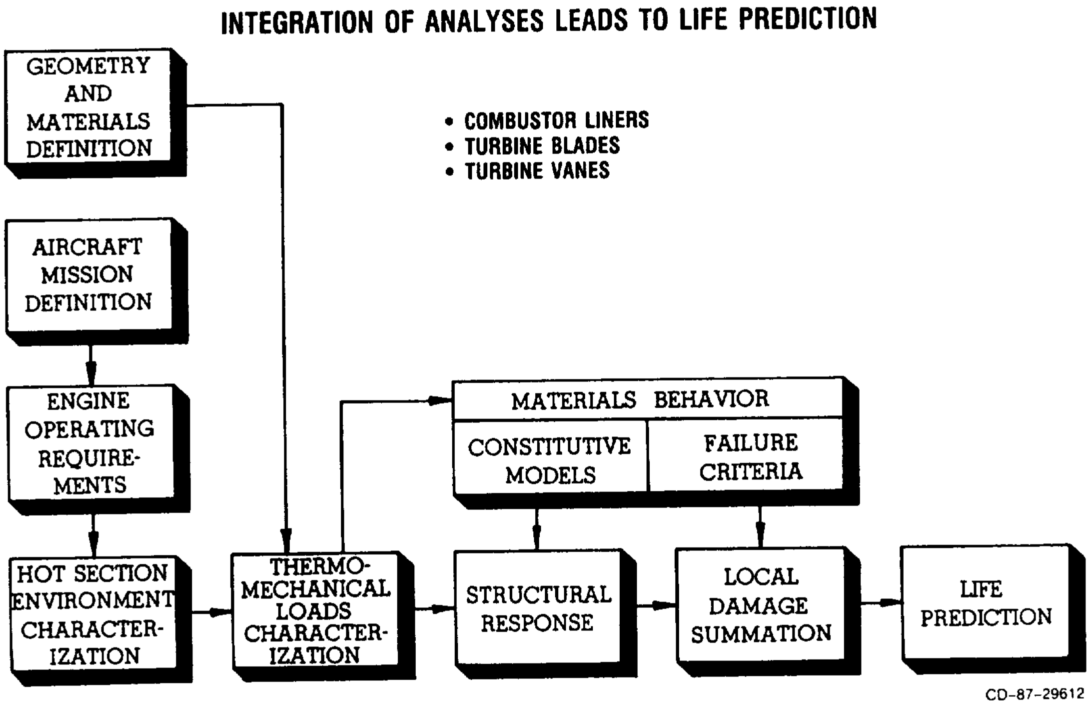

Figure 1. - Framework for HOST Project.