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LIFE PREDICTION TECHNOLOGIES FOR AERONAUTICAL PROPULSION SYSTEMS

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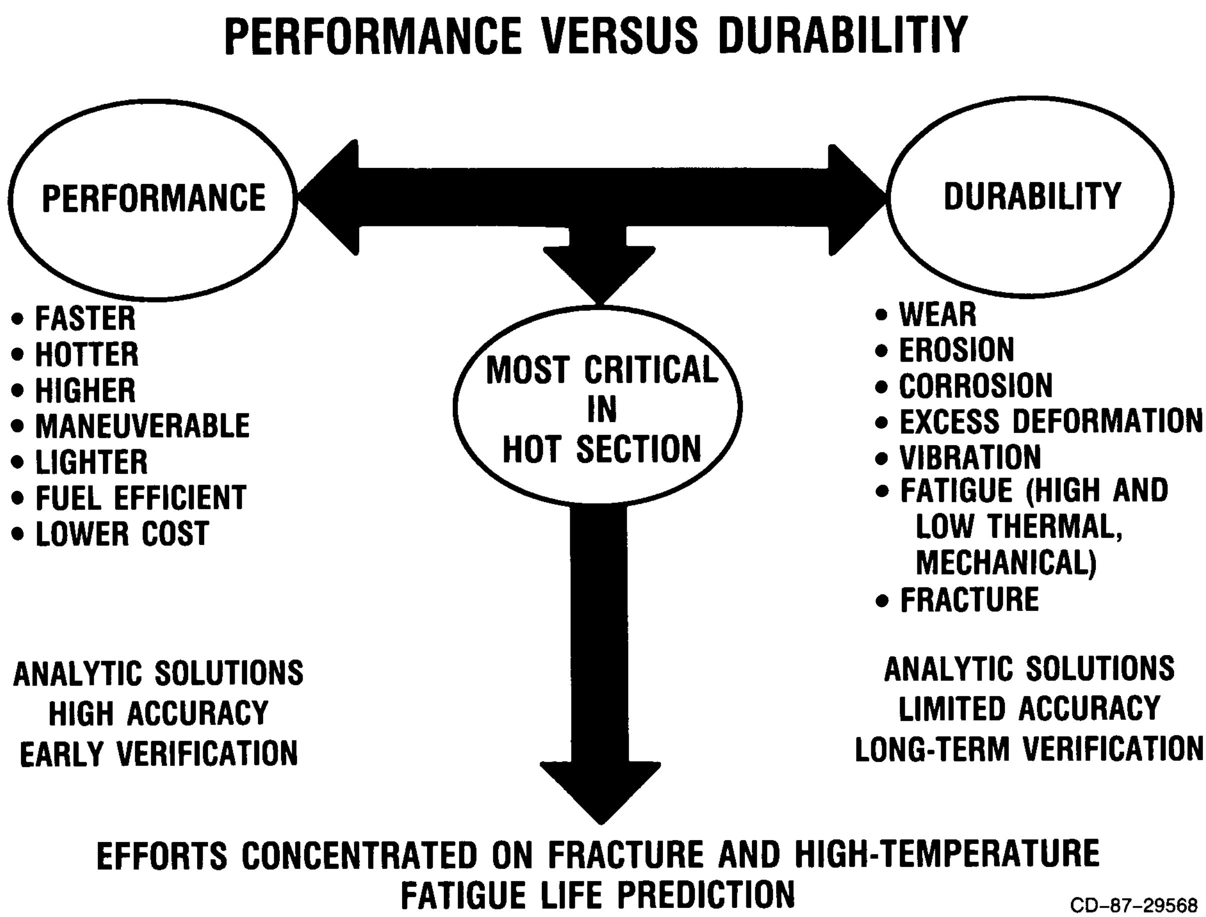
ABSTRACT

Fatigue and fracture problems continue to occur in aeronautical gas turbine engines. Components whose useful life is limited by these failure modes include turbine hot-section blades, vanes, and disks. Safety considerations dictate that catastrophic failures be avoided, while economic considerations dictate that noncatastrophic failures occur as infrequently as possible. The decision in design is therefore making the tradeoff between engine performance and durability. The NASA Lewis Research Center has contributed to the aeropropulsion industry in the area of life prediction technology for over 30 years, developing creep and fatigue life prediction methodologies for hot-section materials. At the present time, emphasis is being placed on the development of methods capable of handling both thermal and mechanical fatigue under severe environments. Recent accomplishments include the development of more accurate creep-fatigue life prediction methods such as the total strain version of Lewis' Strainrange Partitioning (SRP) and the HOST-developed Cyclic Damage Accumulation (CDA) model. Other examples include the development of a more accurate cumulative fatigue damage rule - the Double Damage Curve Approach (DDCA), which provides greatly improved accuracy in comparison with usual cumulative fatigue design rules. Other accomplishments in the area of high-temperature fatigue crack growth may also be mentioned. Finally, we are looking to the future and are beginning to do research on the advanced methods which will be required for development of advanced materials and propulsion systems over the next 10 to 20 years.

PERFORMANCE VERSUS DURABILITY

Fatigue and fracture problems continue to occur throughout aeronautical gas turbine engines. Safety considerations dictate that life-threatening catastrophic failures be avoided, and economic considerations dictate that noncatastrophic failures occur as infrequently as possible. The failure rate, however, can be related directly to the performance extracted from the machine. We thus have the perennial dichotomy: performance versus durability. Because the primary driver for aeropropulsion is performance, we must view lack of adequate durability as a constraint to the desired performance. Knowledge of both aspects is necessary to understand and quantify the tradeoffs between the two. Performance may take a variety of forms, some of which are listed in the figure. Similarly, various failure modes are noted which give rise to the overall durability. Nowhere is the tradeoff more critical than in the hot section, where all of the failure modes are present in varying degrees.



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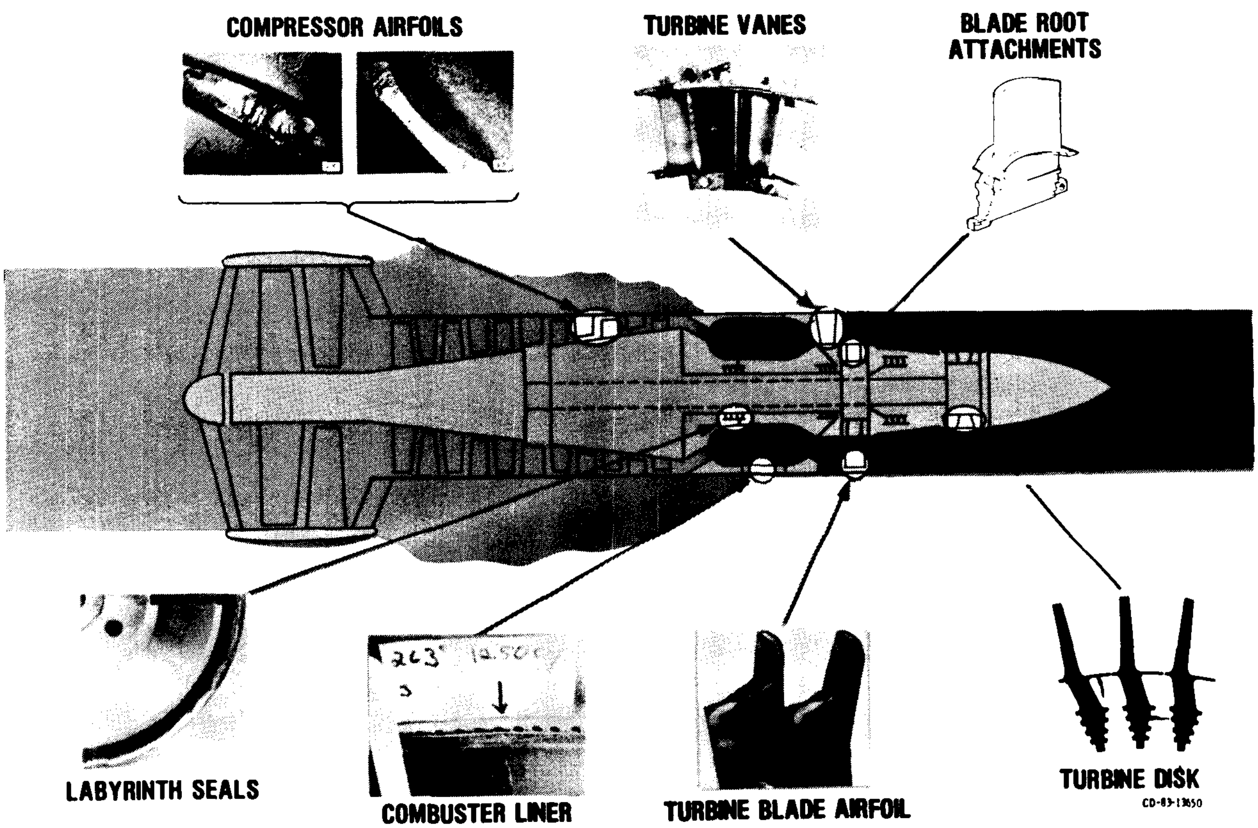
GAS TURBINE FATIGUE AND FRACTURE PROBLEM AREAS

This figure illustrates typical components that have exhibited histories of limited durability. Compressor blades, combustor liners, guide vanes, turbine blades, disks, shafts, bearings, and spacers are just a few of the more common components that have exhibited cyclic crack initiation, propagation, and fracture phenomena. These failure phenomena arise because of repeated thermal and/or mechanical loading induced by the service cycle.

GAS TURBINE FATIGUE AND FRACTURE PROBLEM AREAS



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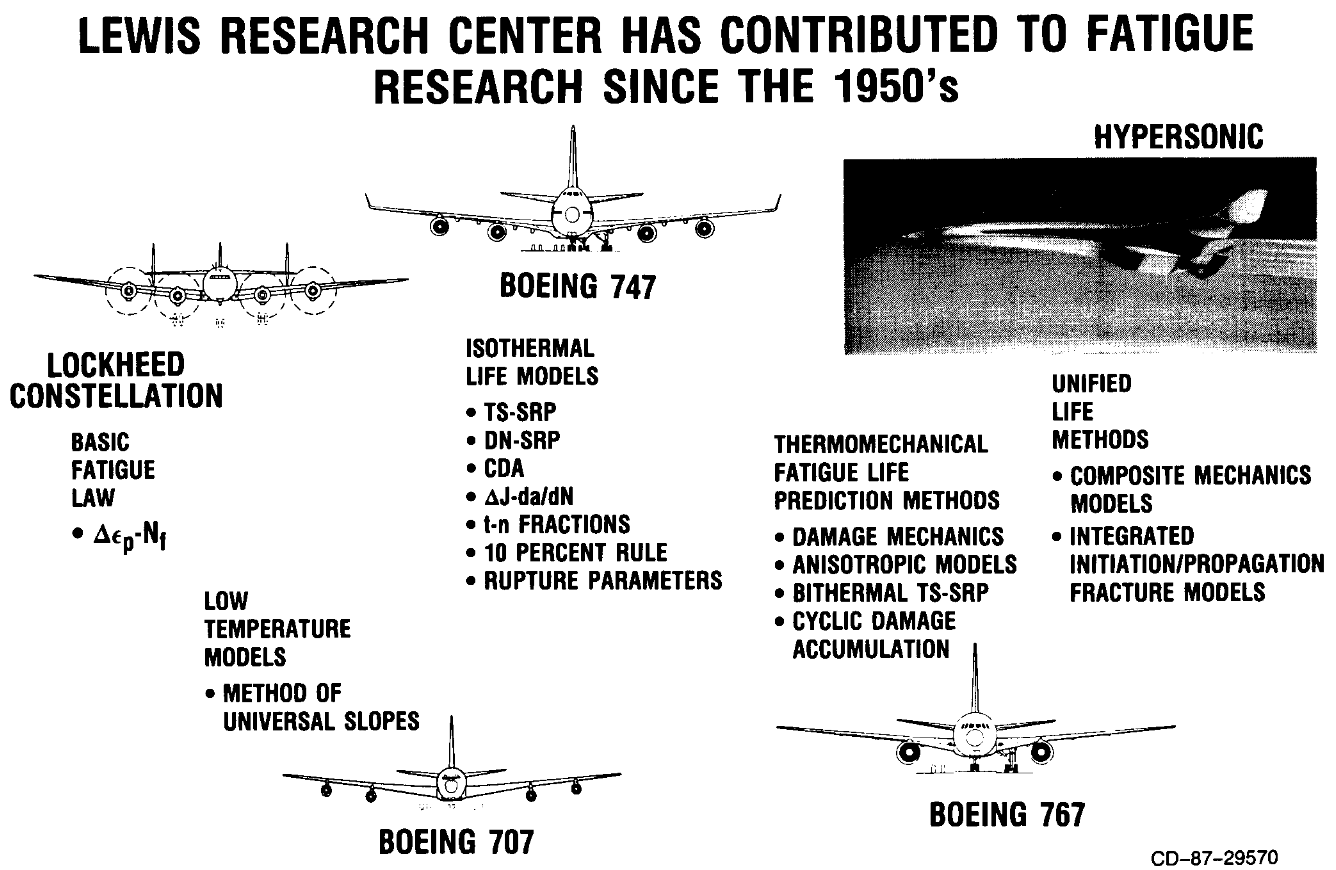
LEWIS RESEARCH CENTER CONTRIBUTIONS

At the Lewis Research Center, we have aided the aeropropulsion industry by concentrating on developing fracture and elevated-temperature fatigue life prediction methods. As aeropropulsion became more sophisticated and advanced materials were developed, we increased our level of intensity and degree of sophistication in life prediction modeling. At the present time, emphasis is placed on methods capable of dealing with both thermal and mechanical fatigue under severe environments. The methods listed in the heavy-lined box are the ones we are currently pursuing, and as such, they are too new to have been used in hardware. We are also looking to the needs of the future and are beginning to do research on the advanced methods that will be required of advanced materials and propulsion systems over the next 10 to 20 years.



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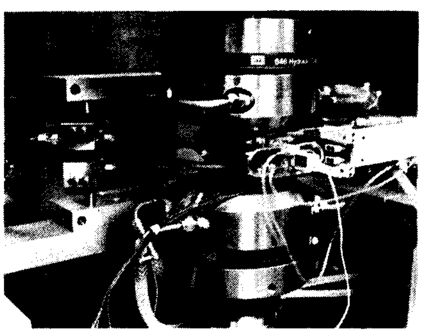
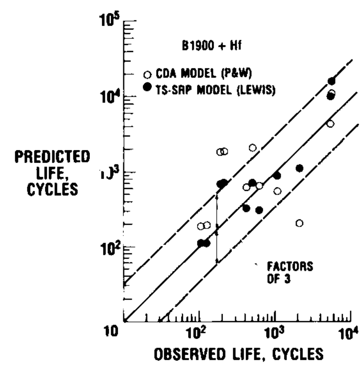
HIGH-TEMPERATURE FATIGUE CRACK INITIATION

In this figure, we compare the predictive accuracy of two relatively recent (1983, 1984) isothermal life prediction methods for fatigue crack initiation (0.030-in.-length surface crack): the HOST Cyclic Damage Accumulation (CDA) model developed by Pratt & Whitney under contract to Lewis, and the total strain version of Lewis' Strainrange Partitioning (TS-SRP). Note the rather sizeable factors of ±3 in our inability to predict the high-temperature, low-cycle fatigue lives of coupons of a cast nickel-base turbine alloy. Factors of safety of nearly an order of magnitude on average life would have to be applied if these methods were to be used in a design situation. While this appears to be a very large factor, it is considerably less than would be required by alternate methods.

HIGH-TEMPERATURE FATIGUE CRACK INITIATION



ISOTHERMAL VERIFICATION



CYCLIC DAMAGE ACCUMULATION (CDA) MODEL INSET

$$\dot{\epsilon}_{Pnet} - \left[\int_0^N \frac{dD}{dN}\right]_{Ref} \times \left\{ \left(\frac{\sigma_t}{\sigma_{t_{Ref}}}\right)\left(\frac{\Delta\sigma}{\Delta\sigma_{Ref}}\right) + \left[\left(\frac{\Delta\sigma_{Ref}}{\Delta\sigma}\right)\left(\frac{\sigma_t}{\sigma_{t_{Ref}}}\right)\right]^{B'} \times \left[\left(\frac{t}{t_{Ref}}\right)^{C'} - 1\right]\right\} dN = 0$$

TOTAL STRAIN, STRAINRANGE PARTITIONING (TS-SRP)

$$\Delta\epsilon = C'\left[K_{ij}\, N_f^{\,b} + N_f^{\,c}\right]$$

$$C' = \left[\Sigma\, F_{ij}(C_{ij})^{1/c}\right]^{c}$$

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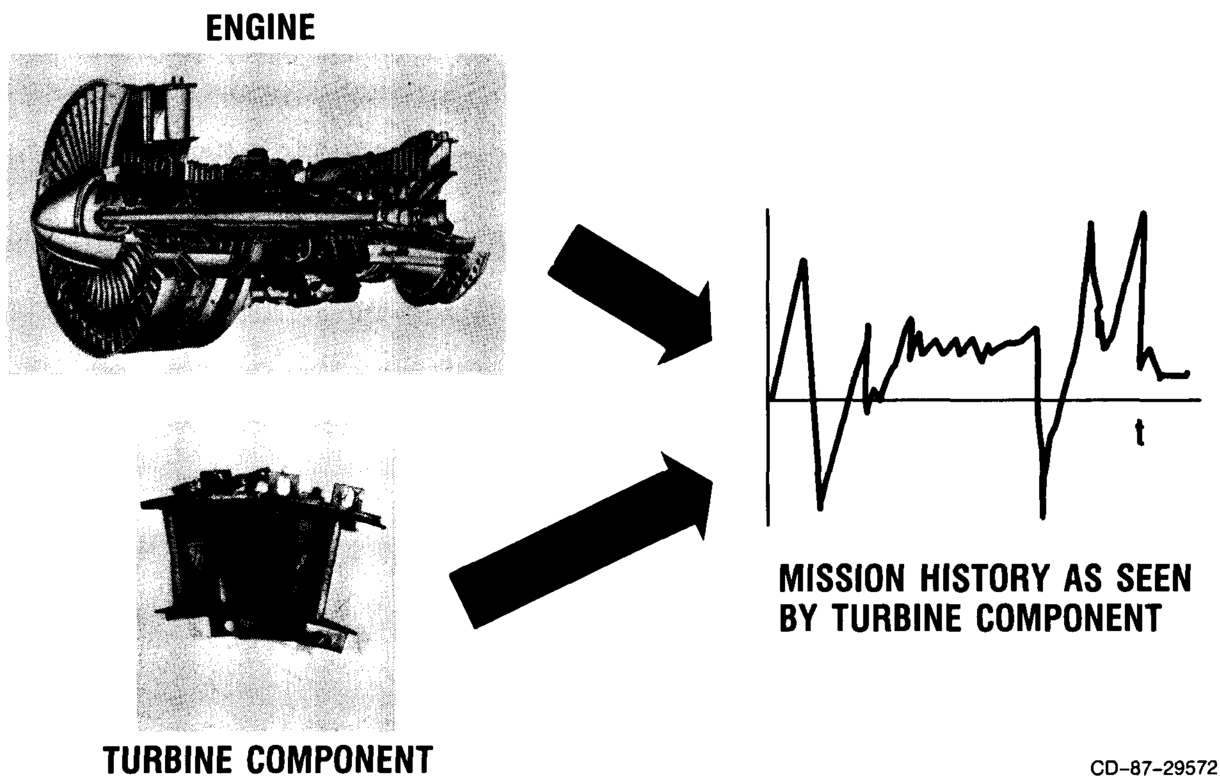
COMPLEX COMPONENT LOADING HISTORIES

Mission profiles resolve into complex thermal and mechanical loading histories on many components. Components whose lives are limited as a result undergo creep and fatigue in varying and interacting degrees, which eventually lead to failure. One such typical component is a hot-section turbine blade. In this figure we see the mechanical load history induced by the mission cycle as seen from the life-limiting, or critical, location of the turbine blade.

MISSION HISTORY PRODUCES COMPLEX COMPONENT LOADING HISTORIES



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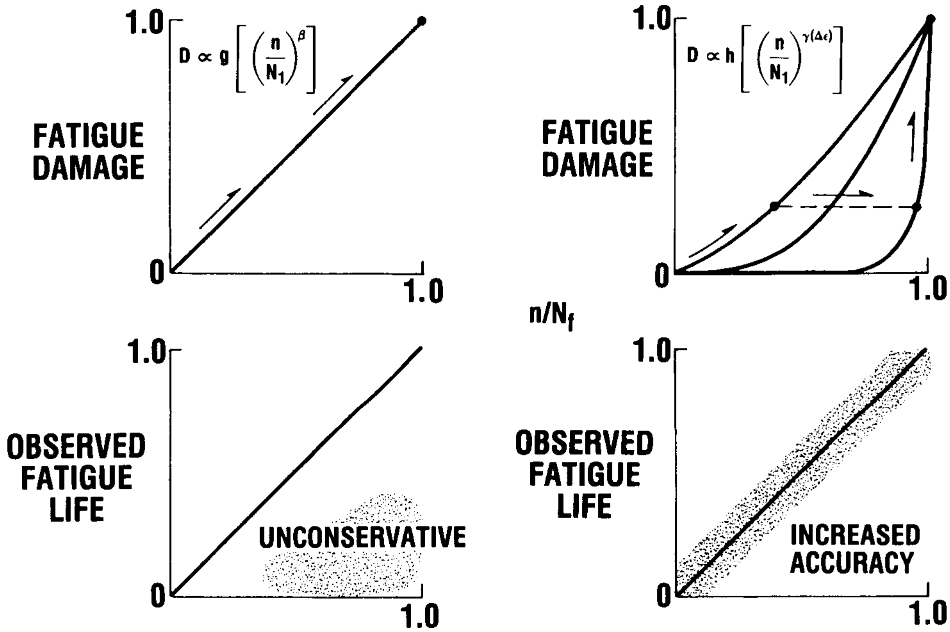
A MORE ACCURATE CUMULATIVE FATIGUE DAMAGE RULE

When considering the life of components subjected to complex mechanical loading histories, it is common to use a fatigue crack initiation life criterion in conjunction with a suitable damage accumulation expression. Traditionally, the damage accumulation expression used is the classical Linear Damage Rule. While this rule simplifies life prediction calculations, it can often result in unconservative designs, especially under certain loading conditions. An advancement in increasing the accuracy of life predictions by using a nonlinear damage accumulation rule was made at Lewis recently. This new expression, called the Double Damage Curve Approach, accounts for loading level dependence in damage evolution. The resulting increase in predictive accuracy is substantial, as much as nearly an order of magnitude improvement over the Linear Damage Rule.

LEWIS NONLINEAR DAMAGE ACCUMULATION THEORIES ACCURATELY MODEL CUMULATIVE FATIGUE



(a) LINEAR DAMAGE ACCUMULATION (b) NONLINEAR DAMAGE ACCUMULATION

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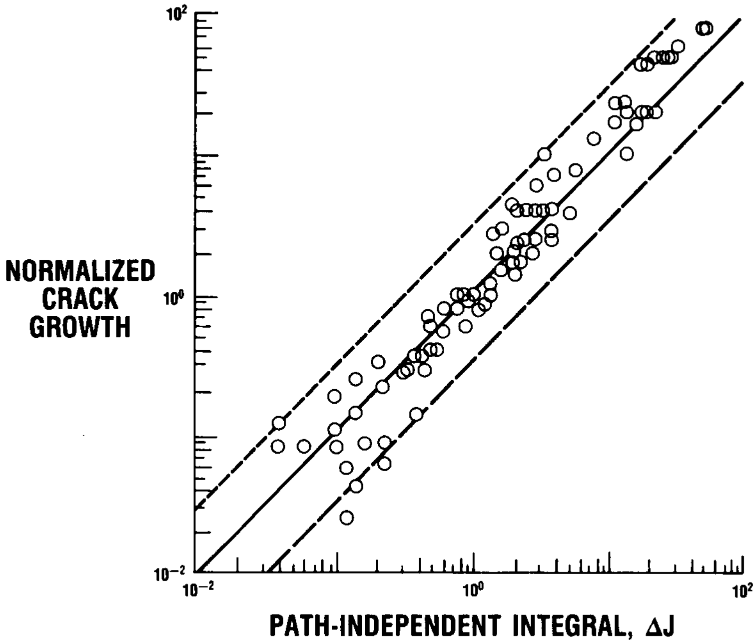
HIGH-TEMPERATURE FATIGUE CRACK PROPAGATION MODEL

High and low-temperature cyclic crack propagation life predictions based upon the concepts of path-independent integrals and crack tip oxidation mechanisms are shown for turbine alloys. This life prediction method is the result of several years of research conducted by H.W. Liu of Syracuse University under the HOST sponsorship of NASA Lewis. Note again the rather sizeable scatter of factors of three on crack propagation rate even for well-controlled laboratory coupon tests.

ISOTHERMAL FATIGUE CRACK PROPAGATION MODEL

ΔJ PARAMETER FOR LOW TEMPERATURE
OXIDATION MODEL FOR HIGH TEMPERATURE



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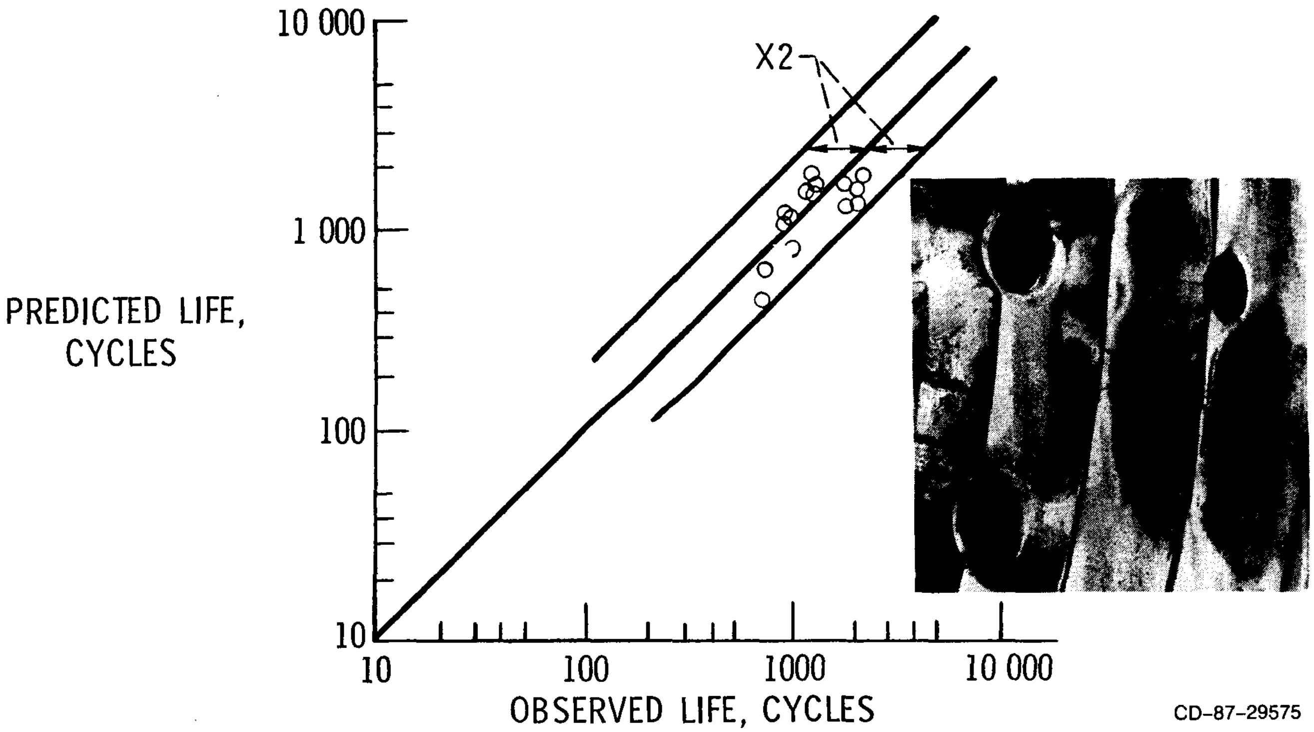
COMBUSTOR LINER STRUCTURAL AND LIFE ANALYSIS

An application of the Lewis-originated creep-fatigue life prediction method, Strainrange Partitioning (for crack initiation), is shown in this figure. Pratt & Whitney modified the approach to suit their unique requirements and used the method in the design and evaluation of combustor liners in the JT9D high-bypass-ratio engine. Factors of about ±2 in cyclic lifetime are noted by the upper and lower bound lines. This remarkable good accuracy is obtained, in part, by the manner in which the Pratt & Whitney version of the method is calibrated to the failure behavior of real hardware. The variation in predicted lives results from different engine usage which can be accommodated by the predictive method.

ACCURACY OF PRATT & WHITNEY'S VERSION OF DUCTILITY NORMALIZED STRAINRANGE PARTITIONING IN PREDICTING COMBUSTOR LINER LIFE IN HIGH-BYPASS-RATIO ENGINES



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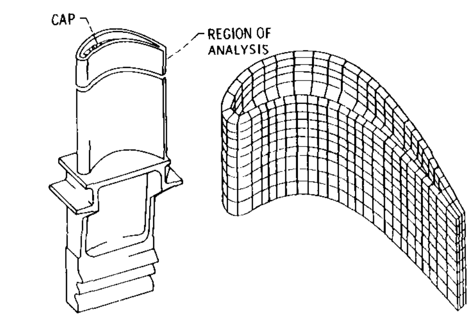
TURBINE BLADE STRUCTURAL AND LIFE ANALYSIS

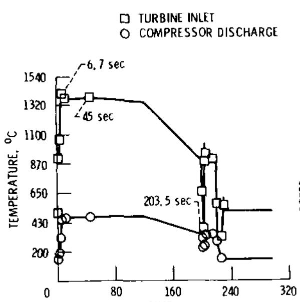
In another application of the Lewis-originated creep-fatigue life prediction method, Strainrange Partitioning, the General Electric Company analyzed an air-cooled turbine blade, making an assessment of expected service life. This particular blade, a first-stage, high-pressure turbine blade, is subjected to cyclic thermal straining in the tip cap region because of the service history involved. After conducting a thermal analysis and a nonlinear structural analysis of the cap region, an assessment of component life was performed. The analysis was supplemented by laboratory experiments on the blade alloy for the temperature-strain history calculated from the analysis. Strainrange Partitioning was found to predict component life over a range which spanned the observed service life.

TURBINE BLADE STRUCTURAL AND LIFE ANALYSIS

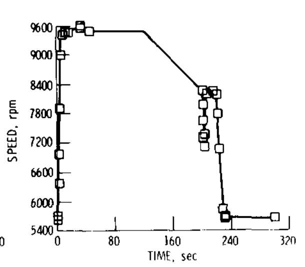


(a) FIRST-STAGE HIGH-PRESSURE TURBINE BLADE AND FINITE-ELEMENT MODEL

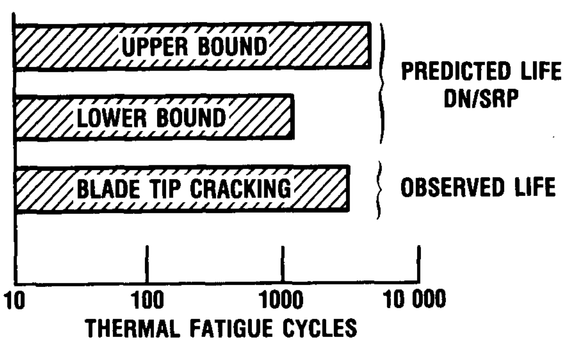
(d) THERMAL FATIGUE CRACKS



(b) TURBINE INLET DISCHARGE TEMPERATURES



(c) CORE ENGINE SPEED



(e) LIFE PREDICTION

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BRITTLE MATERIALS DESIGN METHOD

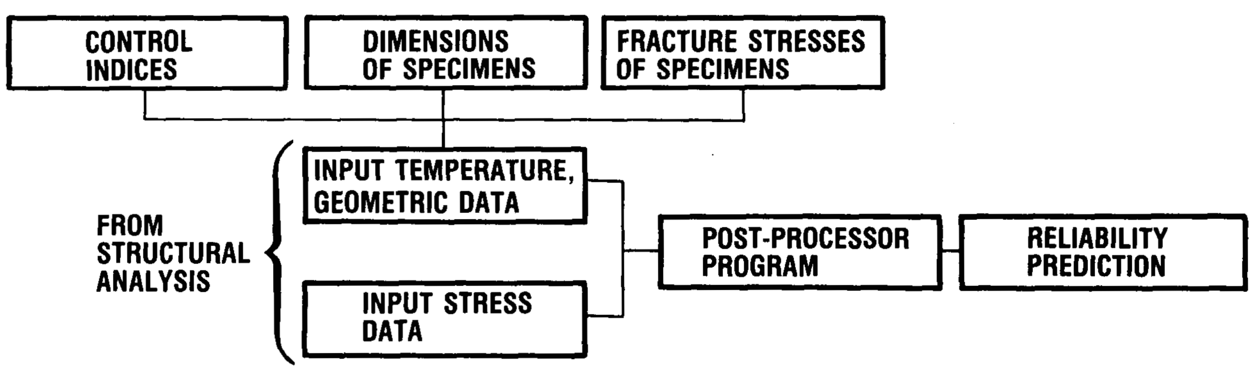
The design of brittle ceramics differs from that of ductile metals because of the inability of ceramic materials to redistribute high local stresses caused by inherent flaws. Random flaw size and orientation require that a probabilistic analysis employing the weakest link theory be performed if the component reliability is to be determined. The lack of adequate design technology, such as general purpose design programs, standards, nondestructive evaluation (NDE) expertise, and codes of procedure has prompted NASA Lewis to initiate research focused on ceramics for heat engines at the beginning of this decade. One of the early accomplishments of this effort has been the development of the unique, public-domain design program called Structural Ceramics Analysis and Reliability Evaluation (SCARE). It is still under development, with new enhancements in improved fast fracture and time-dependent reliability analysis being added and validated.

CERAMICS/BRITTLE MATERIALS LIFE PREDICTION TECHNOLOGY

MATERIAL BRITTLENESS AND PRESENCE OF DEFECTS REQUIRE

- **PROBABILISTIC APPROACH ALLOWING FOR STRENGTH DISPERSION**
- **USE OF WEAKEST LINK THEORY TO TREAT SIZE EFFECT**
- **REFINED THERMAL AND STRESS ANALYSIS—FIELD SOLUTIONS**

RELIABILITY ANALYSIS CODE (SCARE)



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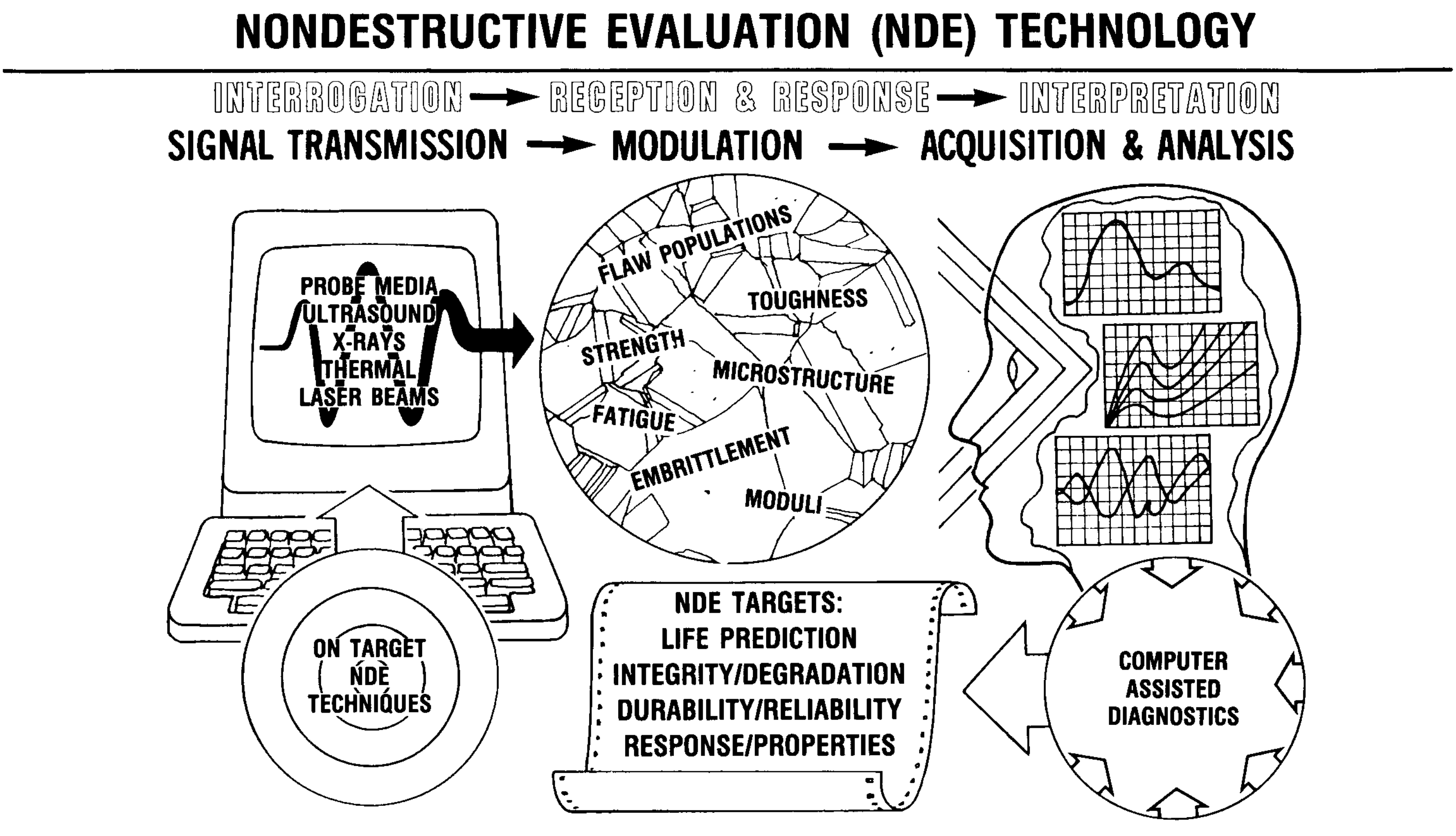
NONDESTRUCTIVE EVALUATION (NDE) TECHNOLOGY

The need for nondestructive materials characterization is indicated where local properties are critical or where the presence, identity, and distribution of potentially critical flaws can only be assessed statistically. In the latter case, flaws can be so microscopic, numerous, and dispersed that it is impractical to resolve them individually. Large populations of nonresolvable flaws may interact with each other (e.g., surface versus volume flaws) or with morphological anomalies. These interactions would be manifested as degraded bulk properties (e.g., deficiencies in strength and toughness). Although a structure may be free of discrete critical flaws, it may still be susceptible to failure because of inadequate or degraded intrinsic mechanical properties. This can arise from faulty material processing and/or degradation under aggressive service environments. It is important, therefore, to have nondestructive methods for quantitatively characterizing mechanical properties.



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