N88-22404

THERMAL-STRUCTURAL ANALYSES OF SPACE SHUTTLE MAIN ENGINE (SSME) HOT SECTION COMPONENTS

Ali Abdul-Aziz* and Robert L. Thompson
Structural Mechanics Branch
NASA Lewis Research Center

ABSTRACT

Three-dimensional nonlinear finite-element heat transfer and structural analyses were performed for the first-stage high-pressure fuel turbopump (HPFTP) blade of the space shuttle main engine (SSME). Directionally solidified (DS) MAR-M 246 and single crystal (SC) PWA-1480 material properties were used for the analyses. Analytical conditions were based on a typical test stand engine cycle. Blade temperature and stress-strain histories were calculated by using the MARC finite-element computer code (MARC Analysis Research Corporation, 1980).

This study was undertaken to assess the structural response of an SSME turbine blade and to gain greater understanding of blade damage mechanisms, convective cooling effects, and thermal-mechanical effects (Kaufman, 1984). Other objectives are also to address problems of calculating the thermal response of high-temperature gas-path components, such as turbopump blades in space power propulsion systems, and to evaluate the stress-strain response at the blade critical location for life prediction purposes. Another purpose is to exercise nonlinear finite-element computer codes on anisotropic SSME components for a typical mission cycle.

Thermal environment on the airfoil was predicted by running a boundary layer analysis using STAN5 code (Gaugler, 1981) to generate the film coefficients needed for the heat transfer analysis. For the complete blade, the heat transfer conditions around the platform and shank regions were provided by Lockheed Missiles & Space Company, Huntsville Research and Engineering Center (1983). Additional assumptions also had to be made to complete the boundary conditions. Transient results were obtained by scaling steady-state heat transfer coefficients based on transient flow and temperature. More details regarding the heat transfer analysis are given by Abdul-Aziz (1987).

Elastoplastic analyses have been conducted for the HPFTP blade with the MARC code. Plastic strains calculations were based on incremental plasticity theory using von Mises yield criterion, the normality rule, and a kinematic hardening model. The material elastoplastic behavior was specified by the yield strength and work hardening properties in the longitudinal direction; transverse properties were not available. Approximately 2 million words of core storage on the

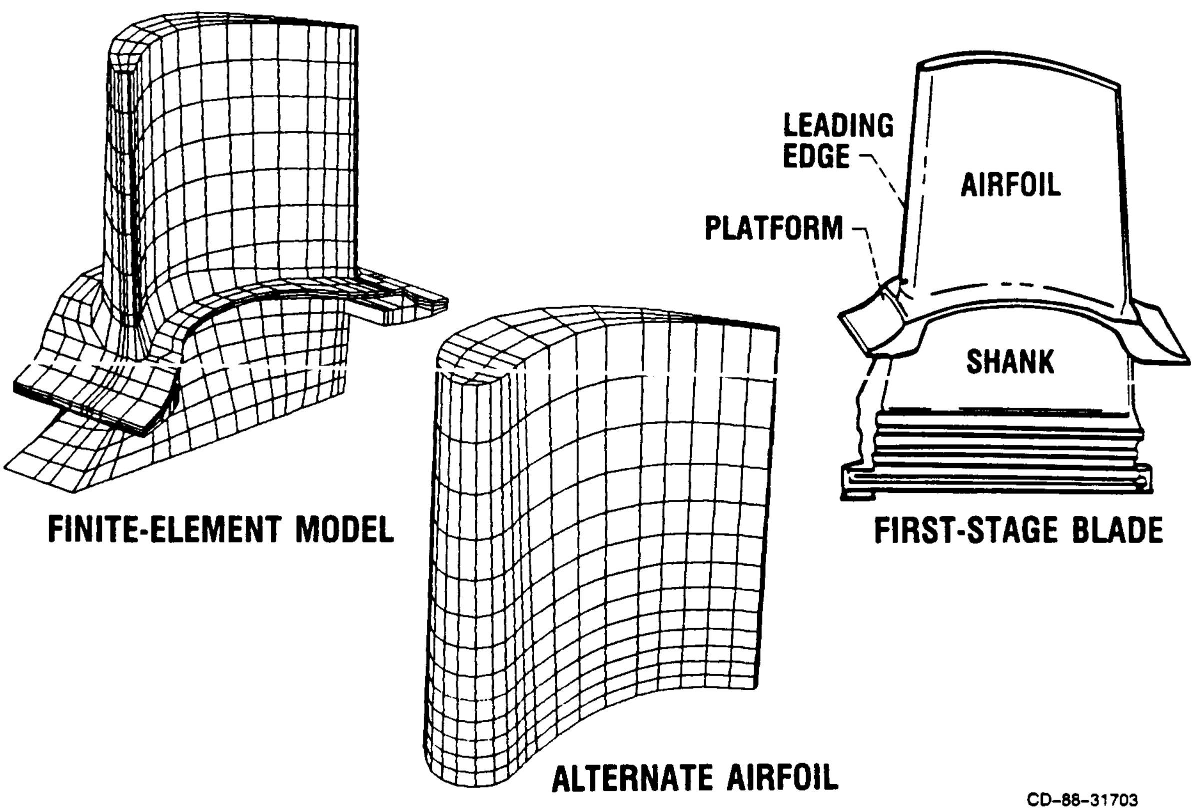
---

*Sverdrup Technology, Inc., Lewis Research Center Group, NASA Lewis Research Center.

Cray XMP computer were needed to run the problem. Analysis required about 4 hours of Cray XMP central processor unit (CPU) time. About half of that was needed for the airfoil problem.

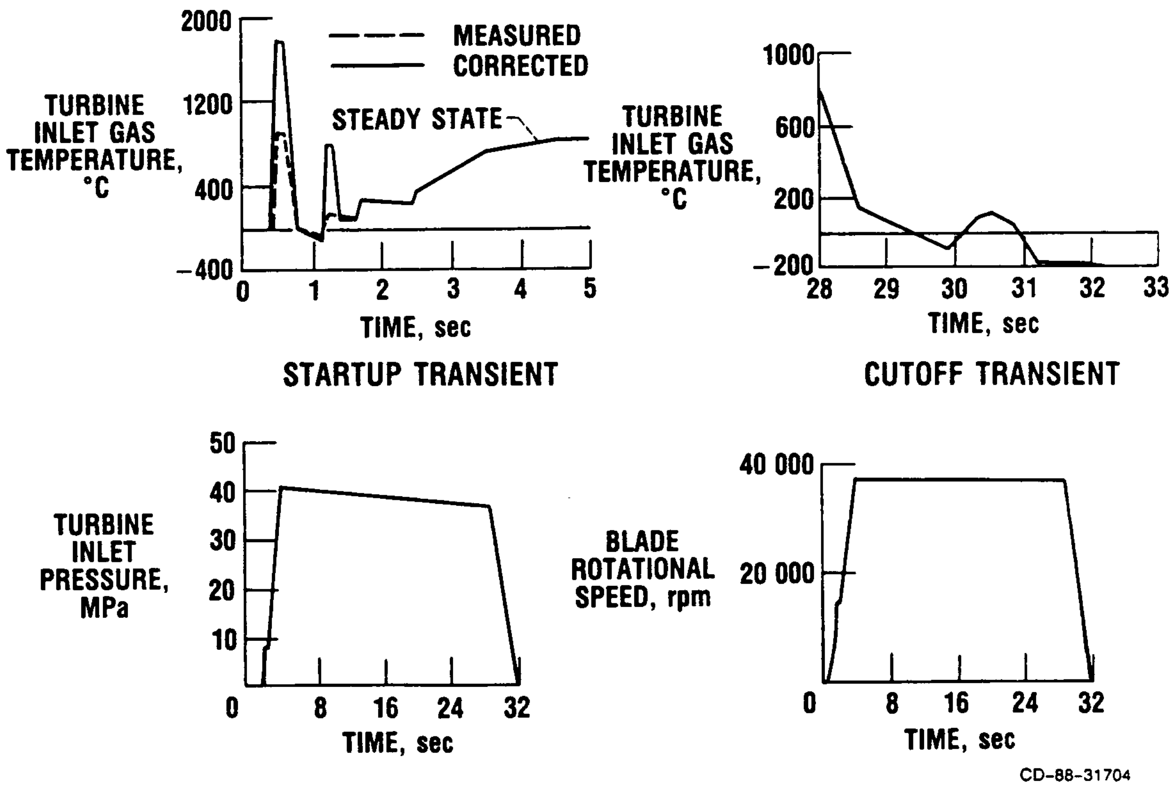
TURBINE BLADE FINITE-ELEMENT MODEL

In the past, first-stage turbine blades in the high-pressure fuel turbopump (HPFTP) of the space shuttle main engine have suffered cracking in the blade shank region and at the leading edge of the airfoil immediately above the platform. A finite-element model for a complete blade has been constructed with eight-node, solid, isoparametric elements. Another model is shown for an alternate airfoil design which is also undergoing thermal-structural analyses. The complete-blade finite-element model consists of 1025 elements and 1575 nodes. The airfoil portion contains 360 elements and 576 nodes, while the alternate airfoil design includes 546 elements and 840 nodes. The MARC code and PATRAN-G graphic package were used to construct these finite-element models.



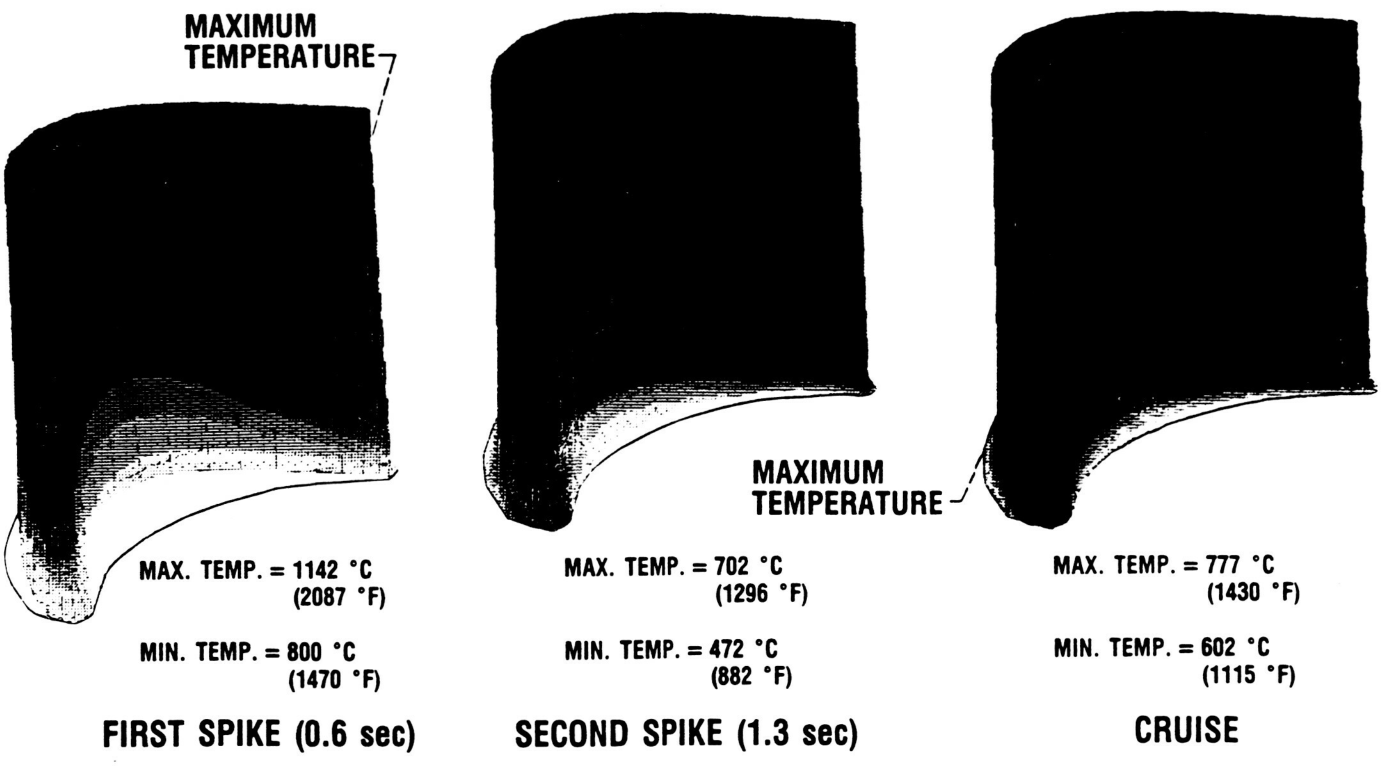
MISSION CYCLE FOR ANALYSIS

The mission cycle used for the analyses in terms of measured and corrected turbine inlet gas temperature, gas pressure, and blade rotational speed is shown below. This cycle is typical of a factory test of the engine; it is also reasonably representative of a flight mission except for the foreshortened steady-state operating time. Since the major factor inducing cracking is the transient thermal stresses caused by the sharp ignition and shutoff transients, deletion of the steady-state portion is acceptable.



AIRFOIL TEMPERATURE DISTRIBUTION

Metal temperatures obtained from MARC heat transfer analysis for the two startup transient spikes are shown below. For the first ignition spike, the highest temperature occurred at the trailing edge near the tip where the airfoil is the thinnest. For the second ignition spike, the maximum temperature was at both the leading and trailing edges. During cruise the airfoil experienced a uniform temperature distribution except near the base because of colder boundary conditions in the region. The maximum temperature location was at the leading and trailing edges and was due to high gas-path pressures, which resulted in high heat transfer coefficients in those areas. The temperature reached 1142 °C during the first spike and 777 °C at cruise.

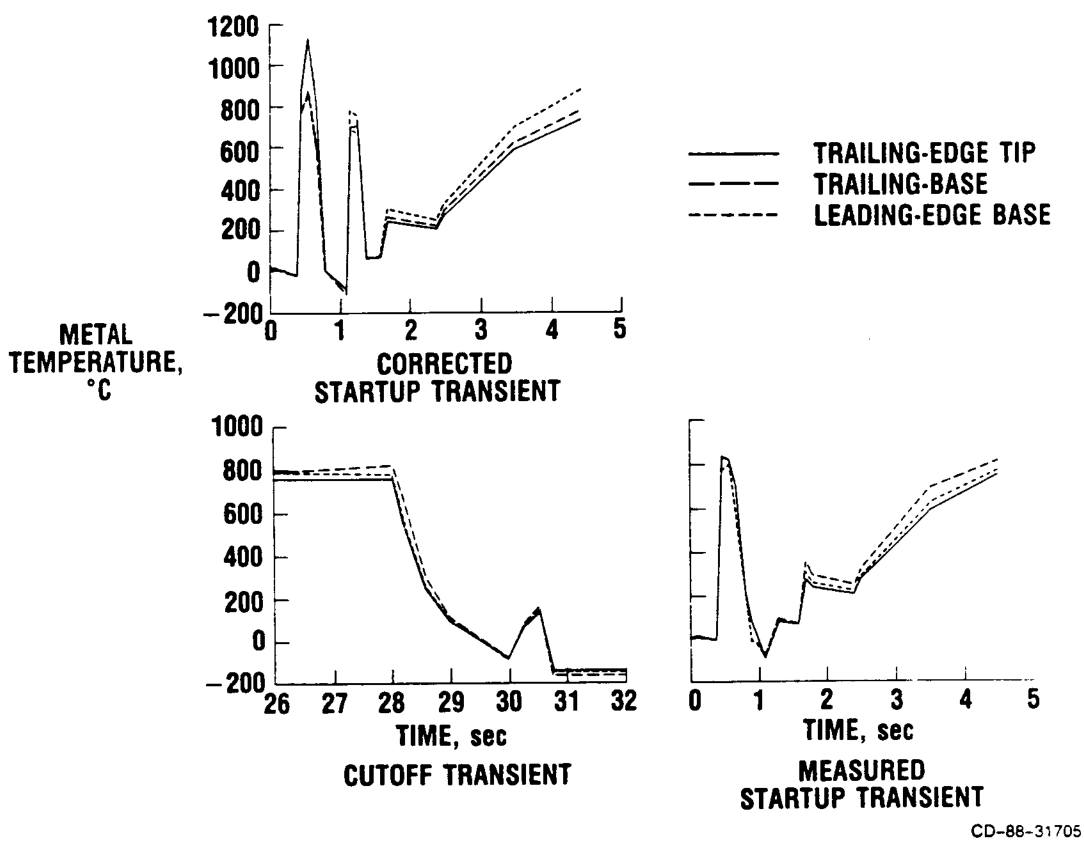


LST '88

CD-88-31771

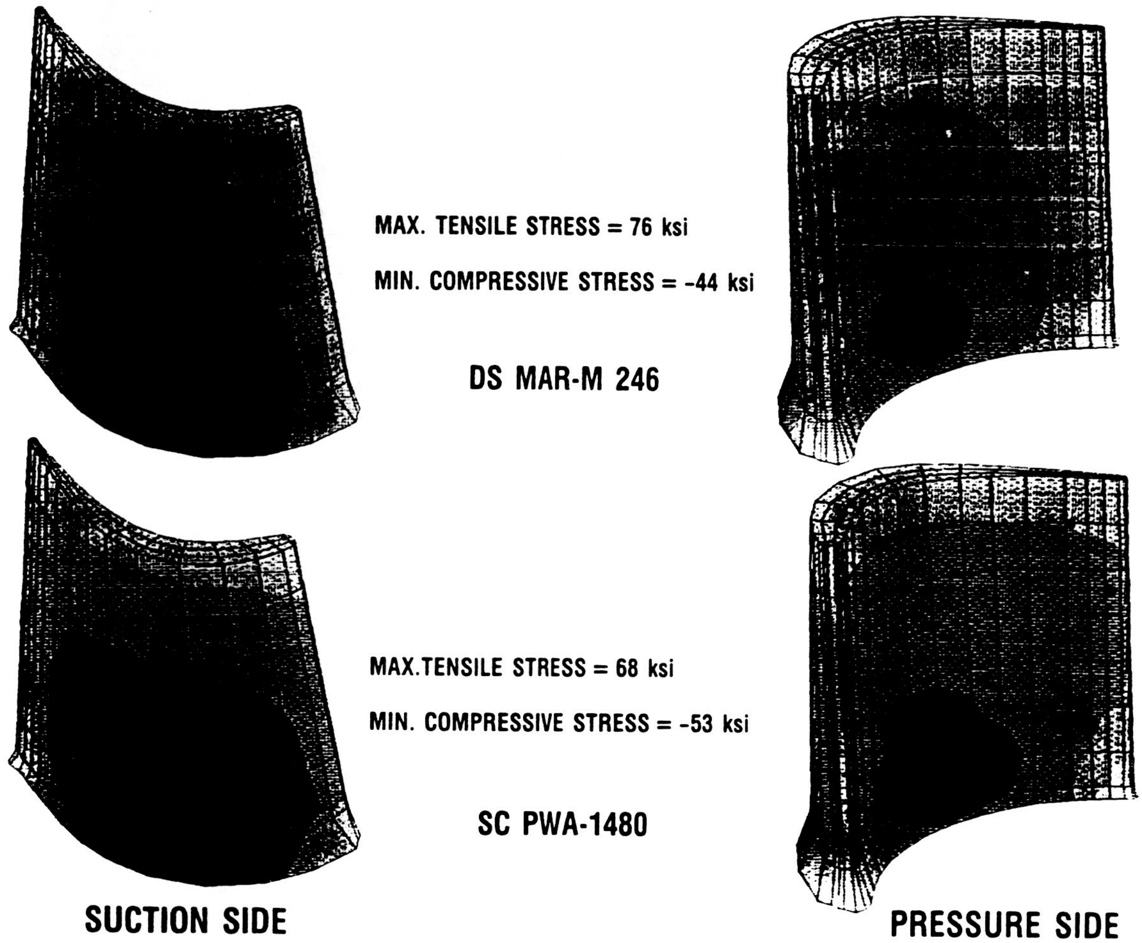
AIRFOIL TRANSIENT TEMPERATURE RESPONSE

The thermal response predicted from the finite-element analysis shown below revealed that the leading and trailing-edge bases of the airfoil are the hottest locations. This was expected because of the presence of high heat transfer coefficients in the region. However, the corrected temperatures (which are higher than those measured by the poor thermocouple response) gave rise to 28 percent higher leading-edge temperatures and a 100 percent higher temperature between the midspan surface and the leading-edge base. The coldest spot was always at the airfoil base because of colder boundary conditions.



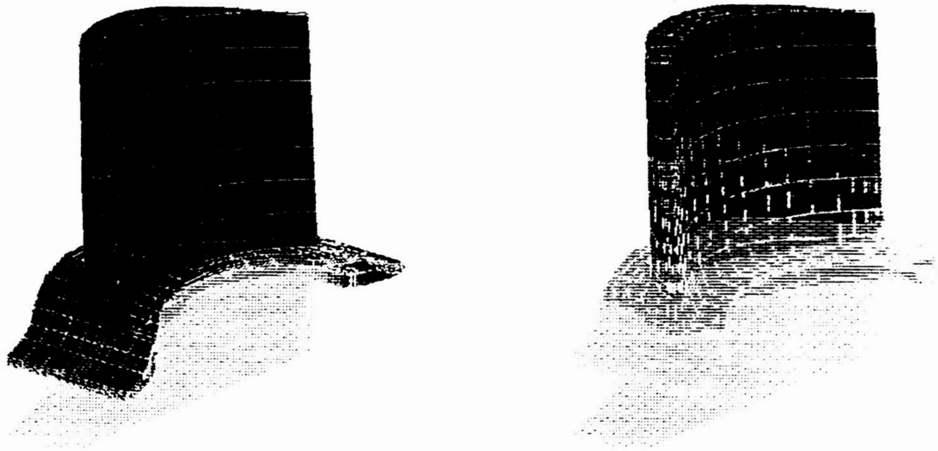
AIRFOIL RADIAL STRESS DISTRIBUTION AT CRUISE

The radial stress components (i.e, along the span) are shown for the elasto-plastic MARC airfoil analyses of directionally solidified (DS) MAR-M 246 and single crystal (SC) PWA-1480. Incremental loading included centrifugal and gas-pressure loads and metal temperature distributions as calculated from the heat transfer analysis. Maximum stresses reached 119 ksi for the SC material and 110 ksi for the DS material during the cruise portion of the mission cycle. The radial component of the strain ranges were 2.1 percent for the MAR-M 246 and 1.57 percent for the PWA-1480.



COMPLETE-BLADE TEMPERATURE CONTOURS

Temperature contours on the surface of the blade are shown for the first temperature spike and at cruise. As expected, the hottest spot of about 1110 °C occurred at the trailing-edge tip of the airfoil during the first temperature overshoot. Uniform temperature dominated most of the airfoil except at the junction of the airfoil, platform, and shank, where a steep temperature gradient is clearly shown. This is because of the effects of the cold and hot gas mixture in the region. A lack of reliable data on the thermal environment in the platform and shank regions may have affected the local heat transfer predictions.



MAX. TEMP. = 772 °C (1422 °F)

MIN. TEMP. = 472 °C (882 °F)

CRUISE

MAX. TEMP. = 1179 °C (2150 °F)

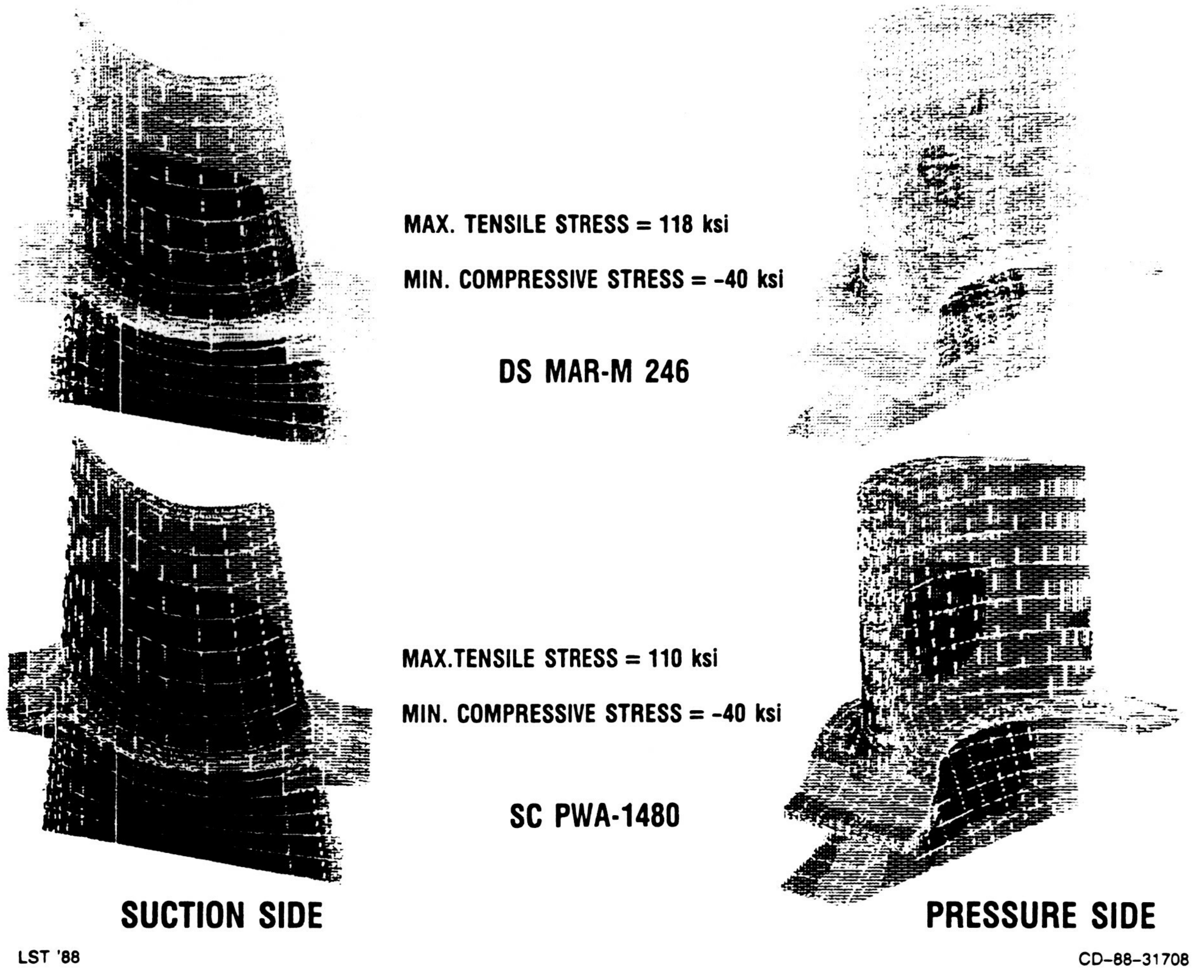
MIN. TEMP. = 589 °C (1092 °F)

FIRST SPIKE

CD-88-31707

COMPLETE-BLADE RADIAL STRESS DISTRIBUTION AT CRUISE

The results of elastoplastic analyses with the MARC code are shown below for the radial components of stress on the complete-blade structure for both DS MAR-M 246 and SC PWA-1480. Considerable difference in structural response has been observed in analyzing the complete blade rather than the airfoil alone. This is mainly due to the uncertainties in the prescribed boundary conditions and assumptions made at the shank-platform interface. However, any difference in life for the two materials would come from their fatigue characteristics. While the fatigue resistances are not well defined, results indicate thermal low-cycle fatigue lives of several thousand cycles.



REFERENCES

Abdul-Aziz, A., Tong, M., and Kaufman, A., 1987, "Thermal Finite-Element Analysis of an SSME Turbine Blade," NASA TM-100117.

Gaugler, R.E., 1981, "Some Modification to, and Operational Experiences With, The Two-Dimensional, Finite-Difference, Boundary-Layer Code, STAN5," NASA TM-81631.

Kaufman, A., 1984, "Development of a Simplified Procedure for Cyclic Structural Analysis," NASA TP-2243.

Lekhnitskii, S.G., and Brandstatter, J.J., eds., 1963, Theory of Elasticity of an Anisotropic Elastic Body," Holden-Day, Inc., pp. 24-25.

Lockheed Missiles & Space Company, Huntsville Research and Engineering Center, 1983, "Space Shuttle Main Engine, Powerhead Structural Modeling, Stress and Fatigue Life Analysis," NASA Contract NAS8-34978, NASA CR-170999.

MARC Analysis Research Corporation, 1980, MARC General Purpose Finite Element Analysis Program, Vol. A: User Information Manual; Vol. B: MARC Element Library; Vol. F: Theoretical Manual, Palo Alto, CA.

Milligan, W. Walter, Jr, 1986, "Yielding and Deformation Behavior of The Single Crystal Nickel-Base Superalloy PWA 1480," NASA CR-175100.