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THERMOSTRUCTURAL ANALYSIS OF SIMULATED COWL LIPS

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ABSTRACT

With the most recent efforts to develop state-of-the-art hypersonic technologies, a significant number of challenging problems have surfaced. One of the major concerns is the development of an aeropropulsion system capable of handling the high heat fluxes during hypersonic flight. On the leading edges of such systems, not only must the maximum heating rates be tolerated, but also distortions to the flow field due to excessive blunting and/or thermal warping of the compression surface must be held to a minimum if high inlet performance is to be achieved. Active cooling schemes are required to maintain acceptable temperatures in the leading edge regions as well as in the relatively large flat panels located in the combustion zone. To assess these problems, an interdisciplinary cowl lip technology team (COLT) has been formed at NASA Lewis. COLT comprises a completely integrated loop of the design, analysis, and experimental verification process in developing actively cooled cowl lip concepts for use on a propulsion system for the proposed National Aerospace Plane (NASP).

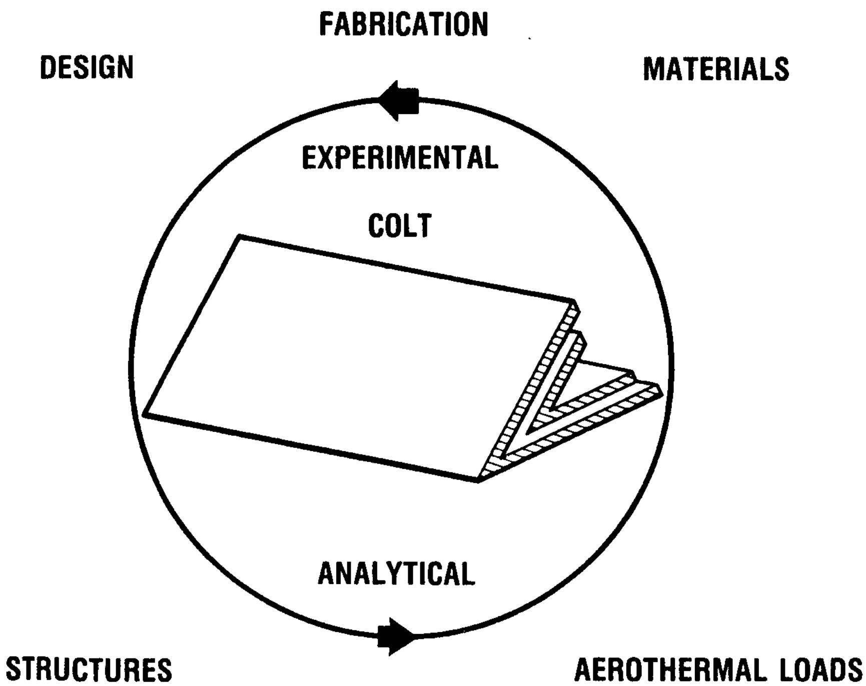
Three-dimensional finite element analyses using MSC/NASTRAN and MARC are performed to predict the thermal and structural response of the various cooling schemes under high heat loads. Steady state heat-transfer analyses and elastic stress analyses are performed using MSC/NASTRAN. Elastic/plastic stress analyses are done using MARC.

To help verify these analyses experimentally, a hydrogen-oxygen rocket engine has been modified to use the exhaust stream as a high-enthalpy, high-heat-flux source to evaluate various actively cooled, simulated cowl lip segments as well as flat structural segments. The facility is capable of providing heat flux levels from about 200 (Btu/ft^2)/sec up to 10 000 (Btu/ft^2)/sec. Crossflow and parallel flow cooling configurations have been tested and analyzed using cooling fluids of water and gaseous hydrogen. In addition, various material types have been tested and compared. These material types include high-conductivity copper, nickel, and a copper and graphite metal matrix composite.

METHODOLOGY OF LEADING EDGE CONCEPT EVALUATION

Engine inlet leading edge surfaces and their associated high heating rates during flight on hypersonic vehicles are one of the major concerns in the development of the proposed National Aerospace Plane (NASP). Ongoing work by an inlet cowl lip technology team (COLT) at the Lewis Research Center has been to analyze, fabricate, and test, in a hot gas facility, generic, actively cooled cowl lip concepts made of both homogeneous and metal matrix composite materials in order to develop analytical, experimental, and material technologies to support the research and development of hypersonic inlet configurations for NASP propulsion.

The approach is an iterative one through analysis, design fabrication, and testing of the actively cooled cowl lip concepts. Integrated thermal and structural analysis codes are used to evaluate the various concepts. Concepts analyzed and tested are made from pure metals, including copper, nickel, and titanium sheets, and a metal matrix composite material, copper/graphite. Configurations are tested in a hot gas test facility at Lewis with the test data acquired used for calibration and verification of the analysis tools as well as for evaluation of the cowl lip concept itself.



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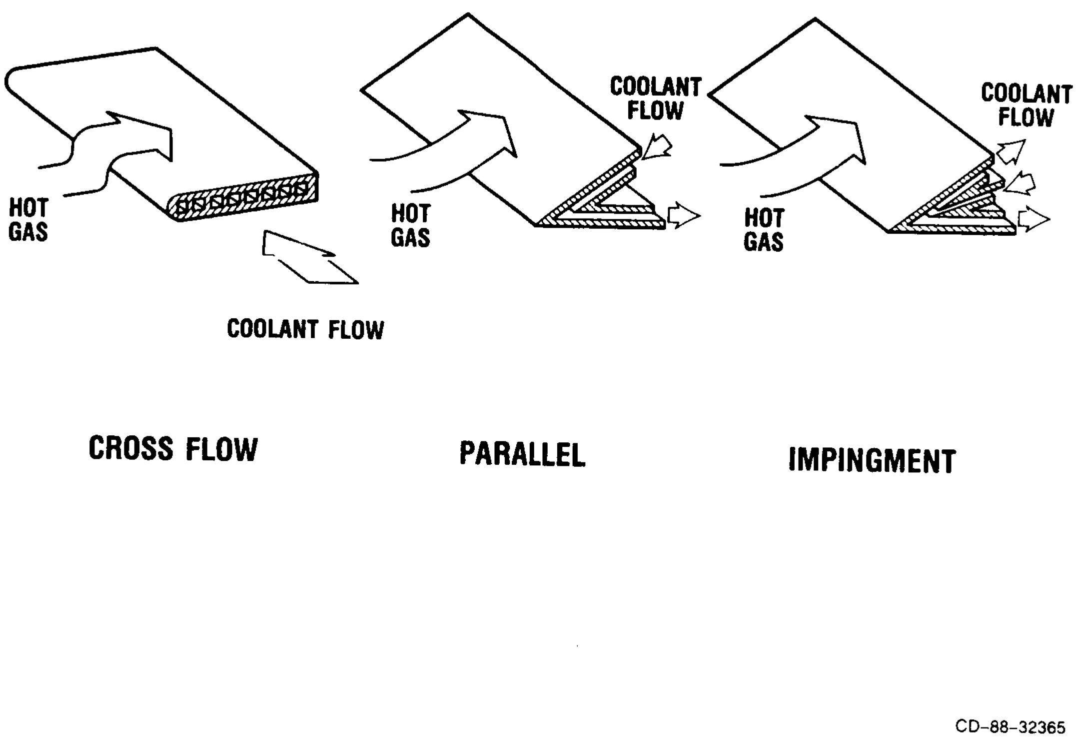
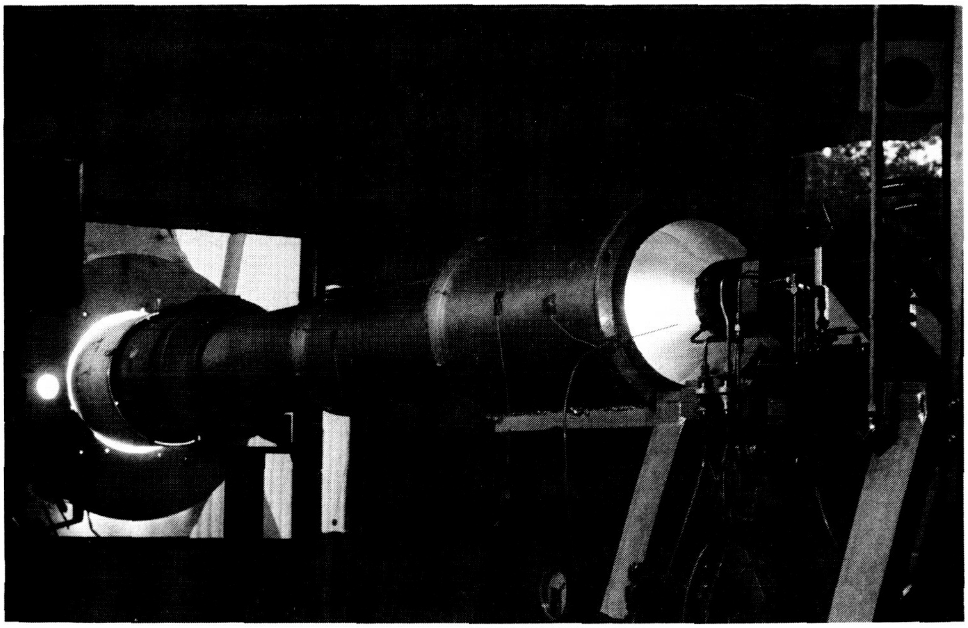
COWL LIP COOLING CONCEPTS

The figure shows three actively cooled cowl lip concepts which will be analyzed and tested in the hot gas facility at Lewis. Included is a generic crossflow cooling concept, a parallel-flow cooled concept, and an impingement-flow concept. To date, crossflow-cooled specimens have been fabricated from copper, nickel, and titanium. A crossflow specimen with a copper/graphite leading edge is very close to completion. The copper and nickel specimens have been tested using both water and gaseous hydrogen as coolants. Several copper parallel-flow test pieces have been fabricated and await testing pending the completion of some modifications to the test cell.



HOT GAS TEST FACILITY

The high heat flux generated in the test facility is obtained from the combustion of a hydrogen-oxygen rocket engine. The rocket engine, on the right in the figure, fires horizontally across a test specimen fixed at the exit of the nozzle. Tests have been conducted for a wide latitude of conditions providing gas temperatures from 1800 to 5000 °F and stagnation point heat fluxes of up to 2000 (Btu/ft^2)/sec.



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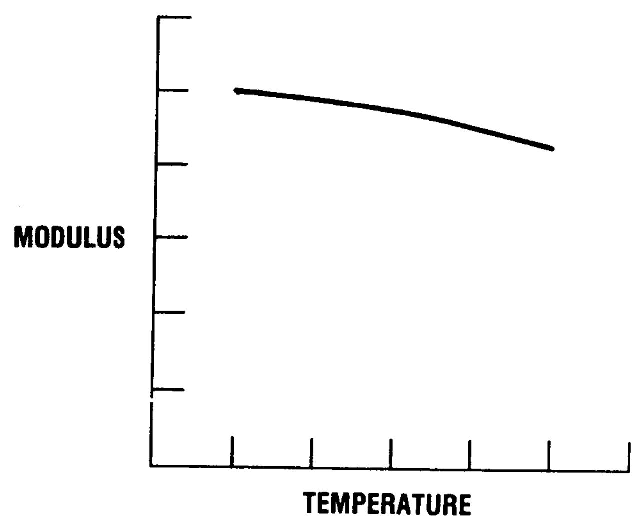
METCAN-GENERATED MATERIAL PROPERTIES FOR METAL MATRIX COMPOSITES

METCAN, a code developed at NASA Lewis, is used to predict the thermal and structural material properties required for the analysis of a metal matrix composite structure. METCAN also predicts composite structural response and composite stress results with detail on failure. Shown in the figure are examples of typical METCAN-generated material properties plotted as a function of temperature. METCAN is discussed in more detail in another presentation at this conference.

ELASTIC MODULI
SHEAR MODULI
POISSON RATIOS
EXPANSION COEFFICIENTS
DENSITY
HEAT CAPACITY
HEAT CONDUCTIVITIES
STRENGTHS
FLEXURAL MODULI
FAILURE ANALYSIS
LOCAL STRESSES



ICAN—POLYMER MATRIX COMPOSITE ANALYZER
METCAN—METAL MATRIX COMPOSITES ANALYZER

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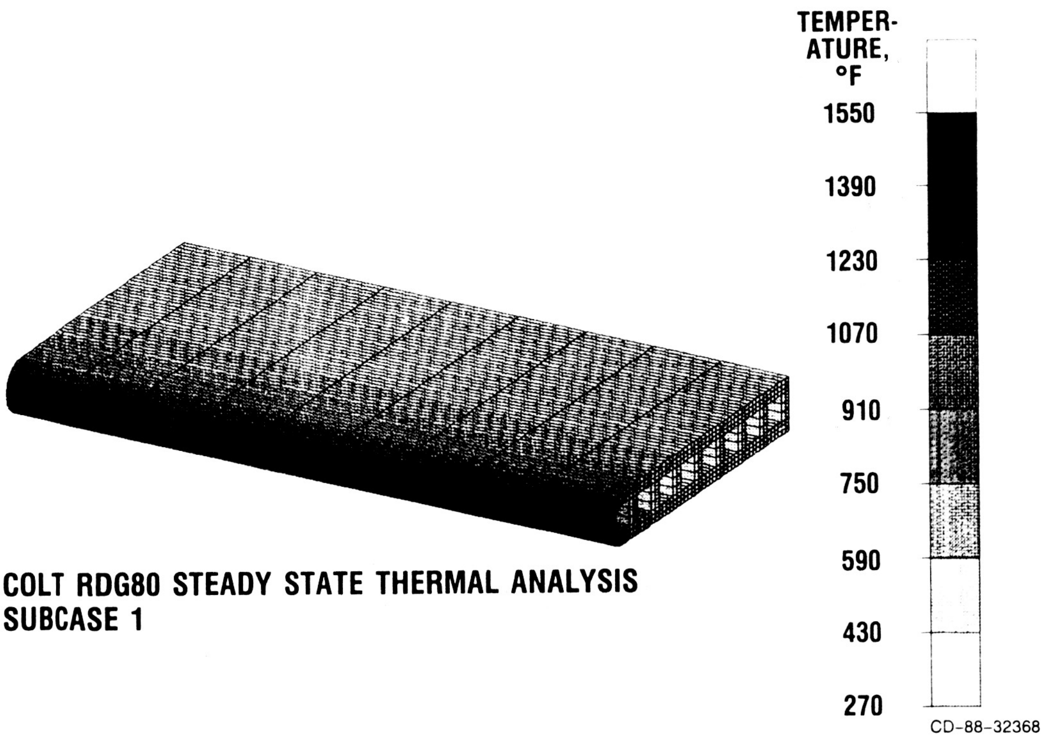
THERMAL FINITE ELEMENT ANALYSIS OF COPPER CROSSFLOW CONFIGURATION

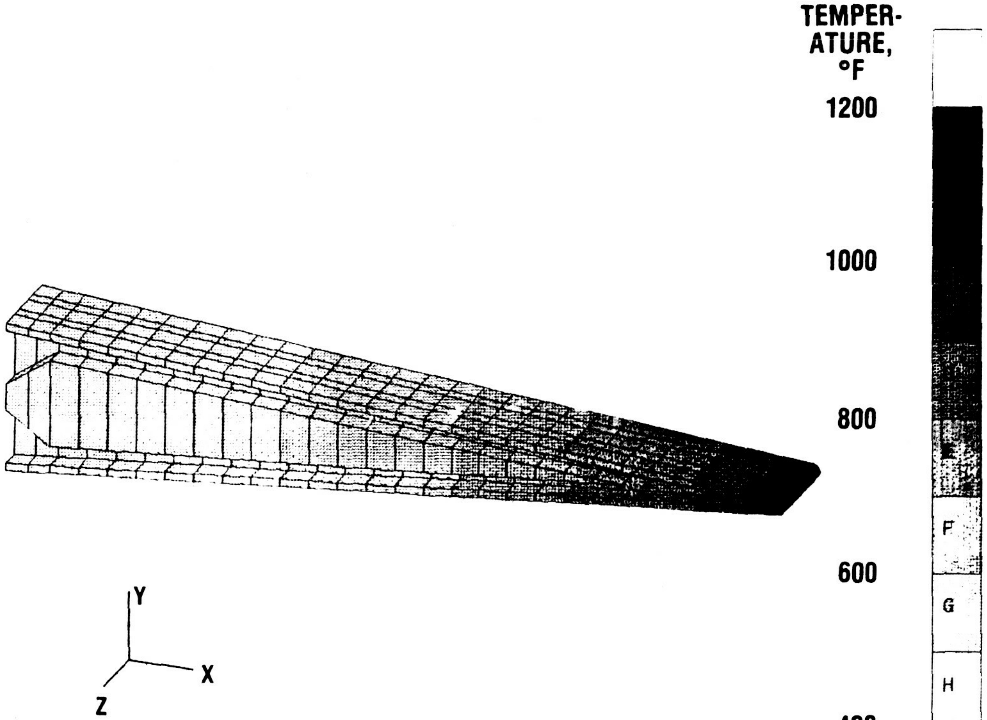
Three-dimensional thermal and structural finite element analyses are performed on copper, nickel, and copper and graphite composite crossflow configurations using MSC/NASTRAN. The model, used for both thermal and stress analysis, consists of 4760 nodes and 3294 eight-node brick elements (HEXA). The PATRAN code is used to generate the mesh and to process the results. The figure shows a thermal profile predicted from a steady state heat-transfer analysis of a copper crossflow specimen with gaseous hydrogen coolant. The hot gas temperature was 2800 °F, and the coolant was 50 °F. The nonsymmetric temperature distribution is due to a pressure differential between the top and bottom surfaces. The predicted nodal temperatures are used as input (thermal loads) for a linear stress analysis with NASTRAN.



COLT RDG80 STEADY STATE THERMAL ANALYSIS
SUBCASE 1

THERMAL FINITE ELEMENT ANALYSIS OF PARALLEL-FLOW CONFIGURATION

The parallel-flow cowl lip concept is evaluated in the same fashion as the crossflow concept. The model, representing a slice of the actual test piece, consists of 532 solid brick elements and 1010 nodes. Analytical thermal boundary conditions are under development for this model; however, a representative temperature profile has been predicted using assumed heat fluxes (see figure). Testing of the copper parallel-flow specimen is in progress.



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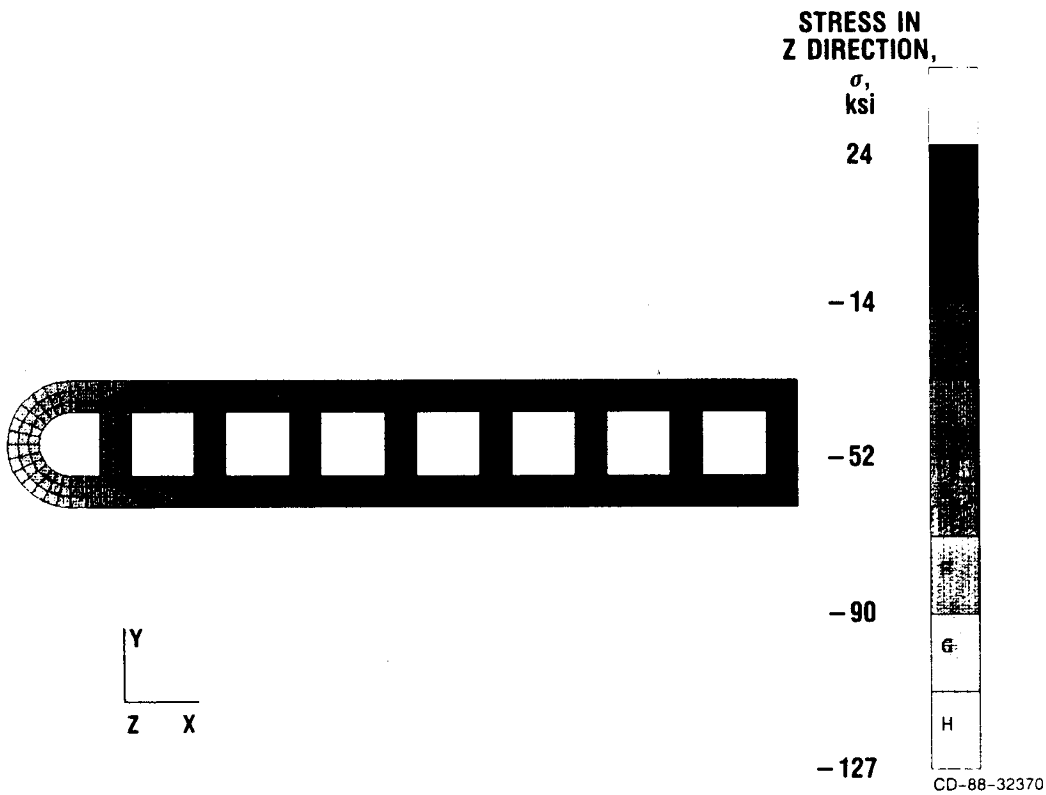
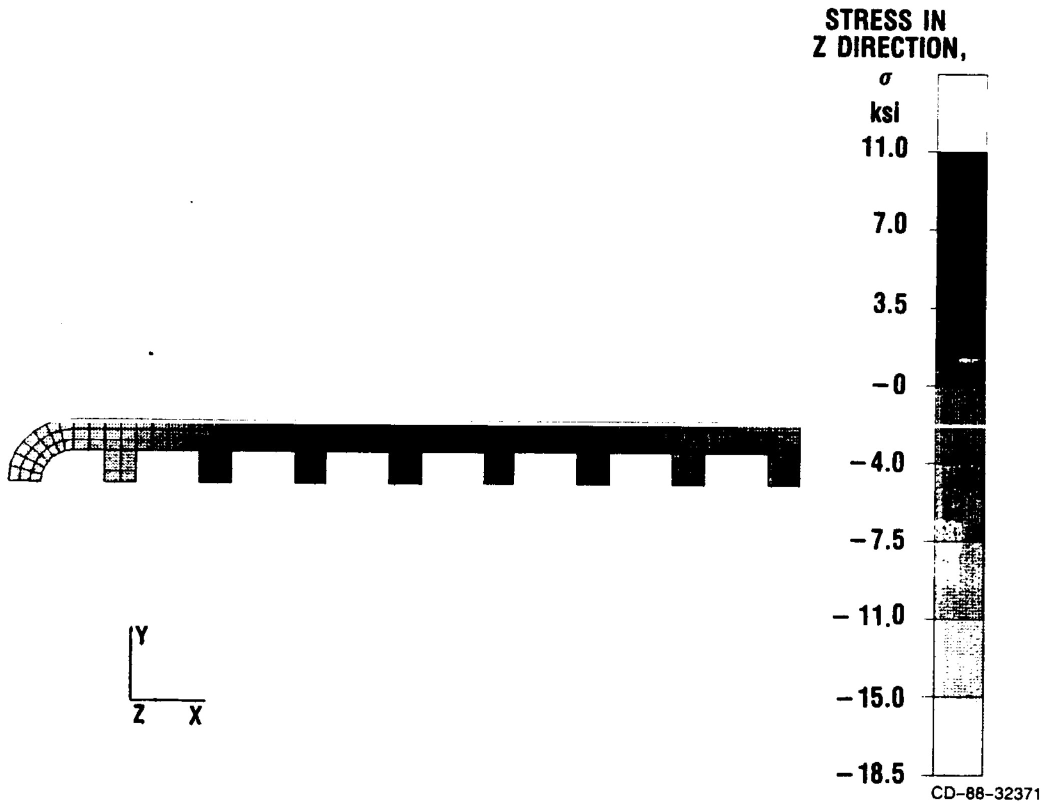
THERMAL STRESS DISTRIBUTION IN COPPER CROSSFLOW CONFIGURATION

Nodal temperature data from the thermal analyses previously described are applied to the same finite element models in order to predict stresses resulting from the constrained thermal expansion. Shown in the figure is an elastic thermal stress profile on a small section of the copper crossflow model. Material properties were input as temperature dependent in this NASTRAN analysis. The stresses plotted are along the Z direction of the axes shown. Stresses in the other directions were calculated but are not shown here. The high compressive stresses along the Z axis, seen analytically to be the most significant in the structure, are due to the high differential of expansion in this direction. The leading edge, at very high temperatures, is trying to expand with the bulk of the material aft of the leading edge at much cooler temperatures restraining it. The elastic analysis indicates yielding at the leading edge and warrants a nonlinear analysis to accurately predict the material behavior in this problem.



NONLINEAR STRESS DISTRIBUTION IN COPPER CROSSFLOW CONFIGURATION

A nonlinear finite element analysis was performed on the crossflow configuration using the MARC analysis code. The model used with MARC made use of symmetry and was half the size of the NASTRAN model. This was necessary due to the intensive CPU time required for a nonlinear analysis. The analysis was a transient one, utilizing a combined isotropic-kinematic hardening rule and temperature-dependent material properties. Shown in the figure is the steady-state resultant stress profile for the stresses along the Z axis shown in the figure. Time-dependent effects will be incorporated into the analysis at a later date, as well as some life-prediction methods.



ELASTIC STRESS ANALYSIS OF CROSSFLOW CONFIGURATION MADE OF COPPER AND GRAPHITE COMPOSITE

A linear, steady state heat-transfer analysis of a crossflow configuration is run using material properties for copper/graphite predicted from METCAN. The model is assumed to be made of a unidirectional (50% P100 fiber) composite with fibers running parallel to the leading edge of the model (Z direction). Resultant nodal temperatures are input for an elastic stress analysis and the stresses in the Z direction are plotted as before. Because of a significantly lower coefficient of thermal expansion and a high modulus in the fiber direction, the global structural stresses are much lower in the leading edge for the copper and graphite composite than for pure copper; however, microstresses within the material itself must also be taken into consideration as they may limit the material's performance at high temperatures. The METCAN code will predict these stresses. This still suggests that the copper and graphite composite and other metal matrix composites might offer realistic solutions to the cowl lip problem. Reduction of the thermal expansion coefficient is the key to controlling stresses in areas of high thermal gradients, and this can be done with metal matrix composites if the fabrication hurdles can be overcome.