NASA Technical Paper 1593

Analysis of Uncertainties in Turbine Metal Temperature Predictions

Francis S. Stepka

APRIL 1980

NASA

NASA Technical Paper 1593

Analysis of Uncertainties in Turbine Metal Temperature Predictions

Francis S. Stepka
Lewis Research Center
Cleveland, Ohio

NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Office

1980

SUMMARY

An analysis was conducted to examine the extent to which various factors influence the accuracy of analytically predicting turbine-blade metal temperatures and to determine the uncertainties in these predictions for several accuracies of the influence factors. The influence factors considered were the gas and coolant temperatures, the gas-to-blade and blade-to-coolant heat-transfer coefficients, and the thermal conductances (conductivities divided by thicknesses) of a metal wall and of a ceramic thermal-barrier coating. The analysis was applied to conditions of an advanced turbofan engine and a highly instrumented high-temperature turbine test rig (gas conditions of 1700 K and 40 atm) and to conditions that simulated the engine conditions in a low-temperature turbine test rig (756 K and 15.6 atm).

The results indicated that with current knowledge of boundary conditions, geometry, heat-transfer coefficients, and material thermal properties the uncertainty in analytically predicting and verifying local turbine-blade surface metal temperature in an average instrumented engine is 98 kelvins (176 deg F), or 7.6 percent of the reference metal absolute temperature, for uncoated blades and 62 kelvins (112 deg F), or 5.7 percent, for ceramic-thermal-barrier-coated blades. The greatest improvement in predicting blade metal temperature could result from improving the accuracy of predicting the local gas-to-blade heat-transfer coefficient. Improving the prediction accuracy of the gas- and coolant-side heat-transfer coefficients to the best assumed attainable levels could reduce the uncertainty in predicting and verifying metal temperature in a highly instrumented high-temperature turbine test rig to 28 kelvins (50 deg F), or 2.1 percent of the blade absolute temperature, for uncoated blades and to 21 kelvins (38 deg F), or 1.9 percent, for coated blades.

The analysis showed that, despite better knowledge of gas and coolant temperatures, the low-temperature turbine test rig was only a fraction of a percent better in reducing the uncertainty in blade metal temperature prediction, or verification, than the high-temperature turbine test rig.

INTRODUCTION

The large number of turbine durability problems that occur during the development of gas turbine engines and their introduction into service would indicate that, in addition to the inability to accurately predict life with known metal temperatures, local metal temperatures are not well known. This suggests that boundary conditions (local gas and coolant conditions) are not adequately known and/or that the gas and coolant flow and heat-transfer relationships and the correlations and prediction methods for metal temperatures are not adequate. However, those in the field often convey a high confidence in their ability to accurately predict blade metal temperatures. Part of this confidence in undoubtedly due to knowledge gained after testing specific blade or vane hardware in specific cascade rigs or engines and the subsequent readjustments of correlations and prediction models. As a consequence, satisfactory turbine hardware designs for use in gas and coolant environments that are not much different than those previously experienced can be expected with some confidence. However, as has often been the case, when even small changes are made in boundary conditions, components that affect boundary conditions, airfoil aerodynamics, or cooling configuration, excessive metal temperatures occur and turbine durability problems result. Costly hot-section redesigns are then often required.

It is apparent that the accuracy of predicting blade metal temperatures and how various factors influence the accuracy should be examined. The information from such an examination could be particularly important to the structural analyst and designer. It would, for example, provide him with knowledge to estimate the range of expected life that would result from the accuracy range expected in blade metal temperature predictions. It would also aid the turbine researcher and developer by pointing out the variation in metal temperature that can be expected between experiment and prediction and thus providing him a level of confidence in his ability to verify predicted metal temperatures in rig or engine tests.

One purpose of the study reported herein was to examine how various factors influence the accuracy of predicting turbine-blade metal temperatures. Another purpose was to determine the metal temperature prediction accuracies that can be expected for commonly encountered environments. The third purpose was to determine how the prediction capability might be improved by more accurate values of the influencing factors. This information can help in assessing the research effort that might be needed to improve this accuracy and the resulting benefits.

The influence factors considered in this study were the gas and coolant temperatures, the gas-to-blade and blade-to-coolant heat-transfer coefficients, and the thermal conductances (conductivities divided by thicknesses) of a metal wall and of a ceramic thermal-barrier coating. A simple, one-dimensional heat balance across a representative element of a turbine-blade wall with and without a thermal-barrier coating was used. The analysis was applied to conditions of an advanced turbofan engine and a high-temperature turbine test rig (gas conditions of 1700 K and 40 atm) and to conditions of a low-temperature turbine test rig (756 K and 15.6 atm) that simulated the engine.

This report tabulates the expected uncertainties in predicting turbine-blade surface metal temperatures for various assumed accuracies of the influence factors for both uncoated and ceramic-thermal-barrier-coated blades. Also presented is the sensitivity in blade surface temperature to individual changes in the influence factors.

SYMBOLS

h	heat-transfer coefficient
K	thermal conductivity
Pr	Prandtl number
R	thermal conductance, K/τ
Re	Reynolds number
T	temperature
U	uncertainty of function in parentheses
X_g	distance from leading edge
λ	parameter, see eq. (2)
τ	thickness
φ	temperature difference ratio, $(T_g - T_{wo})/(T_g - T_c)$

Subscripts:

b	ceramic thermal barrier
c	cooling air
g	gas
i	inside surface (coolant side)
o	outside surface (gas side)
w	metal wall

ANALYSIS AND CONDITIONS

Heat Balance

A convection-cooled element of a blade wall aft of the leading edge was selected. Radiation was neglected, and heat flow was assumed to be one-dimensional through a ceramic-thermal-barrier-coated blade. For these assumptions the heat flow equations are

$$h_g(T_g - T_{bo}) = R_b(T_{bo} - T_{wo}) = R_w(T_{wo} - T_{wi}) = h_c(T_{wi} - T_c) \qquad (1)$$

From equation (1) we can obtain

$$\varphi = \frac{T_g - T_{wo}}{T_g - T_c} = \frac{1}{1 + \frac{h_g}{h_c}\frac{(1 + h_c/R_w)}{(1 + h_g/R_b)}} \equiv \frac{1}{1 + \lambda} \tag{2}$$

The terms are defined in the section SYMBOLS. This equation is then used to calculate the outside-surface wall temperature T_{wo} for assumed engine conditions. It is also used to determine the sensitivity of T_{wo} to the other variables (or influence factors) - T_g, T_c, h_g, h_c, R_w, and R_b.

Sensitivity Analysis

The sensitivity of the wall temperature T_{wo} to each influence factor was obtained by solving equation (2) for a change in T_{wo} for an assumed perturbation (or error) in each influence factor. It can also be obtained by taking the partial derivative of equation (2) with respect to each influence factor and multiplying by the assumed perturbation (or error) of the influence factor as follows:

$$dT_{wo} = \left(\frac{\partial T_{wo}}{\partial T_g}\right)dT_g + \left(\frac{\partial T_{wo}}{\partial T_c}\right)dT_c + \left(\frac{\partial T_{wo}}{\partial h_g}\right)dh_g + \left(\frac{\partial T_{wo}}{\partial h_c}\right)dh_c + \left(\frac{\partial T_{wo}}{\partial R_b}\right)dR_b + \left(\frac{\partial T_{wo}}{\partial R_w}\right)dR_w \tag{3}$$

This latter method assumes linearity over the range of the perturbation. A tabulation of the partial derivatives is presented to show the interrelationship of the factors involved:

$$\frac{\partial T_{wo}}{\partial T_g} = 1 - \varphi \tag{4}$$

$$\frac{\partial T_{wo}}{\partial T_c} = \varphi \tag{5}$$

$$\frac{\partial T_{wo}}{\partial h_g} = \frac{(T_g - T_c)\varphi^2\lambda}{h_g(1 + h_g/R_b)} \tag{6}$$

$$\frac{\partial T_{wo}}{\partial h_c} = -\frac{(T_g - T_c)\varphi^2 (h_g/h_c)}{h_c(1 + h_g/R_b)} \tag{7}$$

$$\frac{\partial T_{wo}}{\partial R_b} = \frac{(T_g - T_c)\varphi^2 \lambda\left(h_g/R_b^2\right)}{(1 + h_g/R_b)} \tag{8}$$

$$\frac{\partial T_{wo}}{\partial R_w} = -\frac{(T_g - T_c)\varphi^2\left(h_g/R_w^2\right)}{(1 + h_g/R_b)} \tag{9}$$

Error Analysis

The effect of uncertainties in each influence factor on the prediction of the blade outside-surface metal temperature was calculated by using the method of determining the uncertainties of independent, normally distributed variables described in reference 1. The uncertainties in the blade outside-surface metal temperatures $U(T_{wo})$ were obtained by taking the square root of the sum of the squares of the uncertainties in blade temperature due to individual effects of the influence factors. It can be written as

$$U(T_{wo}) = \left\{\left[\frac{\Delta T_{wo}}{\Delta T_g} U(T_g)\right]^2 + \left[\frac{\Delta T_{wo}}{\Delta T_c} U(T_c)\right]^2 + \left[\frac{\Delta T_{wo}}{\Delta h_g} U(h_g)\right]^2 + \left[\frac{\Delta T_{wo}}{\Delta h_c} U(h_c)\right]^2 + \left[\frac{\Delta T_{wo}}{\Delta R_b} U(R_b)\right]^2 + \left[\frac{\Delta T_{wo}}{\Delta R_w} U(R_w)\right]^2\right\}^{1/2} \tag{10}$$

The quantities $\Delta T_{wo}/\Delta T_g$, etc., were obtained from equation (2) by perturbating each influence factor. For the assumed turbine conditions (table I), reference surface metal temperatures (table II) were calculated by using equation (2). The percent uncertainties in blade outside-surface metal temperatures were obtained by using the reference temperatures.

APPLICATION TO TURBINE CONDITIONS

For this analysis the heat-transfer coefficients, the thermal conductances, the hot-gas and cooling-air temperatures, and the probable uncertainties in the values of these influence factors were calculated or assumed for three conditions. These were conditions of an advanced turbofan engine, a high-temperature turbine test rig, and a low-temperature turbine test rig that simulated the engine hydrodynamic conditions.

Heat-Transfer Coefficients and Thermal Conductances

Equation (2) requires that we determine the gas-to-blade and blade-to-coolant heat-transfer coefficients. For simplicity the gas-side coefficient was determined by using the equation of turbulent heat transfer to a flat plate (ref. 2):

$$h_g = 0.0296 \left(Re_g\right)^{0.8} \left(Pr_g\right)^{1/3} \frac{K_g}{X_g} \tag{11}$$

where the Reynolds number Re_g was evaluated at the assumed engine conditions, for a distance X_g from the leading edge of 1.27 centimeters (0.5 in.) and a constant Prandtl number of 0.705. The transport properties were evaluated by using the data of reference 3. For the purpose of this analysis the blade-to-coolant heat-transfer coefficient was assumed to be

$$h_c = 1.5\ h_g \tag{12}$$

The wall and ceramic-thermal-barrier thermal conductances R_w and R_b in equation (2) were obtained for a blade wall thickness of 0.102 centimeter (0.040 in.) and a ceramic thickness of 0.025 centimeter (0.010 in.) and by using equations for the thermal conductivity of the blade wall (MAR-M509) and of the ceramic (yttria-stabilized zirconia) from references 4 and 5, respectively.

Boundary Conditions

For the advanced turbofan engine or the high-temperature turbine rig the turbine-inlet gas temperature and pressure were 1700 K (2600° F) and 40 atmospheres, respectively, and the cooling-air temperature was 922 K (1200° F). To obtain the low-temperature conditions simulating the advanced turbofan engine, the method of reference 6 was used. For an inlet gas temperature to this turbine rig of 756 K (900° F), the gas pressure was determined to be 15.6 atmospheres and the cooling-air temperature, 409 K (278° F). The gas-stream Mach number at the element of the turbine blade under analysis was assumed to be 0.4 for the engine and for both test rigs. For convenience these conditions are listed in table I.

Probable Uncertainties

The probable uncertainties in the influence factors are listed in table III. For the average instrumented engine the local gas temperature was assumed to be known within no better than 167 kelvins (300 deg F), or 9.8 percent of the gas absolute temperature. For the highly instrumented engine or high-temperature test rig the gas temperature was assumed to be known within 2 percent. For the low-temperature test rig it was assumed to be known within 1 percent. The coolant temperature was assumed to be known within 28 kelvins (50 deg F), or 3 percent of the coolant absolute temperature, for the average instrumented engine and within 1 percent for either the highly instrumented research engine, the high-temperature test rig, or the low-temperature test rig.

The current uncertainty in predicting the local gas-to-blade heat-transfer coefficient for an arbitrary turbine airfoil shape (for which prior experimental test data were not available) was assumed to be 35 percent. Experimentally measured local heat-transfer coefficients around several airfoil shapes are compared in references 7 and 8 with local coefficients predicted by using the best available computer programs. These data, apparently for two-dimensional flow, show that the uncertainty in predicting local gas-to-blade heat-transfer coefficients is at least as large as that assumed herein. In reference 9 some data from these references are summarized and the fundamental mechanisms that influence the predictions are discussed.

Higher-than-assumed uncertainties in local gas-to-blade heat-transfer coefficients might be expected for low-aspect-ratio blading, where secondary flows are prevalent. Improvement in the accuracy of predicting gas-to-blade heat-transfer coefficients is expected with more research, improved computational methods, and better understanding of flow and heat-transfer mechanisms around airfoils, particularly the effects of such factors as transition, stream turbulence, and unsteady flow. Considering the accuracy with which these data might be obtained, it was assumed that the best predictions of local gas-to-blade heat transfer would be within 10 percent.

The current uncertainty in predicting local blade-to-coolant heat-transfer coefficients (for cooling configurations for which prior experimental test data were not available) was assumed to be 20 percent. The basis for this assumption was reference 10, which showed that the coefficient could not be correlated better than 10 percent for idealized flow through a smooth tube. Correlations for more complex cooling schemes and complex entrance shapes, such as those for a turbine blade, would probably be less accurate for the same understanding of flow and heat-transfer mechanisms.

More realistic models of actual blades, more detailed measurements, and a better understanding of the flow and heat transfer within the coolant passages should improve the accuracy in predicting local blade-to-coolant heat-transfer coefficients. The uncertainty, however, is not expected to be much less than 10 percent.

The uncertainties in the blade-wall and ceramic-coating thermal conductances were determined to be 6 and 14 percent, respectively. These numbers were based on the assumption that the thermal conductivities for a batch of the blade metal and plasma-sprayed ceramic coating materials would be known only within uncertainties of 5 and 10 percent, respectively. It was also assumed that the variations in thickness would be 2.5 percent (0.025 cm out of 1 cm) for the blade metal and 10 percent (0.025 cm out of 0.25 cm) for the ceramic coating. The probable uncertainties of the thermal conductances were the root mean squares of the sum of the uncertainties of the thermal conductivities and the wall thicknesses.

RESULTS AND DISCUSSION

The accuracy of analytically predicting steady-state local turbine-blade metal temperatures was examined. The turbine conditions analyzed are shown in table I, the assumed percentage uncertainties in the values of the influence factors are shown in table III, and the calculated reference conditions for the turbines are listed in table II.

Sensitivity of Metal Temperatures to Influence Factors

In the analysis the following six factors were considered to affect the blade metal temperature: gas and coolant temperatures, gas-to-blade and blade-to-coolant heat-transfer coefficients, and the thermal conductances of the wall and the ceramic coating. Although other factors can influence blade temperatures, such as leakages and uncertainty in cooling airflow rates, they were not considered herein. The sensitivity as a percentage of the blade surface metal absolute temperature change for a 1-percent change in influence factor as obtained by directly perturbating equation (2) is listed in table IV.

Values obtained by partially differentiating equation (2) and using equations (4) to (9) differed only slightly from those in table IV, thus indicating near linearity of these equations.

Table IV shows that a percentage change or uncertainty in the gas absolute temperature would result in the largest percentage change in the metal temperature of an uncoated blade. Uncertainty in the coolant temperature would have the greatest effect on the metal temperature of a ceramic-thermal-barrier-coated blade. However, as discussed later, except for the average instrumented engine, where uncertainty in these two boundary conditions is large, the root mean square of their effect on predictions of local blade metal temperature (using eq. (10)) was small. Their independent effect on local blade metal temperatures was also not large as compared with that due to the current uncertainty in local gas-to-blade heat-transfer coefficients.

Uncertainty in Blade Metal Temperature Prediction

The effects of combinations of assumed uncertainties in the influence factors on blade surface metal temperature prediction as determined by perturbating equation (2) are shown in table V. The data are shown as the uncertainty in the wall temperature in degrees kelvin and as the percent uncertainty when referred to the blade metal absolute temperature. The data are for blades with and without a ceramic thermal-barrier coating. When the uncertainties were determined from the partial derivatives of the blade metal temperature with respect to each influence factor (eqs. (4) to (9) along with eq. (10)), the percent uncertainty in T_{wo} in the worst cases was about 1 percent higher than shown in table V for the uncoated blades and 1 percent lower for the coated blades in an average engine with current uncertainties in the influence factors. This indicates the near linearity of the equations for the conditions analyzed.

Engines or high-temperature turbine test rig. - For an average instrumented engine with the current combination of assumed uncertainties in local boundary conditions, geometry, heat-transfer coefficients, and material thermal properties (table III), the uncertainty in analytically predicting or verifying local blade surface metal temperatures is about 98 kelvins (176 deg F), or 7.6 percent of the metal absolute temperature, for uncoated blades and 62 kelvins (112 deg F), or 5.7 percent, for blades with a ceramic thermal-barrier coating. For a highly instrumented engine or a high-temperature turbine test rig, where the local boundary conditions (gas and coolant temperatures) are less uncertain, the uncertainty in predicting or verifying blade surface metal temperatures was 64 kelvins (115 deg F), or 5 percent of the metal absolute temperature, for the uncoated blade and 30 kelvins (54 deg F), or 2.7 percent, for the coated blade. These metal temperature predictions are more accurate than those for an average instrumented engine by 34 kelvins for the uncoated blade and 22 kelvins for the coated blade.

The analysis showed that once the uncertainties in the boundary conditions are at the level of those for the highly instrumented engine or high-temperature turbine test rig, eliminating all uncertainties in the boundary conditions would not significantly lessen blade temperature prediction uncertainties. For example as shown in table V, with perfect knowledge of the gas- and cooling-air temperatures and the blade metal and ceramic thermal conductances, the blade metal temperature prediction uncertainty would decrease by only a fraction of a percent, or about 2 kelvins (3 deg F) for uncoated blades and 6 kelvins (11 deg F) for coated blades, as compared with the assumed current prediction uncertainty for a high-temperature test rig or highly instrumented research engine.

The results of the analysis in table V show that reducing the uncertainties in heat-transfer coefficients can significantly improve the accuracy of blade temperature predictions. For the highly instrumented research engine or high-temperature turbine test rig, improving the current knowledge of local gas-to-blade and blade-to-coolant heat-transfer coefficients to the best expected attainable levels of accuracy (from within 35 percent to within 10 percent and from within 20 percent to within 10 percent uncertainty, respectively) would reduce the uncertainty in predicting blade surface metal temperatures to 28 kelvins (50 deg F), or 2.1 percent of the metal absolute temperature, for uncoated blades and to 21 kelvins (38 deg F), or 1.9 percent, for coated blades. The improvement in blade metal temperature prediction accuracy obtained with more accurate gas- and coolant-side heat-transfer coefficients might be equivalent to that attainable after testing a specific airfoil and cooling configuration and obtaining adequate measurements. The improvement in blade metal temperature prediction accuracy achieved with more accurate gas-to-blade heat-transfer coefficients was more significant than that achieved with more accurate blade-to-coolant coefficients. For example, reducing the uncertainty in the gas-to-blade heat-transfer coefficient alone reduced the uncertainty in blade metal temperature prediction to 35 kelvins (63 deg F), or 2.7 percent of the metal absolute temperature, for the uncoated blades. Reducing the uncertainty in the blade-to-coolant heat-transfer coefficient alone reduced the uncertainty in metal temperature prediction only to 60 kelvins (108 deg F), or 4.7 percent.

Low-temperature turbine test rig. - The results of the analysis in table V show that with current uncertainties in influence factors the blade metal temperature prediction (or verification) uncertainty for the low-temperature test rig is only a fraction of a percent less than that for the high-temperature rig. Perfect knowledge of both the boundary conditions and the wall and ceramic thermal conductances would have no significant effect on the uncertainty in blade metal temperature prediction. Also, as with the high-temperature rig, better knowledge of the local gas-side heat-transfer coefficient and, to a lesser extent, of the coolant-side coefficient significantly reduced the uncertainty in blade metal prediction.

For all conditions the percent uncertainties in predicting or verifying blade metal temperatures were only slightly lower for the low-temperature turbine test rig than for the high-temperature rig.

CONCLUDING REMARKS

The inability to analytically predict local blade surface metal temperatures in a new turbine design with an accuracy closer than 98 kelvins (176 deg F), or 7.6 percent of the metal absolute temperature, with current knowledge implies that large variability in turbine life can be expected without prior hardware tests. The structural and life analyst should use analytically predicted local blade metal temperatures (obtained with current knowledge of influence factors) with caution.

Improvement in knowledge, such as could be obtained from testing a specific airfoil and cooling configuration, could reduce the uncertainty in predicting blade metal temperatures to 28 kelvins (50 deg F), or 2.1 percent of the metal absolute temperature. The greatest improvement in predicting blade metal temperatures would result from more accurate predictions of local gas-to-blade heat-transfer coefficients. More accurate measurement and knowledge of gas and coolant temperatures than currently assumed to be possible will not significantly improve blade metal temperature prediction accuracy.

Using a low-temperature turbine test rig to simulate engine environments would improve the accuracy of blade metal temperature predictions by only a fraction of a percent as compared with using a highly instrumented high-temperature turbine test rig. Direct use and extrapolation of measured dimensionless metal temperature data from low-temperature turbine rig (simulation) tests to high-temperature turbine conditions would require corrections for wall metal and ceramic thermal conductivities by methods such as that described in reference 11. Otherwise, low-temperature turbine rigs require the use of (often difficult to select) materials with thermal conductivities that would provide simulation of the terms in equation (2). Lower cost, considerably better durability of instrumentation, and convenience, however, can influence the decision to use low-temperature rigs.

SUMMARY OF RESULTS

The following results and conclusions were obtained from the analysis to examine the extent to which various factors influence steady-state, turbine-blade metal temperature predictions and to determine the uncertainty of these predictions for conditions of an advanced turbine engine and a highly instrumented turbine test rig and for the same turbine tested at simulated engine conditions:

1. With current assumed knowledge of local boundary conditions (gas and coolant temperatures), geometry, heat-transfer coefficients, and material thermal properties, the uncertainty in analytically predicting local turbine-blade surface metal absolute temperatures in an advanced engine is about 7.6 percent, or 98 kelvins (176 deg F), for

uncoated blades and about 5.7 percent, or 62 kelvins (112 deg F), for ceramic-thermal-barrier-coated blades.

2. For a highly instrumented high-temperature turbine test rig and with assumed better knowledge of local gas and coolant temperatures than in an engine, the uncertainty in predicting the blade metal surface temperatures is about 5 percent, or 64 kelvins (115 deg F), for uncoated blades and 2.7 percent, or 30 kelvins (54 deg F), for coated blades.

3. Despite improved knowledge or accuracy of local gas temperature measurements in a low-temperature-simulation turbine test rig, analysis indicated only a fraction of a percent improvement in the expected accuracy of predicting the surface metal temperatures as compared with that in the high-temperature turbine test rig.

4. Perfect knowledge of the gas and coolant temperatures and of the wall metal and ceramic thermal conductances, as compared with that currently assumed measurable, would not significantly improve the accuracy in predicting blade metal temperatures in the highly instrumented high-temperature turbine test rig. The accuracy would be improved by only a fraction of a percent, or about 2 kelvins (3 deg F), for uncoated blades and 6 kelvins (11 deg F) for coated blades.

5. Improving the current knowledge of local gas-to-blade and blade-to-coolant heat-transfer coefficients to the best assumed attainable levels of accuracy (from 35 to 10 percent and from 20 to 10 percent, respectively) would significantly improve the ability to predict blade metal temperatures. The prediction accuracy would improve from 5 percent, or 64 kelvins (115 deg F), to about 2.1 percent, or 28 kelvins (50 deg F), for uncoated blades and from 2.7 percent, or 30 kelvins (54 deg F), to 1.9 percent, or 21 kelvins (38 deg F), for coated blades at the conditions in the high-temperature turbine test rig. Improving the accuracy of the gas-to-blade coefficient was more significant than improving the accuracy of the blade-to-coolant coefficient.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 6, 1980,
505-04.

REFERENCES

1. Kline, S. J.; and McClintock, F. A.: Describing Uncertainties in Single-Sample Experiments. Mech. Eng., vol. 75, no. 1, Jan. 1953, pp. 3-8.

2. Gauntner, Daniel J.; and Sucec, James: Method for Calculating Convective Heat-Transfer Coefficients Over Turbine Vane Surfaces. NASA TP-1134, 1978.

3. Hippensteele, Steven A.; and Colladay, Raymond S.: Computer Program for Obtaining Thermodynamic and Transport Properties of Air and Products of Combustion of ASTM-A-1 Fuel and Air. NASA TP-1160, 1978.

4. Liebert, C. H.; and Stepka, F. S.: Potential Use of Ceramic Coating as a Thermal Insulation on Cooled Turbine Hardware. NASA TM X-3352, 1976.

5. Liebert, Curt H.; and Stepka, Francis S.: Industry Tests of NASA Ceramic Thermal Barrier Coating. NASA TP-1425, 1979.

6. Colladay, Raymond S.; and Stepka, Francis S.: Similarity Constraints in Testing of Cooled Engine Parts. NASA TN D-7707, 1974.

7. Louis, Jean F.: Systematic Studies of Heat Transfer and Film Cooling Effectiveness. High Temperature Problems in Gas Turbine Engines, AGARD CP-229, 1977, pp. 28-1 to 28-36.

8. Turner, A. B.: Local Heat Transfer Measurements on a Gas Turbine Blade. J. Mech. Eng. Sci., vol. 13, no. 1, Feb. 1971, pp. 1-12.

9. Graham, R. W.: Fundamental Mechanisms that Influence the Estimation of Heat Transfer to Gas Turbine Blades. NASA TM-79128, 1979.

10. Taylor, Maynard F.: Experimental Local Heat-Transfer and Average Friction Data for Hydrogen and Helium Flowing in a Tube at Surface Temperatures up to 5600° R. NASA TN D-2280, 1964.

11. Gladden, Herbert J.: Extension of Similarity Test Procedures to Cooled Engine Components with Insulating Ceramic Coatings. NASA TP-1615, 1980.

TABLE I. - ASSUMED TURBINE CONDITIONS

Condition	Engine or high-temperature turbine test rig	Low-temperature (simulation) turbine test rig
Gas temperature, K	1700	756
Gas pressure, atm	40	15.6
Cooling-air temperature, K	922	409
Gas-stream Mach number	0.4	0.4

TABLE II. - CALCULATED REFERENCE CONDITIONS

Condition	Engine or high-temperature turbine test rig	Low-temperature (simulation) turbine test rig
Gas-to-blade heat-transfer coefficient, W/m K	8.605×10^3	4.967×10^3
Blade-to-coolant heat-transfer coefficient, W/m K	12.917×10^3	7.460×10^3
Wall thermal conductance, W/m K:		
For coated blade	35.50×10^3	16.80×10^3
For uncoated blade	40.67×10^3	20.15×10^3
Ceramic thermal conductance, W/m K	3.802×10^3	2.514×10^3
Blade metal outer-surface temperature, K:		
For coated blade	1092	493
For uncoated blade	1285	574

TABLE III. - ASSUMED PERCENT UNCERTAINTIES IN INFLUENCE FACTORS

Influence factor	Average instrumented engine	Highly instrumented engine or high-temperature turbine test rig	Highly instrumented low-temperature (simulation) turbine test rig
	Assumed percent uncertainty		
Gas temperature	9.8	2	1
Coolant temperature	3	1	1
Gas-to-blade heat-transfer coefficient:			
Current	35	35	35
Best expected	10	10	10
Blade-to-coolant heat-transfer coefficient:			
Current	20	20	20
Best expected	10	10	10
Blade wall thermal conductance	6	6	6
Ceramic thermal conductance	14	14	14

TABLE IV. - TURBINE-BLADE WALL SURFACE TEMPERATURE CHANGE FOR

1 PERCENT CHANGE IN INFLUENCE FACTOR

Influence factor	Engine or high-temperature turbine test rig		Low-temperature (simulation) turbine test rig	
	Uncoated blades	Coated blades[a]	Uncoated blades	Coated blades[a]
	Change in blade metal temperature, percent of metal absolute temperature			
Gas temperature	0.60	0.48	0.61	0.36
Cooling-air temperature	.37	.70	.36	.61
Gas-to-blade heat-transfer coefficient	.15	.052	.15	.056
Blade-to-coolant heat-transfer coefficient	-.12	-.11	-.12	-.11
Ceramic thermal conductance	0	.087	0	.083
Metal wall thermal conductance	-.029	-.041	-.053	-.037

[a]Thermal-barrier coating.

TABLE V. - UNCERTAINTY IN PREDICTION OF LOCAL BLADE METAL SURFACE TEMPERATURES

	Uncoated blades		Coated blades[a]	
	Temperature change, kelvin	Temperature change, percent of metal absolute temperature	Temperature change, kelvin	Temperature change, percent of metal absolute temperature
Average instrumented engine				
Effect of current uncertainties	98	7.6	62	5.7
Highly instrumented research engine or high-temperature turbine test rig				
Effect of current uncertainties	64	5.0	30	2.7
Perfect knowledge of boundary conditions[b] and conductances	62	4.8	24	2.2
Effect of best expected future knowledge of -				
Both heat-transfer coefficients	28	2.1	21	1.9
Gas-side coefficient only	35	2.7	25	2.3
Coolant-side coefficient only	60	4.7	26	2.4
Low-temperature (simulation) turbine test rig				
Effect of current uncertainties	27	4.7	11	2.3
Perfect knowledge of boundary conditions[b] and conductances	27	4.7	9	1.9
Effect of best expected future knowledge of -				
Both heat-transfer coefficients	11	1.9	8	1.6
Gas-side coefficient only	14	2.4	10	2.1
Coolant-side coefficient only	26	4.5	10	1.9

[a]Thermal-barrier coating.

[b]Boundary conditions defined as local-gas and cooling-air temperatures.

1. Report No.
NASA TP-1593

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
ANALYSIS OF UNCERTAINTIES IN TURBINE METAL TEMPERATURE PREDICTIONS

5. Report Date
April 1980

6. Performing Organization Code

7. Author(s)
Francis S. Stepka

8. Performing Organization Report No.
E-228

10. Work Unit No.
505-04

9. Performing Organization Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Paper

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract
An analysis was conducted to examine the extent to which various factors influence the accuracy of analytically predicting turbine-blade metal temperatures and to determine the uncertainties in these predictions for several accuracies of the influence factors. Advanced-turbofan-engine gas conditions of 1700 K and 40 atmospheres were considered along with those of a highly instrumented high-temperature turbine test rig and a low-temperature turbine rig that simulated the engine conditions. The analysis showed that the uncertainty in analytically predicting local blade temperature was as much as 98 kelvins (176 deg F), or 7.6 percent of the metal absolute temperature, with current knowledge of the influence factors. Expected reductions in uncertainties in the influence factors with additional knowledge and tests should reduce the uncertainty in predicting blade metal temperature to 28 kelvins (50 deg F), or 2.1 percent of the metal absolute temperature.

17. Key Words (Suggested by Author(s))
Turbines
Cooling
Metal temperatures
Prediction accuracies

18. Distribution Statement
Unclassified - unlimited
STAR Category 07

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	18	A02

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1980

National Aeronautics and Space Administration

Washington, D.C. 20546

Official Business

Penalty for Private Use, $300

SPECIAL FOURTH CLASS MAIL
BOOK

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA-451

U.S. MAIL

1 1 1U,A, 042180 S00903DS
DEPT OF THE AIR FORCE
AF WEAPONS LABORATORY
ATTN: TECHNICAL LIBRARY (SUL)
KIRTLAND AFB NM 87117

NASA

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return