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Feasibility of Water Injection into the Turbine Coolant to Permit Gas Turbine Contingency Power for Helicopter Application

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THE FEASIBILITY OF WATER INJECTION INTO THE TURBINE COOLANT TO PERMIT GAS TURBINE CONTINGENCY POWER FOR HELICOPTER APPLICATION

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ABSTRACT

A system which would allow a substantially increased output from a turboshaft engine for brief periods in emergency situations with little or no loss of turbine stress rupture life is proposed and studied analytically. The increased engine output is obtained by overtemperaturing the turbine; however, the temperature of the compressor bleed air used for hot section cooling is lowered by injecting and evaporating water. This decrease in cooling air temperature can offset the effect of increased gas temperature and increased shaft speed and thus keep turbine blade stress rupture life constant. The analysis utilized the NASA-Navy-Engine-Program or NNEP computer code to model the turboshaft engine in both design and off-design modes. This report is concerned with the effect of the proposed method of power augmentation on the engine cycle and turbine components.

A simple cycle turboshaft engine with a 16:1 pressure ratio and a 1533 K (2760° R) turbine inlet temperature operating at sea level static conditions was studied to determine the possible power increase and the effect on turbine stress rupture life that could be expected using the proposed emergency cooling scheme.

The analysis showed a 54 percent increase in output power can be achieved with no loss in gas generator turbine stress rupture life. A 231 K (415° F) rise in turbine inlet temperature is required for this level of augmentation. The required water flow rate was found to be 0.0109 kg water per kg of engine air flow. For a 4.474 MW (6000 shp) engine this would require 32.26 kg (71.13 lbm) of water for a 2.5 minute transient.

At this power level, approximately 25 percent of the uncooled power turbine life is used up in a 2 1/2-minute transient. If the power turbine were cooled, this loss of stress-rupture life could be reduced to zero.

Also presented in this report are the results of an analysis used to determine the length of time a ceramic thermal barrier coating would delay the temperature rise in hot parts during operation at elevated temperatures. It was hoped that the thermal barrier could be used as a scheme to allow increased engine output while maintaining the life of hot section parts during short overtemperature transients.

The thermal barrier coating was shown to be ineffective in reducing blade metal temperature rise during a 2.5-minute overtemperature.

INTRODUCTION

Power from a helicopter engine at levels greater than the maximum rating may be desirable in several emergency situations. One scenario might be: a large twin engine helicopter with a full load loses one engine, the pilot requires increased power for a brief period from the remaining engine to land safely. This is the one engine inoperative (OEI) case. Another situation might be a hot day at high altitude where a power level greater than the 5 to 15 minute maximum power rating is required for a short duration to insure a safe takeoff.

Semple, et al.(1) analyzed combat loss data for twin-engine helicopters. They found that 90 percent of power losses involved only one engine. They claim that if the remaining engine would have been capable of emergency power levels greater than fifty percent of the maximum power rating then power loss mishaps could have been reduced from 13.3 per 100,000 hours to 5.9 per 100,000 hours.

In reference 1 it was also found that emergency power capability in the OEI situation would also benefit commercial helicopter operation. Current gross weight capacity is limited by OEI capability. A 24 percent emergency power increase relative to maximum power rating would allow the load for the Boeing model 107 to be increased from six to twenty passengers on a 38° C (100° F) day.

Methods of augmentation with OEI were studied in reference 2. The main conclusions reached were that a combination of water/alcohol injection into the inlet and overtemperature/overspeed could provide adequate emergency power. With this method of obtaining emergency power, hot section life is reduced to hours. Hot section replacement would thus be required after emergency power application. It is pointed out in reference 2 that to comply with present FAA regulations, emergency power must be demonstrated in a daily preflight check. This limits the use of overtemperature because of damage to hot section parts.

Dugas (3) studied many different possible augmentation systems. He defined two different levels of emergency power; one was hot day, high altitude augmentation. The engine would be required to produce the same power as at sea level standard day for five minutes with no loss of engine life. The second level of augmentation would be at sea level standard day conditions with OEI. The remaining engine would be required to produce 90 percent of the total installed power of both engines for one minute without regard to engine life. The preferred methods of augmentation involved compressor inlet water injection and/or turbine overtemperature with fuel cooling of turbine cooling air.

Brooks (4) investigated the effects on engine operating conditions of power augmentation levels of 10, 20, and 50 percent relative to intermediate rated power (IRP) for a 2 1/2-minute transient. In all cases, the method of augmentation was overspeed/overtemperature and, in addition, for the 50 percent power augmentation level water injection into the compressor inlet was used. He assumed that the ten percent augmentation level would require no specific maintenance but the higher level would require post inspection and repair as necessary. The conclusion was that the ten and twenty percent levels would be feasible and would not adversely affect the engine design by increasing size, weight, SFC, etc. Augmentation levels in excess of 20 percent are expected to be limited by compressor surge and local hot spots which would cause corrosion and/or adversely affect hot component life.

In 1977 while the author was conducting a literature survey on the application of liquid cooling to gas turbines (5), a scheme which would allow water cooling to be applied to the contingency power problem was conceived. Initial calculations showed the scheme had promise and in 1978 more detailed calculations were made using the NNEP computer code (6). The purpose of this report is to document the results of the feasibility study which analytically investigated the maximum possible level of augmentation with constant gas generator turbine stress rupture life as a constraint.

In the proposed emergency power augmentation scheme, the increased engine output is obtained by turbine overtemperature, however, the temperature of the compressor bleed air used for hot section cooling is lowered by injecting and evaporating water. This decrease in cooling air temperature can offset the effect of increased gas temperature and thus keep turbine blade stress rupture life constant. As in references 1, 2, and 4, 2 1/2 minutes was used as the length of time for which contingency power would be required.

It is important to note that liquid water is not allowed to come into contact with the turbine blades. Liquid cooling research performed in the 1950's at Lewis showed that the thermal shock of sudden water application had the potential to fracture turbine blades (7). The coolant in the proposed scheme consists of compressor discharge air mixed with superheated steam.

The NNEP computer code was used to model a typical turboshaft engine of the type in use for helicopter propulsion. The engine selected had a 16:1 overall pressure ratio and a turbine inlet temperature of 1533 K (2760° R). The gas generator turbine was cooled while the power turbine was not. The criterion used to judge the success of the method was whether the gas generator turbine blade stress-rupture life could be maintained the same with application of emergency power. Stress-rupture life is the time required to produce failure in a constant load, elevated temperature environment. The results of the computer analysis of the engine were used along with a stress rupture analysis to determine the maximum level of augmentation possible with the proposed scheme. Also determined from the study were the required water usage rate and power turbine life fraction used for various levels of augmentation.

Also included in this report are the results of a transient heat conduction analysis to determine the length of time a ceramic thermal barrier coating would delay the temperature rise in cooled turbine blades during operation at elevated temperatures. It was hoped that the thermal barrier could be used to allow increased engine output while maintaining the life of hot section parts during short overtemperature transients.

THE PROPOSED METHOD

A schematic diagram of a turboshaft engine utilizing the proposed emergency power augmentation system is shown in figure 1. When emergency power is required, the fuel flow rate to the burner is increased. This causes an increase in the gas temperature, resulting in increased power output for both gas generator and power turbines. Gas generator shaft speed (and thus cycle pressure ratio) increases slightly, further adding to power output.

Unless something is done to keep the turbine blades and other hot parts cool, their temperature will rise with increasing gas temperature until their stress rupture life is completely used up and they fail. To prevent this from happening, it is proposed that the temperature of the compressor bleed air used for turbine cooling be lowered by injecting and evaporating water.

During the application of contingency power, the turbine coolant would be composed of air and saturated steam. Both the rotor and stator are cooled with this mixture. It is theoretically possible to lower the temperature of the cooling air to the saturation temperature of the injected water without having any liquid water left over. The saturation temperature is a function of the pressure. It is thought to be important that no liquid water be allowed to come into contact with hot metal parts. The vast difference in cooling rates between liquid water and air may cause turbine blade failure by thermal shock as demonstrated in reference 7.

ANALYSIS

The proposed emergency cooling scheme was analyzed by using the NNEP computer code to model the thermodynamic performance of a typical helicopter turboshaft engine in both the design and off design modes. To study the effectiveness of the proposed emergency power scheme, the burner temperature was raised above the design value by a small amount and water was mixed and evaporated in the turbine coolant at the rate which produced saturation. The increased gas generator speed and gas temperature were used in a stress-rupture model to determine the blade metal temperature required to give constant stress rupture life. A correlation of coolant flow and dimensionless average blade wall tem-

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perature was used to calculate the required coolant temperature. This required coolant temperature was compared to the temperature of the saturated steam-air coolant mixture and if it was higher, the burner temperature was raised further and the analysis repeated. This was continued until the required and saturated (minimum) coolant temperatures were equal. This was considered to be the point of maximum emergency power for the system with the constraint of constant gas generator turbine stress rupture life.

The analysis will be divided into three sections: the NNEP computer model of the turboshaft engine studied, the stress rupture model, and the thermal barrier-transient conduction model.

The NNEP Engine Model

Figure 2 is a diagram showing the arrangement of components used to model the engine in this study. The square boxes represent individual components and lines between boxes represent flow path. The circled numbers represent stations where flows and pressures were balanced. Heavy dark lines represent shafting between components. Numbers in the boxes are component numbers corresponding to the numbers in Table I which is a summary of each component at the design condition. All calculations were performed at sea level static conditions. At design, the engine has a 16:1 overall pressure ratio. The compressor is split into two parts to allow turbine rotor cooling air to be bled off at a lower pressure. Compressor off design performance is determined from the flow and efficiency maps shown in figure 3a and b. These maps represent no particular compressor but were formulated to be representative of the type of compressor used in a helicopter engine. The same map is applied to both compressors shown in figure 2. At the design condition, the turbine inlet temperature was 1533 K (2760° R). Stator cooling air was mixed in with mainstream hot gas ahead of the gas generator rotor and allowed to do work in the turbine. Rotor cooling air was mixed downstream of the gas generator turbine and does work only in the power turbine. The flow and efficiency maps for both gas generator and power turbine are shown in figures 3c through f. As with the compressor maps they are generic in nature and represent no particular helicopter engine. The water injectors mix water with the turbine cooling air at the proper rate to obtain saturation, thus the coolant temperature is the lowest theoretically possible for all off design cases studied.

Stress Rupture

Gas generator turbine. - To calculate an allowable design point stress for the example turbine several assumptions had to be made. Coolant flow rates were assumed to be 6.85 percent for the stator and 4.80 percent (both based on air flow rate at station 3) for the rotor. These values are reasonable for a modern turbine engine operating at the conditions considered here. To calculate the rotor relative gas temperature for heat transfer the following assumptions were made:

Stator turning angle = 70°

Stator exit critical velocity ratio = 0.85

Mean rotor blade speed = 488 m/sec (1600 ft/sec)

The stator exit critical velocity was then calculated from

$$V_{cr} = \sqrt{\frac{2\gamma}{\gamma+1}\,\frac{R}{m}\,T_9} \qquad (1)$$

The subscripts on the temperature refers to the station number on figure 2. For the combustion products the ratio of specific heats, γ, and the molecular weight, m, were taken from reference 8. The stator exit absolute velocity, V, was then calculated as

$$V = 0.85\ V_{cr} \qquad (2)$$

From the stator exit velocity triangle shown in figure 4 it can be seen that the rotor relative inlet velocity is

$$W = \sqrt{W_x^2 + (V_u - U)^2} \qquad (3)$$

The rotor relative total temperature is then given by (9)

$$T_9'' = T_9' - \frac{V^2 - W^2}{2g_c\,Jc_p} \qquad (4)$$

The specific heat of the combustion products was also taken from reference 8.

A curve fit of data given in figure 9 of reference 10 was used to obtain an expression which correlates blade wall temperature data over a wide range of temperatures and coolant flows. The correlation is

$$\phi = \frac{T_9'' - T_B}{T_9'' - T_{ca}} = \frac{1}{1 + 0.13\left(\dfrac{\dot{w}_g}{\dot{w}_{ca}}\right)^{0.7}} \qquad (5)$$

Given the coolant and main gas stream flow rates, $\dot{w}_{ca}$ and $\dot{w}_g$ respectively and the relative gas temperature T_9'' and relative coolant temperature, T_{ca}, this expression allowed the calculation of blade average metal temperature, T_B.

In order to calculate an allowable design stress, a blade material, B1900, was selected as typical of nickel base superalloys for stress rupture properties. The stress rupture properties of this alloy can be described by (11):

$$T_B(20+\log_{10}t)\times10^{-3} = 3.081 + 33.08(\log_{10}\sigma) - 5.111(\log_{10}\sigma)^2 \qquad (6)$$

The design point stress rupture life was taken as 1000 hours and a factor of safety of 2.5 was used as a multiplier giving

$$t = 2500\ \text{hours} \qquad (7)$$

With the life and calculated metal temperature, T_B, the quadratic formula was applied to equation (6) and the allowable design stress, σ_D, was calculated.

The off design blade stress, or stress during application of emergency cooling, was calculated from

$$\sigma_{OD} = \sigma_D\left(\frac{\Omega_{OD}}{\Omega_D}\right)^2 \qquad (8)$$

Ω_{OD} and Ω_D are the off design and design shaft speeds respectively. The value of σ_{OD} was then used in equation (6) to find the required blade metal temperature, T_B, for constant stress rupture life (t = 2500).

The off design mean blade speed was calculated from the equation

$$U_{OD} = U_D \left(\frac{\Omega_{OD}}{\Omega_D}\right) \quad (9)$$

Equations (3) and (4) were used to calculate the new relative total temperature, T_9''.

The dimensionless wall temperature expression (equation (5)) was then used again to find the required coolant temperature

$$T_{ca} = T_9'' - \frac{T_9'' - T_B}{\phi} \quad (10)$$

The dimensionless wall temperature calculated from equation (5) reflected an increased coolant flow due to the water injection and increased air flows at off-design. Air properties were used for the coolant; the thermal property changes of the coolant due to steam mixing were ignored. This is thought to be conservative since the thermal properties of steam are more favorable for heat transfer than those of air.

Power turbine. - The power turbine in this example engine was uncooled. The proposed scheme to lower coolant temperature thus has no effect on the power turbine and its life can be expected to be shortened due to increased temperature. If a cooled power turbine were utilized, its stress-rupture life could also be preserved by injecting water into its cooling air.

For the present analysis, the fraction of power turbine life used per application of emergency power was estimated using a method similar to that in reference 12. For the power turbine the blade stress remains constant because the rotor speed was held constant. This analysis assumes that the increased bending stresses due to increased blade gas loading are negligible compared to the centrifugal stress. The right hand side of equation (6) is thus constant. The fraction of power turbine life used during a 2.5-minute application of emergency power was calculated as

$$f = 2.5/t_{SR} \quad (11)$$

where t_{SR} is the time-to-stress rupture in minutes at the elevated temperature. t_{SR} was calculated from equation (6) with σ given and T_B assumed to be equal to the hot gas stream temperature at station 11.

Water flow rates. - At the maximum theoretical level of emergency power, the water-air coolant mixture will contain saturated steam. At power levels less than the theoretical maximum, the coolant stream will contain air and superheated steam. All of the off-design NNEP calculations were carried out using the maximum water flow rate—the rate that makes the mixed coolant stream saturated. The water flow rates calculated in this section are estimates of the actual required water flow rate based on the temperature of coolant necessary to maintain constant stress rupture life. The water flow required to obtain this temperature was calculated from a simple energy balance on the mixing water and air streams. Assuming 100 percent water evaporation this gives an expression for the water flow rate into the rotor cooling air

$$\dot{w}_{H_2O,R} = \dot{w}_{ca,R}\left(\frac{H_{ca,in} - H_{ca,T_c}}{H_{H_2O,T_c} - H_{H_2O,in}}\right) \quad (12)$$

$\dot{w}_{ca,R}$ is the rotor cooling air mass flow rate, $H_{ca,in}$ and H_{ca,T_c} are the enthalpies of the cooling air before and after mixing respectively. H_{H_2O,T_c} and $H_{H_2O,in}$ are the enthalpies of the water after and before mixing respectively.

The total water flow rate was then calculated by assuming that the ratio of water to air mass flows remains the same in the stator coolant stream as that required in the rotor coolant stream. The total water flow rate was found from

$$\dot{w}_{H_2O} = \dot{w}_{H_2O,R}\left(1 + \frac{\dot{w}_{ca,S}}{\dot{w}_{ca,R}}\right) \quad (13)$$

where $\dot{w}_{H_2O}$ is the total water mass flow rate required by rotor and stator, $\dot{w}_{ca,S}$ is the stator cooling air mass flow rate.

Thermal Barrier Coating

The ability of a thermal barrier coating to delay the rise in cooled blade metal temperature during an emergency power transient was assessed analytically. A thermal barrier of zirconia 0.038 cm (.015 inch) thick was assumed to be applied to the exterior of the blade. A transient heat conduction computer code was used to compare the rise in blade average metal temperatures for both coated and uncoated blades subjected to a sudden rise in gas temperature. The heat conduction code uses the method of solution described in reference 13.

The following assumptions were made in order to determine a representative value for gas-to-blade heat transfer coefficient:

- Blade average surface Mach number, M = 0.6
- Blade chord, C = 5.72 cm (2.25 inch)
- Pressure, p" = 1.46 k Pa (212 psia)
- Relative total gas temperature, Tg" = 1422 K (2560° R)

The gas side heat transfer coefficient was then calculated from (14):

$$h_g = \frac{0.0325}{C} k_g \left[\frac{p'' M \sqrt{\frac{\gamma T_g''}{(R/m)}}\; C}{\mu\, T_{ref}\left(1 + \frac{\gamma-1}{2} M^2\right)^{(3\gamma-1)/(2(\gamma-1))}}\right]^{.8} \quad (14)$$

The gas properties were taken from reference 8 and the reference temperature, T_{ref}, was the average between wall and hot gas temperatures.

The coolant side air temperature was assumed to be 721 K (1297° R) and average blade metal temperature was assumed to be 1089 K (1960° R). At the average coating

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temperature, the thermal properties of the thermal barrier coating material were assumed to be (15):

$$\text{Thermal conductivity} = 1.506 \frac{W}{m-{}^\circ C} \left(0.87 \frac{Btu}{hr-ft-{}^\circ R}\right)$$

$$\text{Density} = 4636 \frac{kg}{m^3} \left(289.4 \frac{lbm}{ft^3}\right)$$

$$\text{Specific heat} = 0.16 \frac{cal}{gm-K} \left(0.16 \frac{Btu}{lbm-{}^\circ R}\right)$$

The thermal properties of the blade wall material were taken as representative of B 1900 superalloy (16).

$$\text{Thermal conductivity} = 22.50 \frac{W}{m-K} \left(13 \frac{Btu}{hr-ft-{}^\circ F}\right)$$

$$\text{Density} = 7753 \frac{kg}{m^3} \left(484 \frac{lbm}{ft^3}\right)$$

$$\text{Specific heat} = 0.11 \frac{cal}{gm-K} \left(0.11 \frac{Btu}{lbm-{}^\circ R}\right)$$

A simple one dimensional energy balance on the element of blade wall shown in figure 5 then gave the coolant side heat transfer coefficients necessary to maintain the average wall temperature of 1089 K (1960° R). For the cases studied these were:

$1584 \frac{W}{m^2-K} \left(279 \frac{Btu}{hr-ft^2-{}^\circ F}\right)$ for the coated blade and

$3163 \frac{W}{m^2-K} \left(557 \frac{Btu}{hr-ft^2-{}^\circ F}\right)$ for the uncoated blade.

The application of emergency power was simulated by a 256 K (460° R) step temperature rise in turbine inlet temperature. Coolant and gas side heat transfer coefficients as well as coolant temperature were assumed constant during the transient. These assumptions were thought to be accurate enough to assess the value of thermal barrier coating in delaying metal temperature rise during a transient.

RESULTS AND DISCUSSION

A scheme has been proposed which will allow increased power from a turboshaft engine in emergency situations without decreasing gas generator turbine life. Emergency power is derived by increasing turbine inlet temperature and the turbine is protected by lowering its cooling air temperature with water injection and evaporation. An analysis was conducted to determine the level of increased power possible using the proposed coolant water injection scheme. The performance of a modern turboshaft engine was simulated in both design and off design modes with the NNEP computer code. An analysis was also conducted to determine if any significant delay in turbine blade metal temperature rise during an overtemperature transient could be obtained by using a thermal barrier coating.

Maximum power. - The maximum power obtainable using the proposed scheme can be determined from figure 6. Shown on the figure are the required coolant temperature versus percent power increase. This curve was obtained from the NNEP and stress rupture analysis as explained in the ANALYSIS section. The near horizontal line on the figure shows the lowest possible coolant temperature obtainable using water injection and evaporation. Any increase in power where the required coolant temperature curve is higher than the minimum obtainable coolant temperature is thus possible. The point where the two curves cross is the theoretical maximum increase in power for constant gas generator turbine life. For the engine studied the maximum power increase possible was found to be 54.6 percent.

Water flow rate. - The water flow rate required to maintain constant gas generator turbine life can be determined from figure 7. The figure shows dimensionless water flow rate as a function of percent power increase. The water flow rate was made dimensionless by dividing by the air flow rate at station 3 (see figure 2). As an example of how much water would be required for a helicopter engine in an emergency situation consider a 4.474 MW (6000 shp) engine operating at the temperatures and pressure ratio previously described (turbine inlet temperature = 1533 K (2760° R), pressure ratio 16:1). For a 54.6 percent increase in power to 6.92 MW (9276 shp) the air flow at station 3 would be 19.73 kg/sec (43.5 lbm/sec). The weight of water required for a 2 1/2-minute application of emergency power at this level would be:

$$\left(10.9 \times 10^{-3} \frac{kg - H_2O}{kg - air}\right)\left(19.73 \frac{kg}{sec}\right)\left(60 \frac{sec}{min}\right)(2.5 \text{ min})$$

$$= 32.26 \text{ kg} - H_2O \ (71.13 \text{ lbm} - H_2O).$$

Power turbine life. - The fraction of power turbine life used during a 2.5 minute application of emergency power is shown versus percent power increase over the design value on figure 8. At the maximum value of 54.6 percent increased power, the power turbine would use up approximately 25 percent of its total stress rupture life. This is a less than desirable situation but it must be remembered that the power turbine in this study was uncooled. The proposed scheme could be applied to a cooled power turbine and no loss of turbine stress rupture life would occur.

Thermal barrier coating. - The results of the transient heat conduction analysis on the segment of turbine blade wall shown in figure 5 are given on figure 9. The figure shows blade average wall temperature (temperature of the superalloy not the thermal barrier coating) as a function of time from the beginning of the transient step in gas temperature. The coolant side heat transfer coefficients were selected to give the same metal temperature for both coated and uncoated blades. It can be seen from the figure that the thermal barrier coating only has an effect for about six seconds. It can be concluded that the thermal barrier coating is of virtually no value in keeping blade metal temperature transients at acceptable levels for a 2.5 minute overtemperature.

SUMMARY OF RESULTS

An analytical investigation into the feasibility of using water injection and evaporation into the turbine cooling air to allow increased power output from a turboshaft engine has been conducted. The power increase is obtained by turbine overtemperature. The feasibility of using a thermal barrier coating on the blade to delay the rise in blade metal temperature during an overtemperature was also investigated analytically. The results of the study can be summarized as follows:

1. The theoretical maximum power increase possible was found to be 54.6 percent.

2. A dimensionless water flow rate Of 0.0109 kg water per kg of engine airflow would be required to maintain constant gas generator turbine stress rupture life at the maximum power increase of 54.6 percent. It was shown that a 4.474 MW (6000 shp) engine would require 32.26 kg (71.13 lbm) for a 2.5-minute application of emergency power at the maximum level.

3. Approximately 25 percent of the uncooled power turbine stress-rupture life is used up during a 2.5 minute overtemperature. This could be reduced to zero if the power turbine were cooled.

4. The thermal barrier coating was shown to be of no value in reducing the blade metal temperature rise during a 2.5-minute transient.

CONCLUDING REMARKS

While the analysis has shown promising potential for the proposed emergency power augmentation system, the reader should be cautioned that this is a theoretical maximum value. The actual level of power increase obtainable with this system will be somewhat lower for several reasons; the main reason being the efficiency of evaporation. If the water flow rate required for this level of power increase cannot be fully evaporated, liquid water will spill over into the coolant stream. Liquid coming into contact with hot turbine parts could be disastrous. Thus, a lower water flow rate may be required to obtain a safety margin.

Another source of trouble could be the compressor operating point. As the power level is increased, the compressor is driven toward surge. This can be seen on figure 3a; the open symbols are the design points and the closed symbols are the maximum emergency power operating points for compressors 1 and 2. As shown in Table II, the surge margin for compressor 2 goes from 13.54 percent at the design point to 5.65 percent at the maximum power point. This was pointed out in reference 4.

Finally, the analysis does not consider other hot components in the engine. It was assumed that shrouds, combustor liners, etc. would be designed to withstand the required temperature transients. In reference 4 Brooks also warns that overtemperature can lead to local hot spots that could decrease turbine life through increased corrosion.

SYMBOLS

C	blade chord
C_p	specific heat at constant pressure
C_d	discharge coefficient for nozzle
f	life fraction
g_c	gravitational conversion factor (1.0 for metric units)
H	enthalpy
h	heat transfer coefficient
J	mechanical equivalent of heat (1.0 for metric units)
k	thermal conductivity
M	Mach number
m	molecular weight
N	shaft speed
PR	pressure ratio
p	pressure
R	universal gas constant
T	temperature
t	time
U	blade speed
V	velocity in absolute frame of reference
W	velocity in relative frame of reference
$\dot{w}$	mass flow rate

Greek Symbols

γ	ratio of specific heats
ϕ	dimensionless wall blade wall temperature defined by equation (5)
Δ	difference
δ	ratio of inlet total pressure to standard pressure
θ	ratio of inlet total temperature to standard temperature
ϵ	function of specific heat ratio
Ω	shaft speed
σ	normal stress
μ	viscosity
η	efficiency

Subscripts

B	blade
ca	cooling air
cr	critical conditions
D	design conditions
g	hot gas
H_2O	water
in	inlet
OD	off design
out	outlet
R	rotor
ref	reference
S	stator
SR	stress-rupture
T_c	evaluated at cooling air temperature
u	tangential component
x	axial component

Superscripts

(')	total absolute conditions
(")	total relative conditions

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TABLE I. SUMMARY OF ENGINE COMPONENTS IN NNEP MODEL

Component No.	Type	Characteristics at Design Point
1	Inlet	exit pressure/ram pressure = 1.0
2	Duct	$\Delta p/p$ = 0.01; split off IPS bleed air
3	Compressor	η = 0.81; PR = 12:1; surge margin = 12.5 percent
4	Splitter	4.80 percent of flow at station 3 split off for rotor cooling; $\Delta p/p$ = 0.06 cooling flow stream
5	Compressor	η = 79.5 percent; PR = 1.33:1; surge margin = 14 percent
6	Splitter	6.85 percent of flow at station 3 split off for stator cooling; $\Delta p/p$ = 0.5 cooling flow stream
7	Duct (Burner)	burner efficiency = 99 percent; $\Delta p/p$ = 0.06; outlet temperature = 1533° K (2760° R)
8	Mixer	mix stator cooling flow with main stream
9	Turbine	PR = 4.63; η = 0.832 gas generator turbine
10	Mixer	mix rotor cooling flow with main stream
11	Turbine	PR = 3.108; η = 0.87 power turbine (uncooled)
12	Duct	no losses
13	Nozzle	C_d = 0.85; overall pressure ratio = 1.045 inlet total to exit static
14	Shaft	gas generator turbine to compressor; no losses
15	Shaft	power turbine to load; no losses; speed 20,000 RPM
16	Load	shaft power to gear box, etc.
17	Water Injector	spray water into cooling air; not used at design
18	Water Injector	spray water into cooling air; not used at design
19	Duct	$\Delta p/p$ = 0.71; drop pressure to match rotor relative pressure

TABLE II. SUMMARY OF MAJOR COMPONENT PARAMETERS

Component	Design				Off-design			
	Pressure ratio	Efficiency, percent	Surge margin, percent	Speed, percent	Pressure ratio	Efficiency, percent	Surge margin, percent	Speed, percent
Compressor 1	12.00	81.00	10.68	100.00	14.68	79.29	12.61	106.6
Compressor 2	1.33	79.5	13.64	100.00	1.407	81.30	5.66	106.6
	Rotor relative mixed inlet temperature, (°R)	Pressure ratio	Efficiency, percent	Coolant* fraction, percent	Rotor relative mixed inlet temperature, (°R)	Pressure ratio	Efficiency, percent	Coolant fraction* (inc. water) percent
Gas generator turbine	2665	4.63	83.20	4.80	2946	4.72	83.21	6.31
Power turbine	1964	3.11	87.00	0	2186	3.84	86.15	0

*Based on air flow at station 3

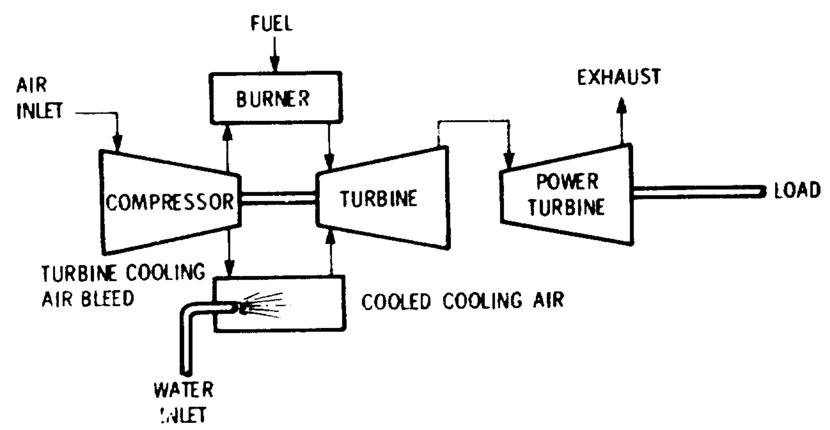


Figure 1. - Schematic diagram of a gas turbine engine utilizing the proposed emergency cooling system.

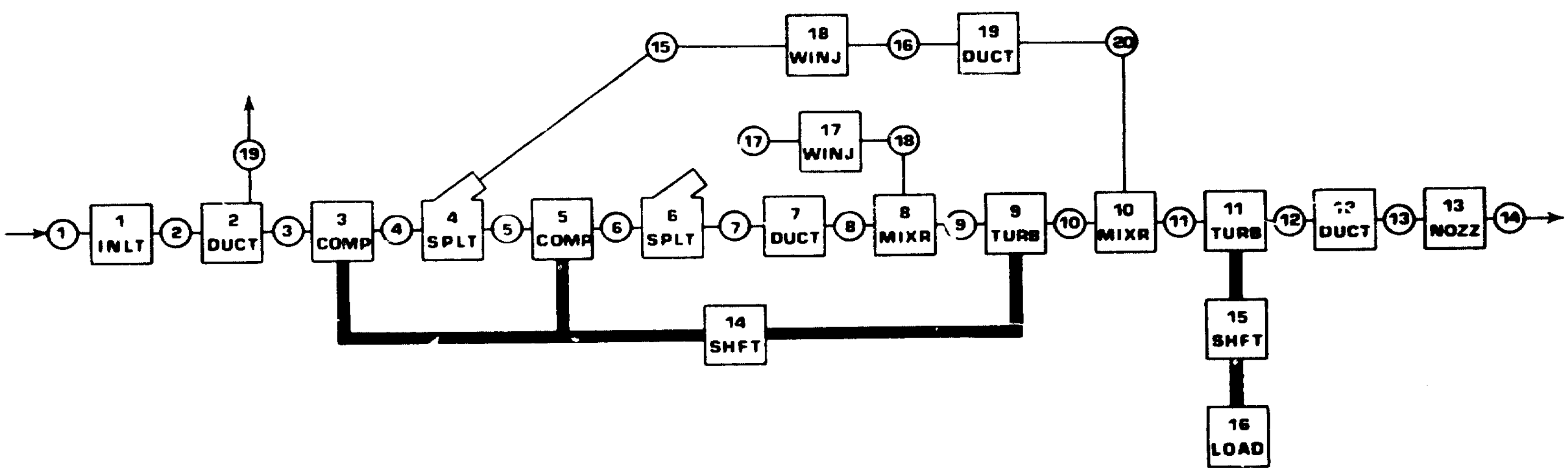
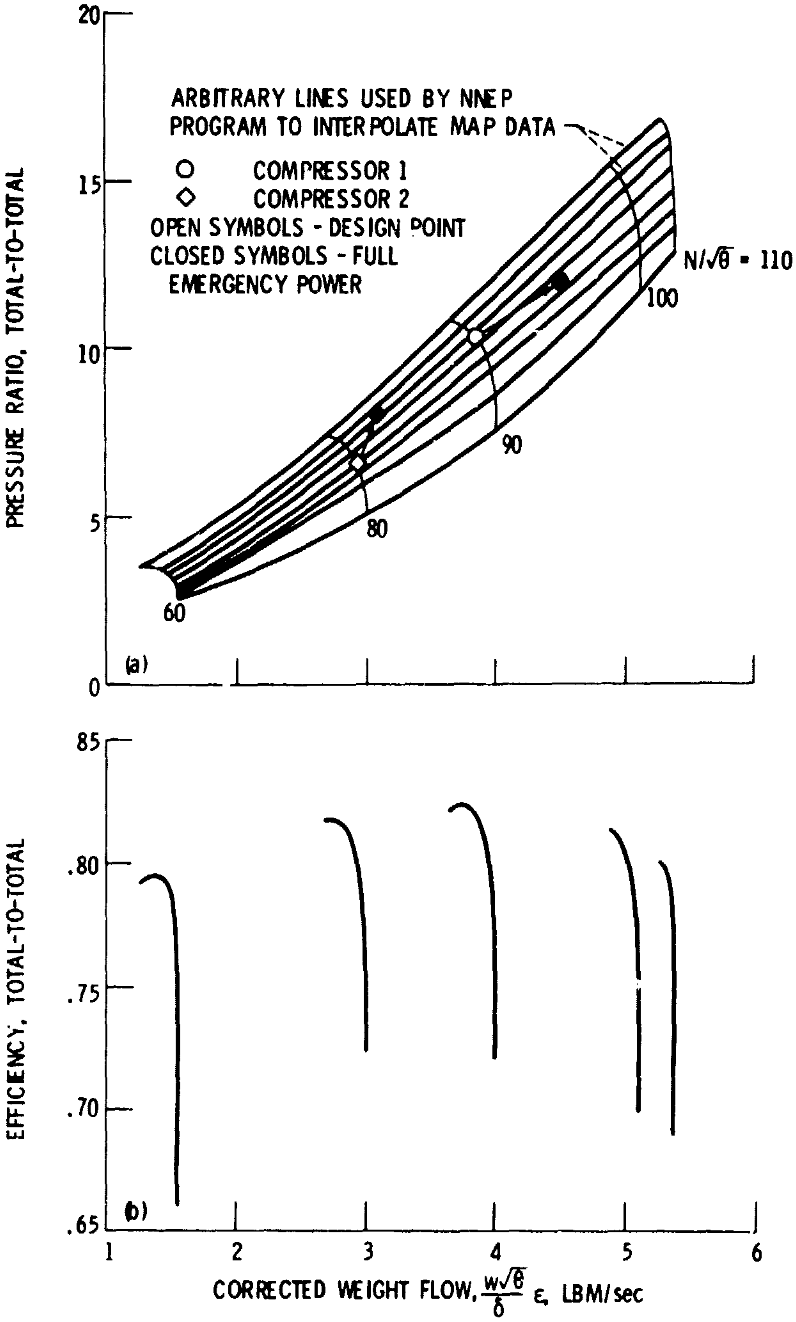


Figure 2. - Schematic diagram of arrangement of components used in NNEP model.



(a) Compressor flow map.

(b) Compressor efficiency map.

Figure 3. - Performance map for compressor and turbines.

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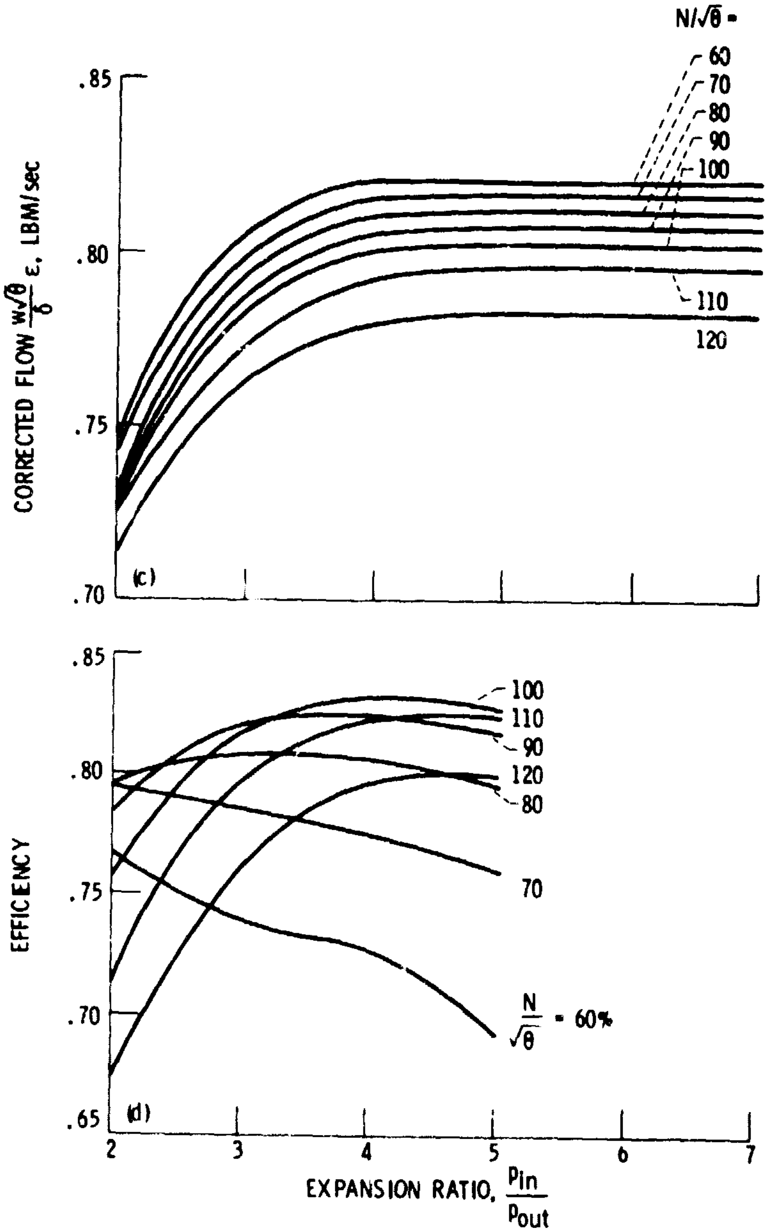

(c) Gas generator turbine flow map.

(d) Gas generator turbine efficiency map.

Figure 3. - Continued.

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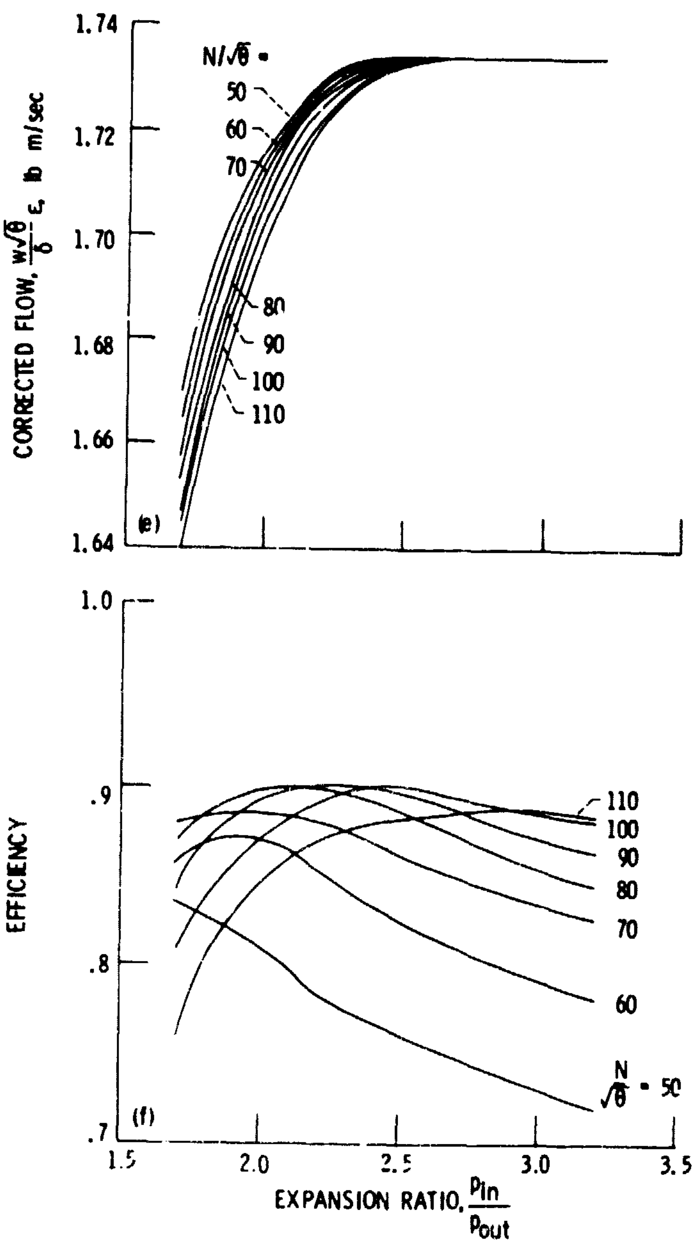

(e) Power turbine flow map.

(f) Power turbine efficiency map.

Figure 3. - Concluded.

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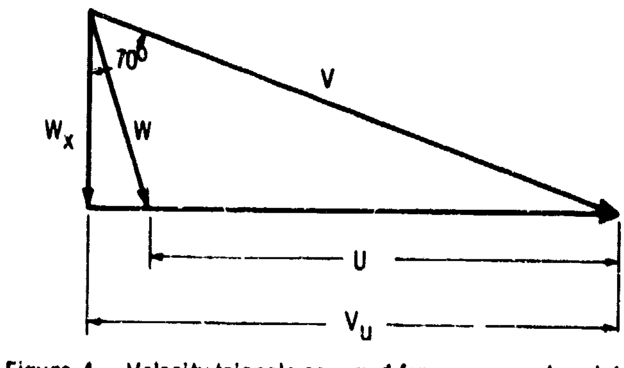

Figure 4. - Velocity triangle assumed for gas generator stator exit.

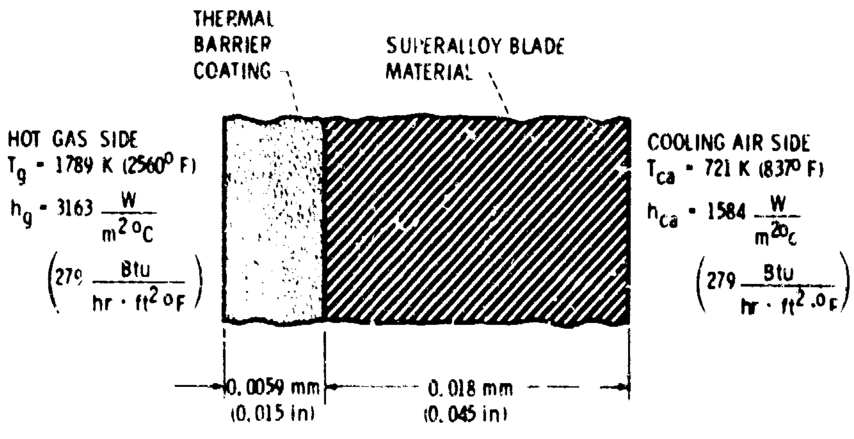

Figure 5. - Cross section of thermal barrier coated turbine blade used in transient model.

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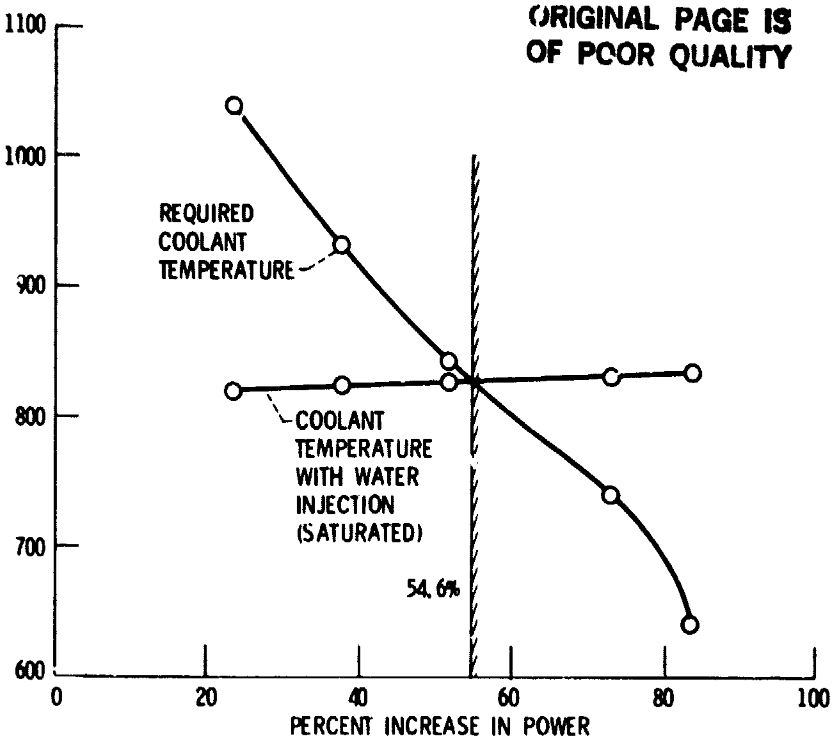

Figure 6. - Required and obtainable coolant temperatures for given power increase.

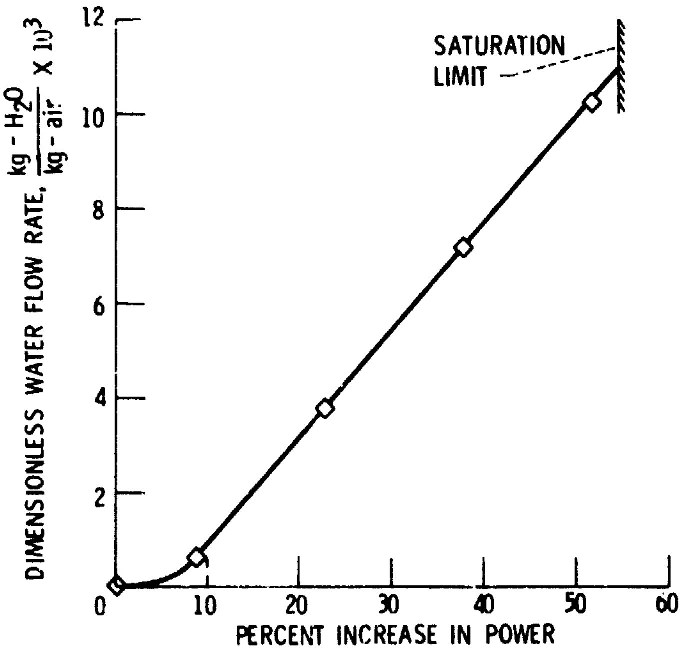

Figure 7. - Water flow rate required to maintain constant gas generator turbine life.

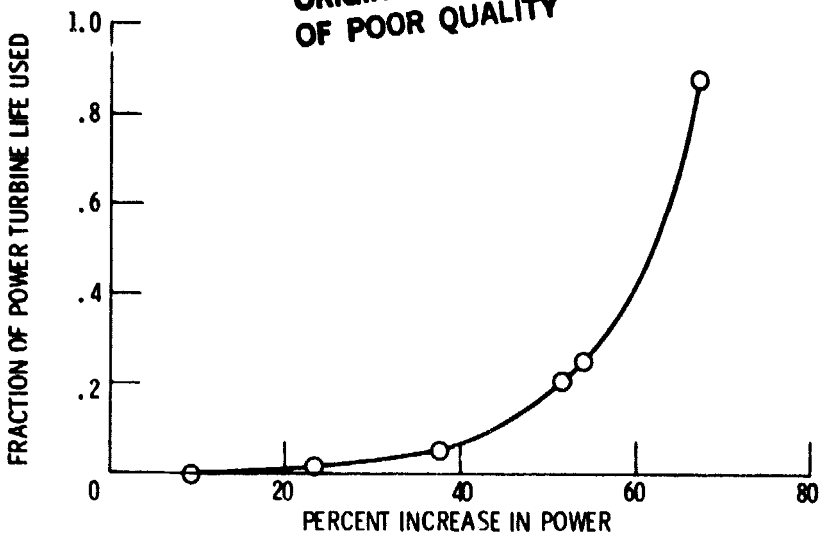

Figure 8. - The effect of increased power on power turbine life fraction used during a 2.5 minute application of emergency power.

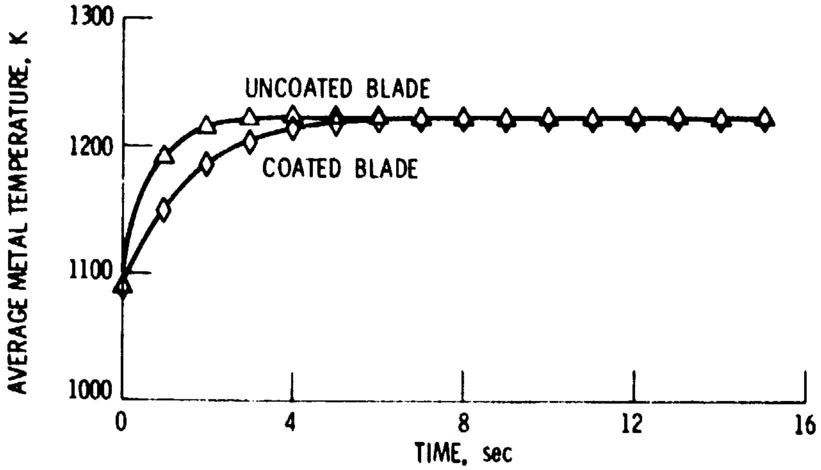

Figure 9. - Transient thermal response of coated and uncoated turbine blades to a 256 K (460° F) step in gas temperature.