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Use of Cooling Air Heat Exchangers as Replacements for Hot Section Strategic Materials

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USE OF COOLING AIR HEAT EXCHANGERS AS
REPLACEMENTS FOR HOT SECTION STRATEGIC MATERIALS

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Abstract

Because of financial and political constraints, strategic aerospace materials required for the hot section of future engines might be in short supply. As an alternative to these strategic materials, this study examines the use of a cooling air heat exchanger in combination with less advanced hot section materials. Cycle calculations are presented for future turbofan systems with overall pressure ratios to 65, bypass ratios near 13, and combustor exit temperatures to 3260°R. These calculations quantify the effect on TSFC of using a decreased materials technology in a turbofan system. The calculations show that the cooling air heat exchanger enables the feasibility of these engines.

Nomenclature

BPR	bypass ratio
FN/WA	specific thrust
OPR	overall pressure ratio
TG	combustor exit temperature
TM	allowable turbine rotor blade bulk metal temperature
TSFC	thrust specific fuel consumption
WC/W2	chargeable cooling flow referred to core compressor flow
WT/W2	total cooling flow referred to core compressor flow

Introduction

Because of financial and political constraints, strategic aerospace materials needed for the hot section of future engines might be in short supply. Also, projections of advancements in materials technology might be too optimistic. If these potential problems occur, strategic materials might have to be eliminated from the hot section. Then, to design reasonable life into future engines, turbine blades and vanes will have to operate at material temperatures which are a few hundred degrees lower than what is currently being projected.

One way to lower the turbine blade temperature is to lower the cooling air temperature. This can be done by rejecting heat from the turbine cooling air to the bypass duct air. Although the concept of cooling the turbine cooling air is not a new idea[1,2], the reason for cooling it is new. Formerly, cooling air heat exchangers were studied because of the energy crisis and the much increased fuel prices. In this study, however, cooling air heat exchangers are being studied as replacements for hot section strategic materials. The study examines the cycle of a turbofan propulsion system for the years 2000-2010 which uses the heat sink capacity of the bypass duct air to reduce the temperature of the turbine cooling air. This paper presents some initial results of the study concerned with the alternatives to strategic materials. When heat is rejected to the bypass air, either a heat exchanger is added to the bypass duct or an existing engine structure is used to transfer the heat. For the former case, weight and friction pressure drop of the heat exchanger must be added to the engine simulation. For the later case, there is no need for the addition of weight or pressure drop.

In the present study, a separate flow turbofan engine is simulated at cruise conditions using a cycle analysis computer code entitled NNEP[3,4]. Shortages in the strategic metals are simulated by assuming lower allowable bulk metal temperatures of the turbine stator vanes and rotor blades. This study is for a turbofan engine with a bypass ratio near 13. Combustor exit temperature ranges from 2760 to 3260°R and overall pressure ratio from 35 to 65. Allowable stator bulk metal temperature ranges from 1860 to 2460°R and allowable rotor bulk metal temperature from 1760 to 2360°R. Heat exchanger effectiveness ranges from 0 to 1. Results are presented which show the effect on the performance of a heat exchanger used to reduce the turbine cooling air temperature. The effect of the pressure drop across the heat exchanger is included in this study.

Analysis

Engine Cycle

Figure 1 shows a cross-section of an advanced turbofan propulsion system considered to be representative of the years 2000-2010. The five darkened areas in the figure represent the rotating components in the engine. From left to right, these are the fan, the low pressure compressor, the core compressure, the core turbine, and the low pressure turbine. The line leaving the core compressor represents the turbine cooling air. After leaving the compressor, it passes through a fan air heat exchanger and into the core turbine (and also into the low pressure turbine, if required).

Consider an engine cycle of fixed engine airflow, fixed bypass ratio, fixed specific thrust and fixed allowable turbine blade bulk metal temperatures. Next, constrain this engine cycle so that the turbine blades and vanes must

operate at lower allowable bulk metal temperatures. To accomplish this, more compressor bleed flow is required to cool the turbine and, consequently, less core flow is available to drive the turbine. So, to maintain constant specific thrust, the turbine inlet temperature must increase. This in turn requires the chargeable cooling flow to further increase.

When the engine is again balanced at a lower turbine blade temperature, the net changes are a higher chargeable cooling flow, a higher turbine inlet temperature, and an increased thrust specific fuel consumption. In effect, a decreased materials technology is used at the cost of a decreased fuel efficiency. This relationship can be studied by examining combustor exit temperature (TG), chargeable cooling flow ratio (WC/W2), and thrust specific fuel consumption (TSFC) as functions of allowable bulk metal temperature (TM) of the turbine blade.

In an attempt to operate the engine at this lower level of materials technology and yet not give up fuel efficiency, a heat exchanger can be added to the engine cycle. The compressor bleed flow passes through the heat exchanger rejecting heat to the duct flow. Since the cooling flow is now at a lower temperature, less chargeable cooling flow is required, more of the core flow passes through the turbine, and a lower combustor exit temperature is required to maintain the specific thrust.

So, the addition of a heat exchanger allows a decrease in materials technology without as severe an increase in TSFC. Also, the rejected heat increases the temperature level of the duct which tends to increase the thrust and further decreases the combustor exit temperature necessary to maintain the specific thrust.

Of course, the addition of a heat exchanger will cause a pressure drop in the fan duct flow. And there exists some value of pressure drop which will exactly offset the benefit in TSFC gained by the heat exchanger. At a pressure drop greater than this value, the addition of a heat exchanger will not be helpful to the TSFC of the engine cycle. However, it will allow the use of a decreased materials technology (lower TM) in the hot section.

The ideal heat exchanger will be weightless and will not cause an increase in the friction pressure drop. To obtain such a heat exchanger, existing engine structures could be used as heat exchangers. Examples of such structures are the inner and outer walls of the annular duct and the outlet guide vane of the fan.

For this study, the definition of heat exchanger effectiveness can be stated as the ratio of the decrease in the turbine cooling air temperature to the increase in core air temperature across the compressor. This restatement implies that all bleed is from the compressor exit rather than from an intermediate compressor stage.

Engine Simulation

Figure 2 is a schematic diagram showing the arrangement of components used to model the engine in this study. The boxes represent individual components and the single lines between boxes represent flow paths. Double lines represent shafting between components. The two compressors near the top of the figure connected by shafting represent a split fan, that is, the outer region of the flow experiences a greater compression than does the inner region. The line from the high pressure compressor, which represents the total cooling airflow, passes first through the duct (heat exchanger) and then reenters the mainstream fore and aft of both the core and low pressure turbines.

The core turbine has two stages with four rows of cooled airfoils. All four rows of airfoils are assumed to be cooled by advanced convection with limited film cooling. The cooling air ejected from the first stator is mixed with the mainstream hot gas ahead of the first rotor and allowed to do work in the core turbine. The cooling air for the other three rows of airfoils in the core turbine is mixed with the mainstream down stream of the core turbine and does work only in the low pressure turbine.

In this study, chargeable cooling flow is defined as that flow which cannot completely expand through the rotor of the core turbine. By this definition, only the cooling flow associated with the first stator of the core turbine is completely nonchargeable to the cycle. However, even this nonchargeable cooling flow, if it is injected into the gas stream, will have an adverse effect on the turbine efficiency.

A subroutine[5] of the cycle code[3,4] determines on a row-by-row basis both the quantity of compressor bleed flow required to cool turbine and the decrease in turbine efficiency caused by cooling air injected into the gas stream. The subroutine allows the user to choose from among ten different cooling configurations for each row of cooled airfoils. Also, the user may choose one allowable bulk metal temperature for all the turbine rotor blades in the engine and another temperature for all the turbine stator blades. The combustor exit temperature which is used in the subroutine is incremented row by row to include effects of dilution, rotation, work extraction, pattern factor, and safety factor.

Results and Discussion

Figure 3 presents combustor exit temperature (TG) as a function of the allowable bulk turbine rotor blade temperature (TM) with duct flow heat exchanger effectiveness values of 0.0, 0.5, and 1.0. The effectiveness value of 0.0 corresponds to the case without a heat exchanger. The allowable bulk metal temperature of the stator blade is assumed to be higher than that of the rotor blade by 100°R. In this study, the TM is decreased from the design point value of 2360°R because of the assumed loss of strategic materials. As the TM is decreased, more compressor bleed is required to cool the turbine and so less core flow is available to drive the turbine. Then, to maintain constant compressor work, the TG must increase. So, as shown in figure 3, as TM decreases, TG must

increase to maintain constant specific thrust (FN/WA).

Also shown in figure 3 by the upper curve, without the use of a heat exchanger, the TG rises so rapidly that the engine can no longer maintain the FN/WA. Thus the heat exchanger enables the feasibility of this engine for values of TM below 2060°R. Or, for a given value of TG, the heat exchanger will provide a decrease in the TM of several hundred degrees thus greatly decreasing the required level of materials technology (or greatly increasing the durability of the engine). If the compressor bleed air is cooled by rejecting heat to the bypass flow, then a lesser amount of cooling flow is required for a given level of TM. The exact amount of cooling flow is determined by the heat exchanger effectiveness.

Corresponding to the curves in figure 3 are the curves in figure 4 which present the TSFC as a function of the TM for the heat exchanger effectiveness values of 0.0, 0.5, and 1.0. As the allowable bulk metal temperature decreases and the combustor exit temperature increases, the TSFC increases. Note in the figure that for high values of TM near 2360°R which are accompanied by low values of TG, the duct flow heat exchanger provides no advantage in TSFC. However, for low values of TM near 2060°R which are accompanied by high values of TG, significant savings in TSFC are possible with the use of a heat exchanger.

Figure 5 presents the chargeable turbine cooling flow (WC/W2) required to maintain a given TM, that is, a given level of materials technology. The reason for the rapid increase in TSFC, shown in the previous figure, is the rapid increase in WC/W2 shown in figure 5. And the rapid increase in required WC/W2 is due to the rapid increase in TG required to maintain specific thrust.

The three previous figures show how a decrease in materials technology of 300°R can affect the cycle of a future engine. For example, without the heat exchanger, if the TM is decreased from 2360°R to 2060°R, the WC/W2 must increase from 0.04 to 0.24, the TG must increase from 2887°R to 3515°R, and the TSFC increases from 0.4650 to 0.5065. So, for a decrease of 300°R in TM, the trading of a decrease in materials technology against an increase in specific fuel consumption is hardly a workable solution. And for decreases in TM greater than 300°R, the engine will not even converge, that is, there is no solution.

The three previous figures also show how a decrease in materials technology of 300°R in combination with an ideal (effectiveness of unity) duct air heat exchanger can affect the cycle of a future engine. For example, if the TM is decreased from 2360°R to 206?°?, the WC/W2 must increase from 0.04 to 0.047 the TG increases from 2887°R to 2913°R, and the TSFC increases from 0.4650 to 0.4752. So, for a decrease of 300°R in TM, the addition of a duct air heat exchanger provides an acceptable solution. And with the addition of a heat exchanger, a decrease in TM greater than 300°R will not preclude the engine.

The preceding discussion has considered an engine with an OPR of 64, a TG of 2860°R, and a TM of 2360°R both with and without a heat exchanger. Figure 6 presents the TSFC for a family of engines with a range of both OPR and TG where material technology has been decreased by 300°R to a TM of 2060°R without a heat exchanger. The curves validate the current interest in high OPR, high BPR turbofans for future engines. However, the purpose of this figure is to form the basis for the results presented in figure 7.

As in the previous example, if a duct air heat exchanger is added to the cycle, then less cooling air is needed so more core air is available to expand through the turbine and a lower TSFC results. Figure 7 presents the percent decrease in TSFC which can ideally be achieved by the addition of a duct air heat exchanger to the family of engines presented in figure 6. For example, at an OPR of 65, a 1 percent decrease in TSFC results when one cycle with a 2860°R TG with no heat exchanger is replaced by a second cycle with a 2700°R TG with a heat exchanger, holding FN/WA constant. The inference that can be drawn is that the larger the difference between TG and TM, the larger the payoff of a heat exchanger.

The previous figures present data in which the fan air pressure drop through the duct heat exchanger is not a function of the effectiveness. Physically, this corresponds to the situation in which the wall of the duct, or some other engine structure, is used as the heat exchanger. It may be possible to cool the cooling air without a separate heat exchanger since the duct flow which is the heat sink exceeds the cooling flow which is the heat source by a factor of the bypass ratio (BPR) divided by the total cooling air flow ratio (WT/W2). For example, with a BPR of 12.8 and a WT/W2 of 0.128, the ratio of the mass flow rates of the heat sink to the heat source would be 100. However, should an actual heat exchanger in the duct prove necessary, then the pressure drop across the heat exchanger will be a function of the effectiveness.

Figure 8 presents TSFC as a function of heat exchanger effectiveness with fan air pressure drop across the separate heat exchanger in the duct flow as the parameter. As expected, high values of effectiveness and low values of pressure drop lead to decreased values of TSFC. And with heat sink to heat source ratios approaching 100, high values of effectiveness and low values of pressure drop are possible. Although high heat exchanger pressure drops can lead to large penalties in TSFC, nevertheless, the heat exchanger can still enable the feasibility of the engine for large decreases in allowable hot section temperatures.

Summary of Results

If shortages occur in hot section strategic materials for future engines, then turbine blade metal temperatures will have to be substantially lower than those currently being projected. The present study indicates that a cooling air heat exchanger can be used as a substitute for hot

section strategic materials while maintaining the engine specific thrust. However, further studies are required to design the heat exchanger for the engine cycle and to examine the benefits of reoptimizing the engine cycle with the heat exchanger.

1. If turbine blade temperatures must be lowered by less than a few hundred degrees, the addition of a heat exchanger will allow the use of less critical materials in the turbine for a smaller penalty in TSFC.

2. If turbine blade temperatures must be lowered by more than a few hundred degrees, the addition of a heat exchanger will allow the feasibility of the engine.

3. Because of the high ratios of mass flow rates of the heat sink to heat source which are expected to be present in future engines, existing engine structures might be used as the heat exchanger, thus avoiding the penalty caused by additional weight and pressure drop of a separate heat exchanger.

References

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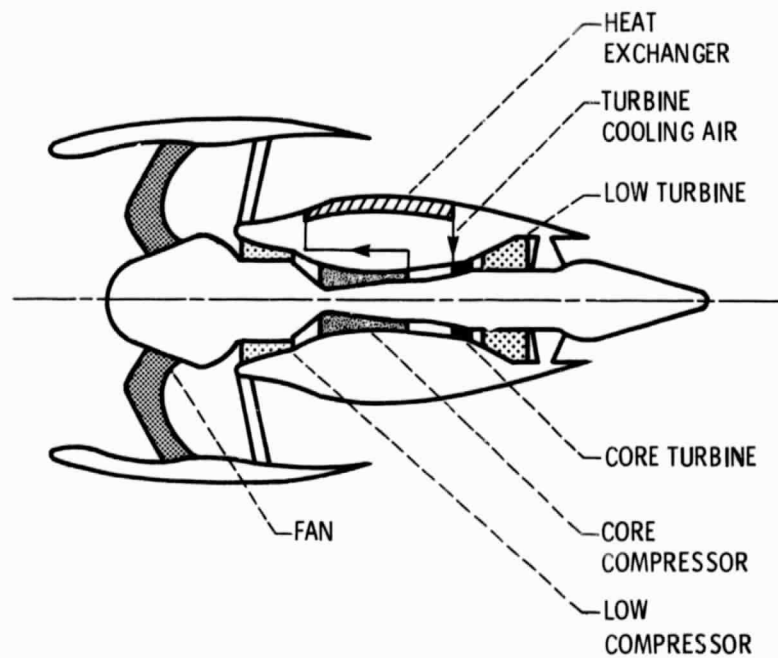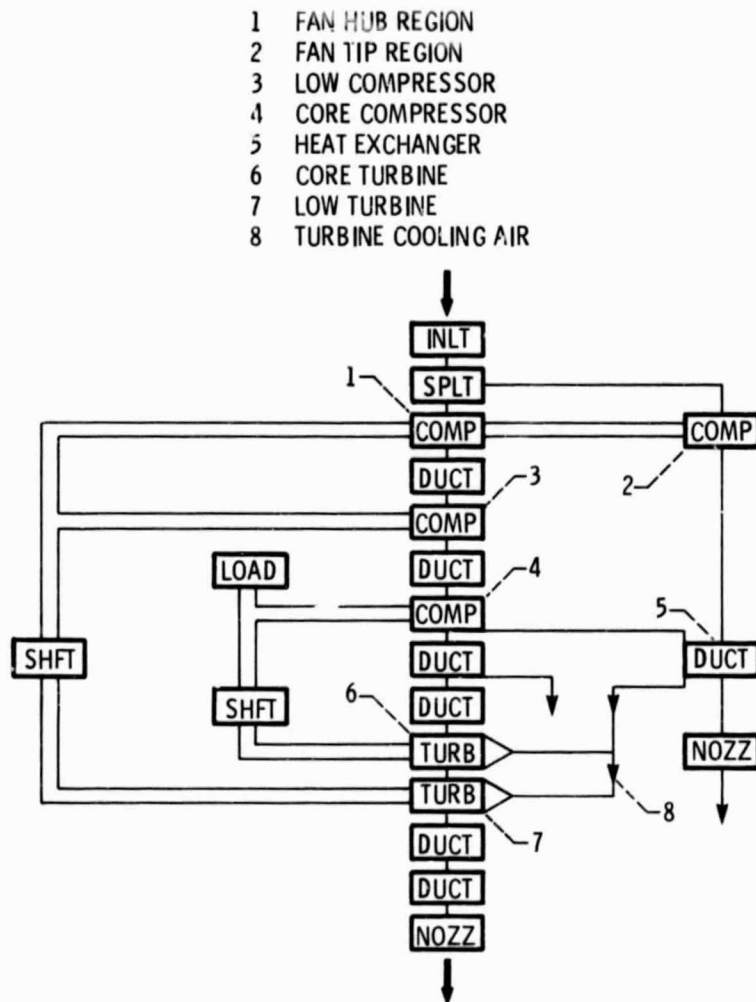Figure 1. - Advanced turbofan propulsion system for the years 2000-2010.

1　FAN HUB REGION
2　FAN TIP REGION
3　LOW COMPRESSOR
4　CORE COMPRESSOR
5　HEAT EXCHANGER
6　CORE TURBINE
7　LOW TURBINE
8　TURBINE COOLING AIR

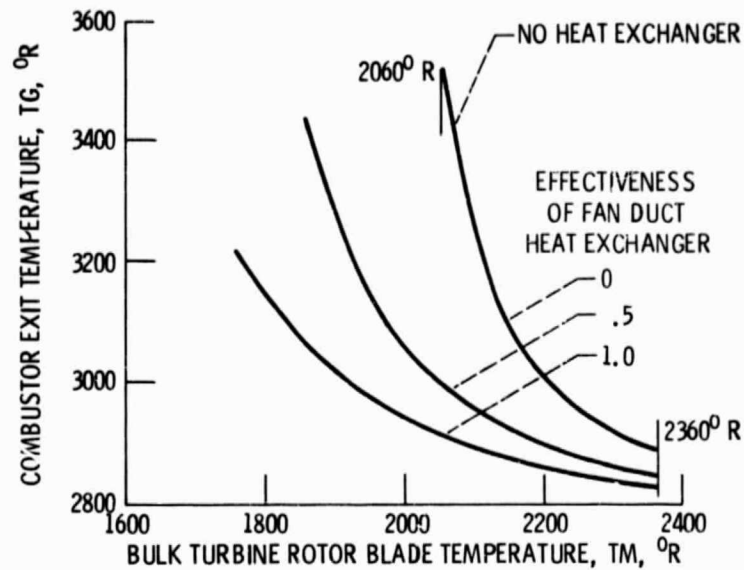Figure 2. - Schematic diagram of arrangement of components used in NNEP model.

Figure 3. - Increased gas temperature required to maintain constant specific thrust at decreased turbine blade temperature.
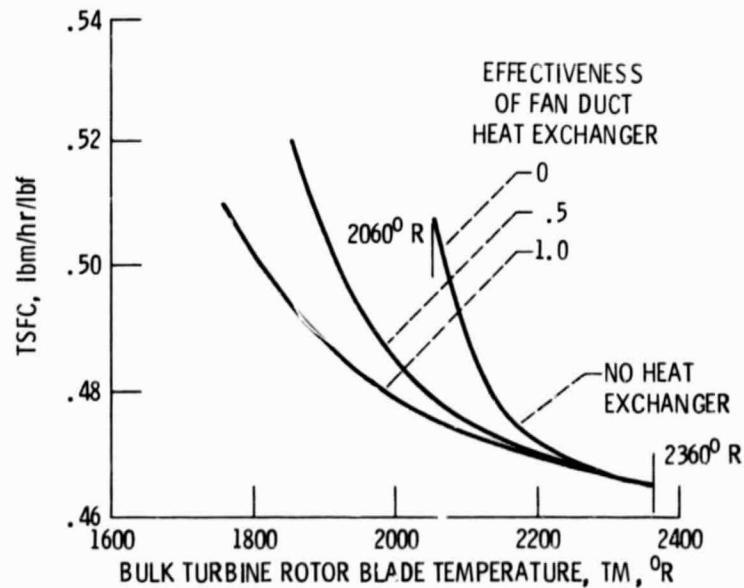

Figure 4. - Increased fuel consumption required to compensate for reduced turbine materials technology while maintaining constant specific thrust.
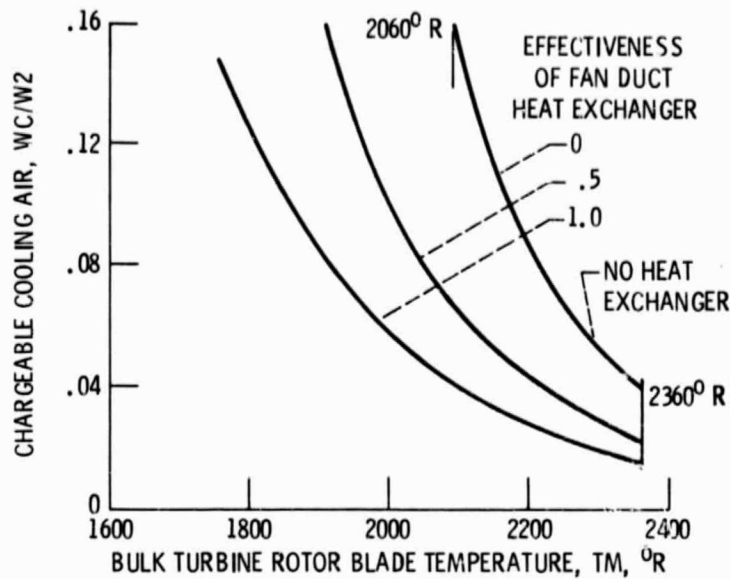
Figure 5. - Turbine cooling flow required to maintain
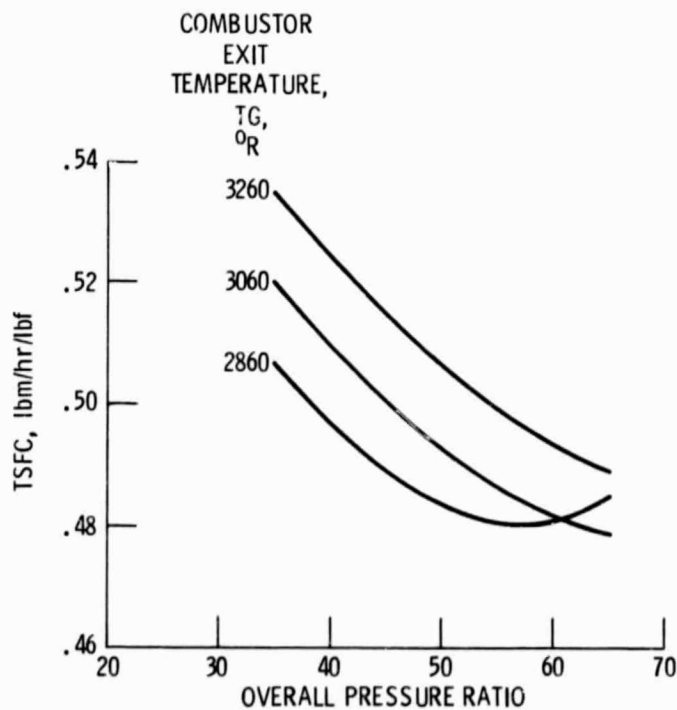turbine blade temperature.

Figure 6. - Cruise TSFC trends for a family of engine
cycles with bypass ratio of 12.8. No heat exchanger.
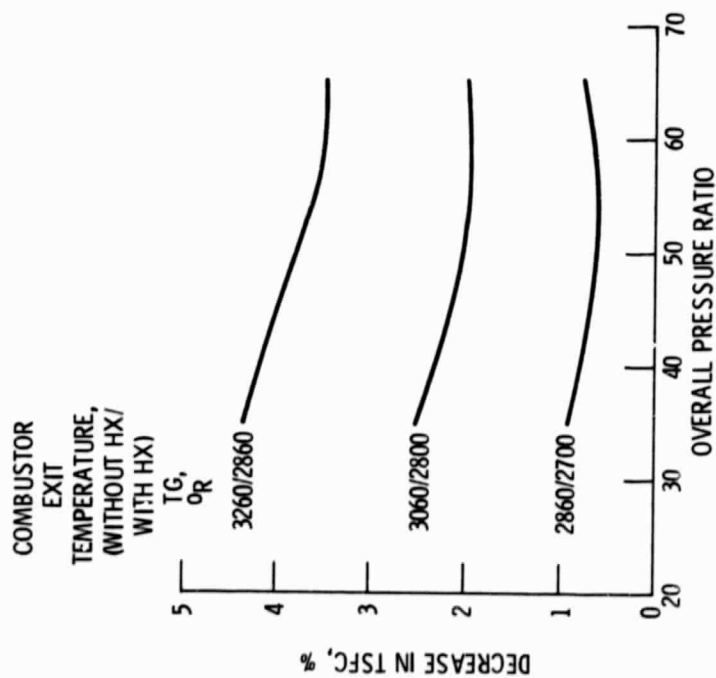Bulk rotor blade temperature, TM, 2060° R.

FAN DUCT
PRESSURE
DROP

.03

.02

.01

TSFC, lbm/hr/lbf

.52

.50

.48

.46

0   .2   .4   .6   .8   1.0

HEAT EXCHANGER EFFECTIVENESS

Figure 8. - Effect of pressure drop across heat exchanger on fuel consumption for reduced turbine rotor blade temperature.

COMBUSTOR
EXIT
TEMPERATURE,
(WITHOUT HX/
WITH HX)
T_G,
°R

3260/2860

3060/2800

2860/2700

DECREASE IN TSFC, %

5

4

3

2

1

0

20   30   40   50   60   70

OVERALL PRESSURE RATIO

Figure 7. - Decrease in fuel consumption resulting from addition of turbine cooling air heat exchanger with an effectiveness of unity. Bulk roto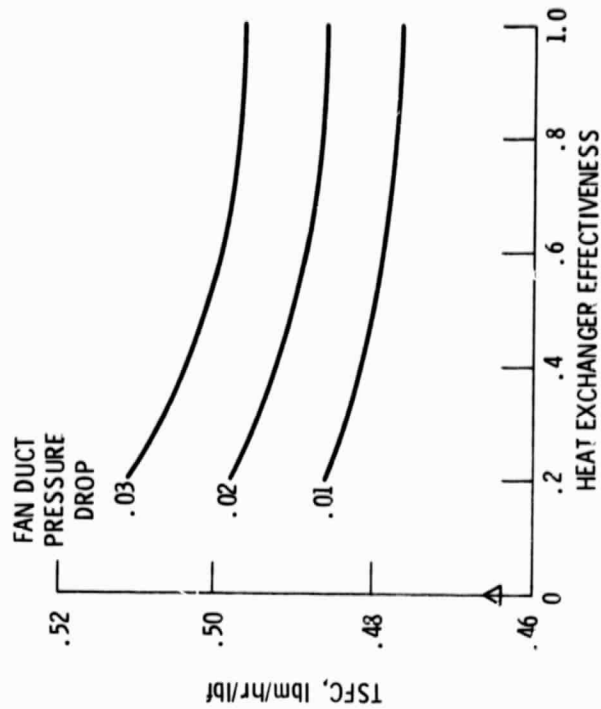r blade metal temperature, TM, 2060° R.