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ALGORITHM FOR CALCULATING TURBINE
COOLING FLOW AND THE RESULTING
DECREASE IN TURBINE EFFICIENCY

James W. Gauntner
Lewis Research Center
Cleveland, Ohio

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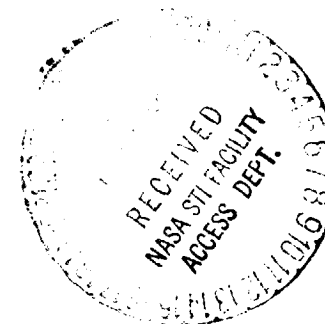
ALGORITHM FOR CALCULATING TURBINE COOLING FLOW AND THE RESULTING DECREASE IN TURBINE EFFICIENCY

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SUMMARY

This report documents an algorithm for calculating both the quantity of compressor bleed flow required to cool the turbine(s) and the decrease in turbine efficiency caused by cooling air injection into the gas stream. The technique is presented in the form of a Fortran program which can be used as a subroutine in a properly written thermodynamic cycle code. The user has the option of choosing from ten different cooling configurations for each row of cooled airfoils in the turbine. Results from the algorithm have been substantiated by comparison with flows predicted by major engine manufacturers for given bulk metal temperatures and given cooling configurations. Presented in the report are a listing of the subroutine and a list of definitions for the terms in the subroutine.

This subroutine was originally developed to replace a simpler turbine cooling model in the NAVY NASA Engine Program (NNEP). To use this new routine in NNEP, minor changes are required to three other subroutines. These changes are shown in this report.

INTRODUCTION

The NASA Lewis Research Center employs a general computer program (refs. 1 and 2), for calculating thermodynamic performance of jet propulsion engines. This thermodynamic performance is sensitive to the quantity of compressor bleed flow required to cool the turbine(s). And the quantity of required cooling flow increases with the trend toward higher turbine inlet temperatures. Because of this trend, it becomes increasingly more important to accurately predict the required cooling flow so as to accurately calculate the thermodynamic performance.

The present report documents a turbine cooling algorithm for an axial-flow, air-breathing engine which determines both the quantity of compressor bleed flow required to cool the turbine(s) and the decrease in turbine efficiency caused by cooling air injection into the gas stream. The purpose of this report is to explain the use and to examine the accuracy of this algorithm.

To help explain its use, the turbine cooling algorithm

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is discussed from three different aspects. First, the method is presented; next, the flow chart is traced; and finally, the required input is examined. The accuracy of the algorithm is evaluated by comparing its predictions of required cooling flow with those of major engine manufacturers.

The algorithm is presented in the form of a Fortran program which can be used as a subroutine in a properly written thermodynamic cycle code. For example, it is used herein as a new version of subroutine COOLIT in the thermodynamic cycle code NNEP of references 1 and 2. A listing of the subroutine and a list of definitions for the terms in that subroutine are presented. Minor changes to three other subroutines in the code of references 1 and 2, NNEP, which are required for the use of the COOLIT subroutine in that code, are also presented.

ANALYSIS

Turbine Cooling Method

The quantity of required cooling flow and the corresponding decrease in stage efficiency are calculated for each row of airfoils throughout the turbine. These values are then used to obtain the quantity of compressor bleed flow required to cool the turbine and the decrease in cooled-turbine efficiency caused by cooling air injection into the gas stream. The calculations depend on both the type of cooling configuration and the value of cooling effectiveness.

Cooling configuration. - The allowable cooling configurations in this cooling algorithm are described in table I. In this table, column 1 contains NFACT(I) which is used to identify the cooling configuration shown in column 2. Columns 3 and 4 are aids for choosing the proper cooling configuration for each row of airfoils. Column 5 lists the required cooling flow for each configuration relative to that flow required by a full coverage film cooled turbine blade. For example, a transpiration cooled turbine blade requires only 0.8 of the cooling flow required by a full coverage film cooled turbine blade for a given value of cooling effectiveness. Columns 6 and 7 list the percent decrease in stage efficiency for each percent of core flow required to cool the stator(s) and rotor(s), respectively.

The values of relative cooling flow, FACTOR, which appear in column 5 of table I come from both analytical and experimental sources. Reference 3 presents an analysis relating the required flow for convection, advanced convection, full coverage film, and transpiration cooling. These values are sensitive to gas, coolant, and metal

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temperatures and to airfoil geometry. However, for the purpose of this investigation, nominal values of relative cooling flow are sufficient. From reference 3 values of FACTOR of 2.0, 1.5, 1.0, and 0.8 are obtained corresponding to cooling configurations 1, 3, 8, and 9, respectively.

From figure 8 of reference 4, a convection cooled turbine blade with a 0.025 centimeter coating requires only three-fourths of the cooling flow of that of an uncoated convection cooled blade. So the value of FACTOR of 1.5 for a coated convection cooled blade can be obtained from the value of 2.0 for a convection cooled blade.

Values of FACTOR for cooling configurations 4, 5, and 6 are 1.3, 1.2, and 1.1, respectively. These values have been obtained by interpolating between values of FACTOR for cooling configurations 3 and 8. The value of FACTOR for cooling configuration 7 was obtained by using a weighted average of FACTOR values for cooling configurations 3 and 9.

Values of the dimensionless loss in stage efficiency, DELV and DELN, which appear in columns 6 and 7 of table I, were obtained in a personal communication from Thomas P. Moffitt, a member of the Turbine Branch at Lewis Research Center.

Cooling effectiveness. - Cooling effectiveness, PHI, is defined as the ratio of the difference between the hot gas temperature and the allowable bulk metal temperature to the difference between the hot gas temperature and the compressor bleed temperature.

$$PHI = (T - TM)/(T - TC)$$

The hot gas temperature entering a given row of airfoils is the average combustor exhaust temperature incremented to include the following five effects: (1) Hotspot profiles are accounted for by using a pattern factor of 0.3 for the first stage stator of the high pressure turbine and a value of 0.13 for all other rows of cooled airfoils in the turbine(s). (Pattern factor is defined as the ratio of the difference between the hotspot and the average row inlet temperature to the difference between the average row inlet temperature and the combustor inlet temperature.) (2) The correction to the hot gas temperature due to the dilution of upstream cooling air is obtained from a mass averaged enthalpy from which a revised gas temperature is calculated. (3) Currently, the correction due to relative velocity is merely an approximation; the relative total temperature is assumed to equal 0.92 of the absolute total temperature. This value is a modification of the 0.90 value found in reference 3 which included dilution from the stator cooling air. (4) Because work is extracted

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from the gas stream, the downstream rows of cooled vanes and
blades are subjected to a lower gas temperature. (5) The
gas temperature used to determine the required cooling flow
is first increased by 150° R to provide a safety factor for
the cooled turbine airfoils.

Allowable bulk metal temperature depends upon the year
of material technology, the desired life and the duty cycle.
(Duty cycle includes mission, atmosphereic conditions and
power settings.) In an attempt to simplify these
relationships the following equations relate
state-of-the-art bulk metal temperatures to both life and
year of material technology. (See APPENDIX A for the
definition of the variables.)

$$TMVANE = (10.*YEAR -17640.) - (100*log(ELIFE)-400.)$$
$$TMBLAD = (10.*YEARB-17740.) - (100*log(ELIFE)-400.)$$

These equations have been obtained from information
similar to that contained in figure 8 of reference 5. In
that figure metal temperature is presented as a function of
the year of material technology. The figure shows both a
turbine blade material temperature of 2110° R for 1985
technology and also a historic increase of almost 10° R per
year in the the allowable metal temperature. Stator blades
are herein assumed to operate at a temperature 100° R higher
than the rotor blades so that they will operate at 2210° R
for 1985 technology.

The cooling air temperature reflects the stage of the
compressor from which the bleed flow is extracted.

Dimensionless cooling flow. - After the relative
cooling flow, FACTOR, has been chosen from table I for the
row of airfoils, and after the cooling effectiveness, PHI,
has been evaluated from the above temperatures, then the
dimensionless cooling flow can be determined from the
following equation. For example, for a FACTOR OF 1.0 and a
cooling effectiveness of 0.5, the dimensionless cooling flow
is 0.022 for a full coverage film cooled turbine blade.

$$W(I)/WG = FACTOR*0.022*(PHI/(1.-PHI))**1.25$$

The form of this equation is derived from a heat
balance across the surface of a turbine blade in which
turbulent flow is assumed for both the hot gas and the
cooling air. The constant 0.022 is obtained by
extrapolating experimental data presented in figure 23 of
reference 6 for a full coverage film cooled turbine vane.

To account for endwall, shroud and disk cooling, and
leakage, the dimensionless cooling flow for each row of
airfoils is increased by a factor of 4/3. Although this

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value will vary from engine to engine, its use seems
reasonable when comparisons are made with flowrates
predicted by other methods.

Cooled turbine efficiency. - First, the
uncooled-stage efficiency, EFF2, is calculated from the
uncooled-turbine efficiency, EFF1, using equation (6.5.6) of
reference 7. This calculation assumes that all
uncooled-stage efficiencies and all stage pressure ratios
are equal.

EFF2=(1-(1-EFF1*(1-RP**GAM))**(1/XN))/(1-RP**(GAM/XN))

Next, the dimensionless cooling flows from the stator
and the rotor, excluding the endwall, shroud, disk, and
leakage flows, are then used to determine the decrease in
the thermodynamic efficiency of the turbine stage. This
decrease in stage efficiency is equal to the product of the
dimensionless cooling flow, one of the last two columns in
table I, and the uncooled-stage efficiency. Subtracting the
change in stage efficiency from the uncooled-s'age
efficiency, EFF2, will yield the cooled-stage efficie :y,
EFF3.

EFF3=EFF2-(W(I)/WG)*DELV*EFF2-(W(I+1)/WG)*DELN*EFF2

Finally, the thermodynamic cooled-turbine efficiency,
EFF4, is reconstructed from the cooled-stage efficiencies
using equation (6.5.5) also of reference 7. This equation
allows a different value of cooled-stage efficiency for each
stage.

$$EFF4=(1-\prod_{I=1}^{XN}(1-EFF3(I)*(1-RP**(1/XN))**GAM)))/(1-RP**GAM)$$

Flow Chart of the Algorithm

The sequence for calculating these quantities can be
followed with the aid of APPENDIX A and APPENDIX B. The
former is a symbol list and the latter is a listing of the
new subroutine.

As shown in APPENDIX B, before the "DO 20" loop, the
uncooled thermodynamic stage efficiency, EFF2, is calculated
from the uncooled thermodynamic turbine efficiency, EFF1.

The "DO 20" loop separates the kind of cooling for the
turbine, KINDOF, into the cooling configuration for each row
of the turbine, NFACT(I). For example, in a one stage
turbine with a value of KINDOF equal to 86, the values of
NFACT(1) equals 8 and NFACT(2) equals 6. This indicates
that the stator is cooled by a full coverage film and the

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rotor is cooled partially by film and partially by advanced convection. See table I for NFACT(1)=8 and NFACT(2)=6.

The "DO 80" loop determines for each row of airfoils the effective hot gas temperature, T, the cooling effectiveness, PHI, the required cooling flow for each row, W(I), the change in stage efficiency, DELN, the accumulated required cooling flow made dimensionless by the flow into the turbine, PCBLED, and the cooled-stage efficiency, EFF3.

The "DO 90" loop reconstructs the cooling configuration, KINDOF, from NFACT(I) to reflect any changes made to NFACT(I) inside of subroutine COOLIT. Such changes occur when either a blade row requires cooling but was not originally intended to be cooled or when a blade row does not require cooling but was originally intended to be cooled. For the former case the blade row is assumed to have convection cooled airfoils; for the latter case the blade row is assumed to have solid, uncooled airfoils. See table I where NFACT(I) equals 1 and 0 respectively.

Finally, beyond the "DO 90" loop, the cooled-turbine efficiency, EFF4, is reconstructed from the cooled-stage efficiencies.

Input to the Algorithm

Input to general thermodynamic cycle code. - Input to the algorithm are discussed below. The names marked with an asterisk are not always required because of the reasons cited.

*EFF1 is the thermodynamic efficiency of the uncooled turbine. It is only required if the thermodynamic efficiency of the cooled turbine is to be calculated. If EFF1 is not known then it can be calculated by using the cooling configurations of the airfoils, the corresponding dimensionless cooling flows, and the above three equations relating EFF1, EFF2, EFF3, and EFF4. Or it can be found by a trial and error procedure by varying the input value of EFF1 until the known output value of EFF4 is achieved. An example of such a calculation might be to determine the required cooling flow and cooled-turbine efficiency for a transpiration cooled turbine knowing the corresponding values for a film cooled turbine.

*ELIFE is the desired life of the turbine airfoil. It is assumed to be 10 000 hours if the design values of TMVANE and TMBLAD are known.

*FARCX is the fuel to air ratio of the cooling flow. It is used to evaluate the specific enthalpy, HC. If a gas property subroutine is not available and the diluted gas

temperature is obtained by means of a mass averaged temperature, then FARCX is not required.

*FARGX is the fuel to air ratio of the hot gas stream. It is used to evaluate both the specific heat ratios, GAMIN and GAMOUT, and the specific enthalpy of the hot gas, HG. If an assumption is made for the specific heat ratio and if the diluted gas temperature is obtained by means of a mass averaged temperature, then FARGX is not required.

HPT is the power extracted by the turbine. It is used to adjust the hot gas temperature due to work extracted by upstream stages.

KINDOF is an ordered combination of digits representing the cooling configurations throughout the turbine starting with the stator of the first stage. For example, for a two stage turbine, 9865 indicates that each of the four rows of airfoils in a two stage turbine has a specific cooling configuration as indicated in table I.

*PR is the pressure ratio across the turbine, inlet over exit. It is only required if the thermodynamic efficiency of the cooled turbine is to be calculated.

PROFIL is the combustor pattern factor. The usual input is 0.30. After the stator of the first stage of the high pressure turbine, the value is set to 0.13 to reflect the radial profile.

STAGES is the number of stages in the turbine. It is used to distribute the work of the turbine and to indicate the number of rows of cooled airfoils.

TC is the total temperature of the cooling flow at the point at which it is extracted from the compressor. It is used to evaluate the cooling effectiveness, PHI, and the specific enthalpy, HC.

TIN is the total temperature of the gas into the turbine. The first stage stator is evaluated at this temperature after adjustment for both combustor pattern factor of 0.3 and safety factor of 150^0 R.

*TOUT is the total temperature of the gas out of the turbine. It is only used to evaluate GAMOUT. As with FARGX, it is not always required.

WTFLO is the total gas flow into the turbine.

YEAR is the first year of service for the stator vane material. The algorithm allows one level of material technology for the stator(s), YEAR, and another level for

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the rotor(s), YEARB. For example, let YEAR=2000.0 and YEARB=1977.8. This indicates that the allowable bulk metal temperature of the stator(s) and rotor(s) are 2360° R and 2038° R, respectively. The allowable bulk metal temperature of the rotor blade is assumed to be 100° R less than that of the stator blade for a given year of material technology.

YEARB is the first year of service for rotor blade material.

Changes to the thermodynamic cycle code NNEP. - In the previously published version of NNEP (refs. 1 and 2), one value of turbine efficiency was input and used irrespective of the calculated cooling flow. Now, the new COOLIT subroutine allows (NEWEFF=.TRUE.) for the use of a cooled-turbine efficiency which depends upon the cooling configuration of the airfoil, the calculated cooling flow and the thermodynamic uncooled-turbine efficiency.

Formerly, the value of YEAR indicated the same level of material technology for both the stator and the rotor. Now, the new COOLIT subroutine allows one level of material technology for the stator(s), YEARV, and another level for the rotor(s), YEARB.

Formerly, only one type of cooling configuration was input for all rows of airfoils. Now, the new COOLIT subroutine allows a different cooling configuration for each row of airfoils in the turbine.

APPENDICES C, D, and E list changes to subroutines TURBIN, INPRT, and INPUT, respectively, which are part of the engine performance code NNEP. These changes are required for the use of the new COOLIT subroutine in NNEP.

Accuracy of the Algorithm

Comparison of predicted flows. - Comparisons can be made between the predictions of the algorithm and those of two engine manufacturers. The first two of these predictions are for hypothetical advanced supersonic transport engines having specific cooling configurations and specific bulk metal temperatures. In one case the algorithm predicted 9.6 percent cooling flow whereas the engine manufacturer predicted 10.0 percent. In another case the algorithm and the engine manufacturer both predicted 19.4 percent. In a third comparison, one for an advanced subsonic Energy Efficient Engine, the algorithm predicted 16.5 percent whereas the engine manufacturer predicted 18.2 percent.

So in gene. the flows predicted by the new cooling algorithm agree c.)sely with those predicted by major engine

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manufacturers as long as the proper cooling configuration and bulk metal temperatures are used.

To determine the significance of the new cooling algorithm, a comparison was made between its predictions and those of the old version of the COOLIT subroutine for an advanced engine. The comparison of predicted cooling flows shows that the new cooling algorithm predicts a flow which is about 65 percent higher than that predicted by the old COOLIT subroutine. The major reason for the difference in the predicted flows is the fact that the old COOLIT subroutine did not allow for either a safety margin or a hotspot temperature.

Effect of cooling flow on performance. - In the new algorithm, compressor bleed flow can affect engine performance in two ways. (1) As the cooling flow exits from the turbine blades and enters the gas stream it causes a loss in total pressure of the mainstream due to increased drag and thereby causes a decrease in turbine efficiency. (2) Any cooling flow which is ejected into the gas stream downstream of the rotor is directly chargeable to the engine cycle since work cannot be extracted from it.

The new cooling algorithm predicts a higher required cooling flow than did the old COOLIT subroutine. It therefore follows from the previous paragraph that NNEP in conjunction with the new cooling algorithm predicts lower thrust levels than that predicted by NNEP in conjunction with the old COOLIT subroutine. In one example the net thrust decreases by over 9.2 percent because of the extra cooling flow which bypassed the rotor.

When NEWEFF=.TRUE., the turbine efficiency is degraded by cooling flow injection. When NEWEFF=.FALSE., turbine efficiency is not degraded by cooling flow injection. The difference between these two options for the case cited above is a decrease in net thrust of 1.1 percent. Most of this difference is due to the decrease in the efficiency of the high pressure turbine (HPT) because most of the total cooling flow is required for the HPT. For the case cited the efficiency of the HPT decreases 3.76 points while the efficiency of the LPT decreases 0.88 points.

It is interesting to differentiate between the relative error in thrust attributed to the decrease in turbine efficiency and that attributed to the cooling flow which bypasses the rotor. The error introduced into the thrust level due to inaccurate cooling flow is several times the error due to uncorrected turbine efficiency.

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CONCLUDING REMARKS

A cooling algorithm has been developed for calculating both the quantity of compressor bleed flow required to cool the turbine(s) and the decrease in turbine efficiency caused by cooling flow injection into the gas stream. The technique is presented in the form of a Fortran program which can be used as a subroutine in a properly written thermodynamic cycle code.

1. The cooling algorithm predicts cooling flows which have been substantiated by comparisons with flows predicted by engine manufacturers for the same bulk metal temperatures and cooling configurations.

2. The new cooling algorithm allows for a different cooling configuration for each row of cooled airfoils and allows for different levels of material technology between the stator and rotor. In addition, it will calculate the decrease in turbine efficiency caused by injection of cooling flow into the gas stream.

3. An inaccurate prediction of both required cooling flow and turbine efficiency will result in an inaccurate prediction of engine thrust. However, the error in calculated thrust caused by flow bypassing the rotor is much greater than the error in calculated thrust caused by the decrease in turbine efficiency.

APPENDIX A. - NAMES OF VARIABLES IN SUBROUTINE COOLIT

AIR1	air content of the hot gas at the entrance to a row of airfoils, lbm/sec
AIR2	air content of the bleed flow from the row of airfoils immediately upstream, lbm/sec
CALBLD	indicator which is set to .TRUE. when bleed flow requirement is to be determined
DELN	percent change in thermodynamic efficiencyof a cooled stage for each one percent of required cooling flow; change in thermodynamic stage efficiency due to the rotor
DELV	change in thermodynamic stage efficiency due to the stator
DH	power extracted from each turbine stage, Btu/sec
EFF1	thermodynamic efficiency of an uncooled turbine
EFF2	thermodynamic efficiency of an uncooled stage of a turbine
EFF3	thermodynamic efficiency of a cooled stage of a turbine
EFF4	thermodynamic efficiency of a cooled turbine
ELIFE	desired life of the turbine airfoil
FACTOR	cooling flow weighting factor
FARCX	fuel to air ratio of the cooling flow
FARG	fuel to air ratio of the hot gas stream at the inlet to a row of airfoils
FARGX	fuel to air ratio of the hot gas stream at the inlet to the turbine
FUEL1	fuel content of the hot gas stream at the entrance to a row of airfoils, lbm/sec
FUEL2	fuel content of the bleed flow from the row of airfoils immediately upstream, lbm/sec
GAM	(GAMAVG-1)/GAMAVG
GAMAVG	(GAMIN+GAMOUT)/2
GAMIN	specific heat ratio of the hot gas as function of TIN and FARGX
GAMOUT	specific heat ratio of the hot gas as function of TOUT and FARGX
HC	enthalpy of the cooling flow, Btu/lbm
HG	enthalpy of the hot gas stream at the inlet to a row of airfoils, Btu/lbm
HGUP	enthalpy of the hot gas stream at the inlet to a turbine, Btu/lbm
HPT	power extracted by the turbine, hp
II	number of rows of cooled airfoils in a turbine which exceed nine
KVANE	indicator which determines whether a row of airfoils is a stator or a rotor
KINDOF	an ordered combination of digits representing the cooling configurations throughout the the turbine starting with the stator of the first stage
M	ROWS
NEWEFF	indicator which is set equal to .TRUE. when a new thermodynamic efficiency for the cooled turbine is to be calculated
NFACT(I)	digit representing a particular cooling configuration for a particular row of airfoils in

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	a cooled turbine
N	whole number of stages in the turbine
N1STT	component number of the first turbine
PHI	general name for PHIC(X)
PHIC(X)	cooling effectiveness evaluated at the local value of the effective gas stream temperature
PCBLED	accumulated cooling flow required to cool the turbine, made dimensionless by the flow entering the turbine
PR	pressure ratio across turbine, inlet/exit
PROFIL	combustor pattern factor; or radial temperature profile
RP	pressure ratio across turbine, exit/inlet
ROWS	number of rows of cooled airfoils in the turbine
SAFETY	safety margin of 150°R used when determining the required cooling flow
STAGES	number of stages in the turbine
SUMBLD	sum of dimensionless bleeds from all turbines; approaches unity as engine design converges
T	argument of function PHIC(X); average effective gas temperature, $^\circ$R
TAUT	temperature ratio across turbine as calculated by stage efficiencies
TC	total temperature of the cooling flow at the point at which it is extracted from the compressor, $^\circ$R
TG	gas temperature at the inlet to a row of airfoils, $^\circ$R
TIN	total temperature of the gas into the turbine, $^\circ$R
TM	general name for either TMVANE or TMBLAD, $^\circ$R
TMBLAD	allowable bulk metal temperature for rotor blades, $^\circ$R
TMVANE	allowable bulk metal temperature for stator vanes, $^\circ$R
TOUT	total temperature of the gas out of the turbine, $^\circ$R
WCOOL	dimensionless cooling flowrate for a row of cooled airfoils
W(I)	the cooling flowrate for a row airfoils, lbm/sec; or the cooling flowrate for a row of airfoils in the turbine plus endwall, shroud, and disk cooling and leakage, lbm/sec
WG	gas flowrate at the inlet to a row of airfoils, lbm/sec
WG1	WTFLO, lbm/sec
WTFLO	total gas flow into the turbine, lbm/sec
XDELN	general name for DELN
XFACT	general name for FACTOR
XN	N
YEAR	first year of service for stator vane material; called YEARV in INPUT SUBROUTINE
YEARB	first year of service for rotor blade material

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      SUBROUTINE COOLIT (STAGES,KINDOF,TIN,TOUT,TC,PCBLED,EFF1,EFF4,HP
     1TFLO,FARCX,FARGX,PR)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /JBLEED/ SUMBLD,YEAR,ELIFE,CALBLD
      COMMON /BLADE/ YEARB,TMVANE,TMBLAD,NEWEFF
      COMMON /PF/ PROFIL,N1STT
      LOGICAL CALBLD
      LOGICAL NEWEFF
      DIMENSION NFACT(20), W(20)    ,XFACT(10),XDELN(20)
      DATA XFACT,XDELN/0.0,2.0,1.5,1.4,1.3,1.2,1.1,0.9,1.0,0.8,-
     10.,0.,0.,0.1,0.12,0.15,0.18,0.5,0.35,1.0,-
     10.,0.,0.,0.2,0.24,0.30,0.36,1.0,.60,1.5/
      PHIC(X)=(X-TM)/DABS(X-TC)
      WCOOL(PHI)= .022*(PHI/(1.-PHI))**1.25
      N=STAGES+.1
      N=AMAX0(1,N)
      TMVANE=(10.*YEAR-17640.)-(100.*DLOG10(ELIFE)-400.)
      TMBLAD=(10.*YEARB-17740.)-(100.*DLOG10(ELIFE)-400.)
      GAMIN=THERM(5,TIN,FARGX)
      GAMOUT=THERM(5,TOUT,FARGX)
      GAMAVG=(GAMIN+GAMOUT)/2
      GAM=(GAMAVG-1)/GAMAVG
      TAUT=1
      RP=1/PR
      XN=N
      EFF2=(1.-(1.-EFF1*(1.-RP**GAM))**(1./XN))/(1.-RP**(GAM/XN))
      DH=HPT/FLOAT(N)/1.415
      HC=THERM(4,TC,FARCX)
      SAFETY-150.
      FARG=FARGX
      TG=TIN
      HG=THERM(4,TG,FARG)
      PCBLED=0.
      WG1=WTFLO
      WG=WG1
      HGUP=HG
      KVANE=-1
      ROWS=2*STAGES+.1
      M=ROWS
      M=AMAX0(2,M)
      II=M-9
      DO 20 I=1,M
      IF (M.GT.9.AND.I.LE.II) GO TO 10
      NFACT(M+1-I)=KINDOF-10*(KINDOF/10)
      KINDOF=KINDOF/10
      GO TO 20
   10 NFACT(M+1-I)=1
   20 W(I)=0.
      DO 80 I=1,M
      KVANE=KVANE*(-1)
C     COOLING FLOW WEIGHTING 'FACTOR' ASSIGNED TO 'KINDOF'
```

```
C         COOLING CONFIGURATION
          N=NFACT(I)+1
          FACTOR=XFACT(N)
          IF (KVANE.LT.0) GO TO 30
          TM=TMVANE
C         DIMENSIONLESS CHANGE IN STAGE EFFICIENCY FOR A ONE
C         PERCENT CHANGE IN STATOR COOLING FLOW
          DELN=XDELN(N)
          GO TO 40
30        TM=TMBLAD
C         DIMENSIONLESS CHANGE IN STAGE EFFICIENCY FOR A ONE
C         PERCENT CHANGE IN ROTOR COOLING FLOW
          DELN=XDELN(N+10)
C         APPROXIMATION FOR RELATIVE TOTAL TEMPERATURE
          TG=.92*TG
C         CORRECTION TO 'T' FOR SAFETY MARGIN OF 150 DEG
40        T=TG+SAFETY
          PHI=PHIC(T)
C         CORRECTION TO 'PHI' FOR PATTERN FACTOR/RADIAL PROFILE
C         'PROFIL' HAS VALUE OF 0.30 FOR THE FIRST STATOR OF THE HPT
          PHI=(PROFIL+PHI)/(PROFIL+1.)
          PHI=DMAX1(PHI,0.D0)
C         IF THE BLADE IS MEANT TO BE COOLED AND IT NEEDS TO BE COOLED
          IF (NFACT(I).GT.0.AND.PHI.GT.0.) GO TO 50
C         IF THE BLADE DOES NOT NEED TO BE COOLED
          IF (PHI.EQ.0.) GO TO 60
C         IF THE BLADE NEEDS TO BE COOLED
C         BUT WAS NOT MEANT TO BE COOLED
          FACTOR=2.0
          NFACT(I)=1
50        W(I)=WCOOL(PHI)*FACTOR*WG
          GO TO 65
60        NFACT(I)=0
65        DELN=DELN*W(I)/WG*EFF2
          IF (.NOT.NEWEFF) DELN=0
          IF (KVANE.GT.0) DELV=DELN
C         CORRECTION FOR ENDWALL COOLING/LEAKAGE
          W(I)=W(I)*4/3
C         NEW FUEL/AIR RATIO AFTER DILUTION FROM UPSTREAM ROW
          AIR1=WG/(1.+FARG)
          FUEL1=WG*FARG
          AIR2=W(I)/(1.+FARCX)
          FUEL2=W(I)*FARCX
          FARG=(FUEL1+FUEL2)/(AIR1+AIR2)
          IF (KVANE.GT.0) GO TO 70
          EFF3=EFF2-DELN-DELV
          TAUT=(1.-EFF3*(1.-(RP**(1./XN))**GAM))*TAUT
          HG=HG-DH/WG
70        HG=(WG*HG+W(I)*HC)/(WG+W(I))
          TG=THERM(1,HG,FARG)
          WG=WG+W(I)
          PROFIL=.13
80        PCBLED=PCBLED+W(I)/WG1
```

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```
      MM=AMINO(9,M)
      DO 90 I=1,MM
90    KINDOF=KINDOF*10+NFACT(I)
      EFF4=(1-TAUT)/(1-RP**GAM)
      RETURN
      END
```

APPENDIX C. - CHANGES TO SUBROUTINE TURBIN

1. After the statement
"IMPLICIT..."
on line 2, insert the statement
"DIMENSION KIND(20)".

2. After the statement
"COMMON /JBLEED/..."
on line 10, insert the two statements
"COMMON /BLADE/YEARV,TMVANE,TMBLAD,NEWEFF"
and
"COMMON /PF/ PROFIL,N1STT".

3. After the statement
"LOGICAL CALBLD"
on line 11, insert the statement
"LOGICAL NEWEFF".

4. After the statement
"EFFT=DATINP(6,JCX)"
on line 45, insert the two statements
"IF (.NOT.NEWEFF) DATOUT(8,JCX)=DATINP(11,JCX)"
and
"IF (NEWEFF.AND.NIT.EQ.0) DATOUT(11,JCX)=DATINP(11,JCX)".

5. Replace the statement
"EFF=DATINP(11,JCX)"
on line 95 with the statement
"EFF=DATINP(8,JCX)".

6. After the statement
"TOTEMP(JP1)=TOUT"
on line 109, insert the six statements
"IF (N1STT.EQ.0) N1STT=JCX",
"IF (JCX.EQ.N1STT) PROFIL=0.3"
"IF (HPT.EQ.0) KIND(JCX)=DATINP(14,JCX)",
"KINDOF=KIND(JCX)",
"IF (HPT.EQ.0) GO TO 121",
and
"IF (KINDOF.EQ.0.) KINDOF=88".

7. Delete the two statements
"FACTOR=DATINP(14,JCX)"
on line 110 and
"IF (FACTOR.EQ.0) FACTOR =1.0"
on line 111.

8. Change the term "NSTAGE" on line 113 to "STAGE".

9. Change the terms "NSTAGE,FACTOR" on line 114 to "STAGE,KINDOF".

10. Change the term "LED)" on line 115 to the terms

"LED, DATINP(11,JCX),DATOUT(8,JCX),HPT,WT1,FAR2,FAR1,PR)".

11. After the statement
"IF (DABS... GO TO 60"
on line 121, insert the statement
"IF (DABS(EFF-DATOUT(8,JCX)).GT.1.D-4) GO TO 60".

12. After the statement
"SUMBLD=SUMBLD..."
on line 122, insert the statement
"CONTINUE".

13. After the statement
"DATOUT(7,JCX)..."
on line 133, insert the statement
"IF (IDONE(JCX).EQ.0) GO TO 125".

14. Change the statement
"DATOUT(9,JCX)=PR"
on line 135, to
"125   DATOUT(9,JCX)=PR".

15. After the previous statement on line 135, insert the statement
"DATINP(14,JCX)=KINDOF".

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APPENDIX D. - CHANGES TO SUBROUTINE INPRT

1. After the statement
"COMMON /JBLEED/..."
on line 11, insert the statement
"COMMON /BLADE/YEARB, TMVANE, TMBLAD, NEWEFF".

2. After the statement
"10) I,DATINP(2,I)"
on line 98 insert the statement
"KINDOF=DATINP(14,I)".

3. After the term "DATINP(2,I)" on line 99, insert the
terms ",KINDOF, TMVANE, TMBLAD".

4. Replace on the right-hand-side parenthesis, ") ", with a hyphen
and add to format statement 520 the continuation
"1.'   THE COOLING CONFIGURATION IS ,I9,' TMVANE IS
',F6.0,' TMBLAD IS ',F'.0)".
(Note the blank after the parenthesis.)
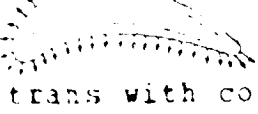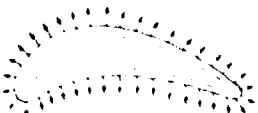
APPENDIX E.- CHANGES TO SUBROUTINE INPUT
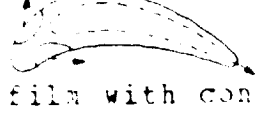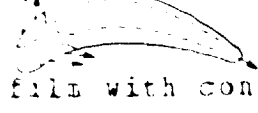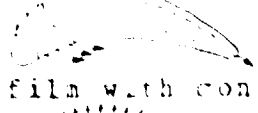
1. After the term "CALBLD" on line 16, insert the term ",NEWEFF".

2. After the statement
"COMMON /JBLEED/..."
on line 23, insert the two statements
"COMMON /BLADE/ YEARB, TMVANE, TMBLAD, NEWEFF"
and
"COMMON /PF/ PROFIL,N1STT".

3. Replace the term "YEAR" on line 28 with the terms
"NEWEFF, YEARB, YEARV".

4. After the statement
"CALBLD=.FALSE."
on line 38, insert the three statements
"NEWEFF=.FALSE.",
"YEARV=1985.",
and
"YEARB=1985.".

5. Delete the statement
"YEAR=1985."
on line 39.

After the statement
"READ (8,D)"
on line 50,
insert the statement
"N1STT=0".

7. After the statement
"READ(8,D)"
on line 76, insert the statement
"YEAR=YEARV".

REFERENCES

1. Fishbach, Laurence H.; and Caddy, Michael J.: NNEP: The Navy-NASA Engine Program. NASA TM X-71857, 1975.

2. Fishbach, Laurence H.; and Caddy, Michael J.: User's Manual Navy-NASA Engine Program NNEP. NASA 1977. (Internal document available from authors.)

3. Esgar, Jack B.; Colladay, Raymond S.; and Kaufman, Albert: An Analysis of the Capabilities and Limitations of Turbine Air Cooling Methods. NASA TN D-5992, 1970.

4. Gladden, Herbert J.; and Liebert, Curt H.: Effects of a Ceramic Coating on Metal Temperatures of an Air Cooled Turbine Vane. NASA TP 1598, 1980.

5. Hennecke, Dietmar K.; and Winterfeld, Gert, eds.: International Symposium on Air Breathing Engines, 3rd DGLR-Fachbuck Vol. 6, Deutche Gesellschaft fur Luft-und Rahmfahrt (Koln), 1976.

6. Livingood, John N. B.; Ellerbrock, Herman H.; and Kaufman, Albert: 1971 NASA Turbine Cooling Research Status Report. NASA TM X-2384, 1971.

7. Oates, Gordon C., ed.: The Aerothermodynamics of Aircraft Gas Turbine Engines. AFAPL TR 78-52, Air Force Aero Propulsion Laboratory, 1978, p. 6-10. (AD-A059784)

TABLE I.- ALLOWABLE COOLING CONFIGURATIONS

Cooling configuration, NFACT(I)	Percent trailing edge ejection	Impinge- ment insert	Relative cooling flow, FACTOR	Loss in stage efficiency, stator DELV	rotor DELN
0 uncooled	0	no	0.0	0.00	0.00
1 convection	100	no	2.0	0.00	0.00
2 conv with coat	100	no	1.5	0.00	0.00
3 advanced conv	100	yes	1.4	0.10	0.20
4 film with conv	75	yes	1.3	0.12	0.24
5 film with conv	50	yes	1.2	0.15	0.30
6 film with conv	25	yes	1.1	0.18	0.36
7 trans with conv	25	yes	0.9	0.50	1.0
6 full cover film	0	yes	1.0	0.35	0.80
9 transpiration	0	yes	0.8	1.00	1.50