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J. ALKINS
GENERATION OF THE TURBINE CHARACTERISTICS
OF A TWIN-SPOOL TURBOJET AND ITS
APPLICATION TO ENGINE HEALTH MONITORING

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the
Degree of Master of Engineering

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ABSTRACT

This thesis sets out to develop a computer program to analyse the performance of a twin-spool non-afterburning turbojet engine for purposes of determining the health of such gas turbines. By using the technique of Gas Path Analysis, engine variables that are not normally measured on an operational gas turbine are obtained, thus giving a complete set of pressures, temperatures, and mass flow rates at the various engine stations from which the performance characteristics of the various components are obtained. Emphasis is laid on obtaining credible performance characteristics of the turbine component.

Test data from two Pratt & Whitney J57 engines were available to validate the program. The component characteristics of both engines were found to conform to the general performance characteristics of such components. Arguments are presented to support the conclusion that the data obtained from the program give a credible description of engine condition.
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Finally, I would like to dedicate this thesis to LIs for being a Dear Mother and also for her efforts in helping me to realize some of my dreams.
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HP T  High Pressure Turbine

h  Enthalpy of Fluid at Station in Question

h_{3,HP}  Enthalpy of Gas at Station 5 Computed from HP Rotor Work Balance

h_{3,LP}  Enthalpy of Gas at Station 5 Computed from LP Rotor Work Balance

ITT  Inter - Turbine Temperature

JPT  Jet Pipe Temperature

K  Constant of Proportionality in the Expression for Compressor or Jet Pipe Pressure Loss

LP  Low Pressure

LPC  Low Pressure Compressor

LPT  Low Pressure Turbine

m_f  Fuel Flow Rate

N_1  LP Rotor Speed

N_2  HP Rotor Speed

P  Total Pressure at a Station

PR  Pressure Ratio

Q  Corrected Mass Flow Parameter, \( W\sqrt{\beta/\delta} \), at Station in Question

Q_{3,a}  Actual Mass Flow Parameter at Station 3, \( W_3\sqrt{T_3/P_3} \)

Q_{7,a}  Actual Mass Flow Parameter at Station 7, \( W_7\sqrt{T_7/P_7} \)

Q_{7:D}  Design Point Corrected Mass Flow at Station 7

sfc  Specific Fuel Consumption

T  Total Temperature at a Station

TIT  Turbine Inlet Temperature

TR  Temperature Ratio
$W$ Mass Flow of Fluid at a Station

$W_{cb}$ Turbine Blade Cooling Bleed Flow in Percentage of Inlet Airflow

$W_{sb}$ Surge Bleed Flow in Percentage of Inlet Airflow

Greek Symbols

$\gamma$ Ratio of Specific Heats

$\gamma_{nv}$ Ratio of Specific Heats at Nozzle Entry

$\Delta P$ Pressure Loss in Compressor or Jet Pipe

$\delta_{i}$ Corrected LP Compressor Inlet Pressure

$\eta$ Efficiency of a Component

$\eta_m$ Mechanical Efficiency of Rotors

$\eta_\infty$ Polytropic Efficiency of Compression or Expansion Process

$\theta_{i}$ Corrected LP Compressor Inlet Temperature

$\theta_{cp}$ Fuel/Air Ratio Correction for $C_p$ of Combustion Product

$\theta_{h}$ Fuel/Air Ratio Correction for Enthalpy of Combustion Products

$\theta_s$ Fuel/Air Ratio Correction for Entropy Function of Combustion Products

$\psi$ Entropy Function for Dry Air at Temperature, $T$

Suffixes

$a$ Air

c Compressor

cc Combustor Chamber

J, J Jet or Nozzle Exit

JP, JP Jet Pipe
1 Turbine
2 Station 1
3 Station 2
4 Station 3
5 Station 4
6 Station 5
7 Station 6
8 Station 7
Chapter 1

INTRODUCTION

The art of monitoring the health of a gas turbine is to obtain measurement data from which meaningful conclusions on engine condition can be drawn, with a view to ensuring safety and economical operation of the engine by correcting any detectable engine faults that are sure signs of engine distress. The monitoring technique includes keeping a close watch on certain engine parameters and then observing the time-history of their deviations from a baseline, or estimating key engine parameters by following the gas path in a thermodynamic analysis. The former gives only an indication of engine deterioration while the latter has the capability to fault isolate down to the component level.

When the performance of an engine changes, this is due to one or more engine faults affecting the performance of some engine components, altering parameters such as mass flow and efficiency. These performance parameters are not practically measurable but may be deduced from the measurable performance variables such as temperature and pressure. By interrelating changes in these measurable performance variables to changes in component performance parameters, a means exists for isolating engine faults to the various components. However, some of the key variables that give an overall assessment of engine health cannot easily be measured by virtue of their positions in the gas stream or by the fact that instruments are not readily available to record them, and thus have to be inferred from other variables which can be measured.

The aim of this thesis is to develop a thermodynamic analysis program which will compute those cycle parameters not usually measured on a twin-spool gas turbine, that are considered prime indicators of engine health. The characteristics of both low pressure (LP) and high pressure (HP) turbines are generated, and so are the LP and HP compressor running lines. The propelling nozzle characteristic is also generated in the case where the gas turbine happens to be a turbojet.

The computer program that will be developed will be able to compute the unmeasured engine
variables from the measured variables. This is made possible by the fact that if mathematical models of engine components represent a valid thermodynamic cycle, then they satisfy the laws of physics governing the operation of the engine, and these are basically compatibility of mass flow and work. The Pratt and Whitney J57 twin-spool non-afterburning turbojet engine was chosen for a case study simply because it was available for investigative work in the area of Engine Health Monitoring Systems.

The importance of the turbine as the component that produces useful output from the energy stored in the burnt gases has often been overlooked, for one reason or another, by gas turbine performance engineers in comparison to the attention given to compressors. As a result, the means for obtaining credible turbine performance characteristics for purposes of engine health monitoring are not readily available. It is hoped that this thesis will provide a means for generating turbine data.

The layout of this text is as follows. Chapter 2 is an introduction to turbine performance. The reader is introduced to the conventional forms of turbine performance representation. The causes of deterioration in turbine performance and the effects of loss in turbine performance on engine performance are also discussed. A detailed description of the computer model is presented in Chapter 3 in the form of a main program and associated sub-programs representing the performance of the various engine components. Storage of the required input data is also explained. In Chapter 4, the developed software is put to test by using test data from two Pratt & Whitney J57 engines. The turbine characteristics of both LP and HP turbines are generated, so are the LP and HP compressor running lines and the propelling nozzle characteristic. The application of the generated engine data to engine health monitoring is discussed in Chapter 5. This includes a diagnosis of engine health and the necessary measures to be taken to ensure performance reliability in the case where the engine's health is poor. Recommendations for future work in this area are also given. A summary of the conclusions arrived at is presented in Chapter 6.
Chapter 2

TURBINE PERFORMANCE

With very few exceptions, gas turbines employ the axial-flow turbine\(^1\) whose duty is to provide power for driving the compressors and accessories, and in the case of engines which do not make use solely of a jet for propulsion, to provide shaft power for a propeller or a rotor. This is accomplished by extracting some of the pressure and kinetic energy from the burnt gases released from the combustor and expanding them to a lower temperature and pressure \(^{[1,2]}\)\(^2\). The turbine may consist of one or more stages depending on the amount of power that it has to develop, the number of stages increasing with increasing compression ratio. Each stage comprises a row of stationary vanes, the stator or nozzle, followed by a row of rotating blades, the rotor. For the turbine to operate efficiently, it is necessary that the blade tips rotate at a very high speed. This speed, established by the allowable blade stress and turbine diameter, determines the number of compressor stages required to provide the required pressure ratio at peak efficiency. The discussion in section 2.3 will show that the performance of the turbine is very critical to obtaining good performance from the compressor.

2.1 Turbine Characteristics

The uses to which gas turbines are put require of them satisfactory performance under varying conditions. For example, an aircraft gas turbine normally finds itself in a situation where it will have to perform differently at take-off, climb, and cruise; and in the case of military applications, could be subjected to varying performance when the aircraft is executing certain manoeuvres. It is

---

1 From hereon, reference is made only to the gas generator turbine
2 Numbers in square brackets represent references at the end of this thesis
then necessary that the performance of a turbine can be calculated over a wide range of operating conditions.

The performance of a turbine is normally expressed by plotting the mass flow parameter, $Q$, at turbine entry and the isentropic efficiency, $\eta$, against turbine stagnation pressure ratio for various rotational speeds. These are shown in Fig. 1 where the gas is assumed to expand from state 3 to state 4. When the turbine has exhausted its swallowing capacity, choking will occur somewhere in the turbine at a critical pressure ratio. It can occur either in the nozzle throats, rotor throats, or at exit annulus. If choking occurs in the nozzle throats, then all the speed lines will merge into one as seen in Fig. 1. Otherwise, the maximum mass flow will vary slightly with speed, Fig. 2. The speed dependence of mass flow at low pressure ratios is not that great, and the more the number of stages the more nearly can the mass flow characteristics be represented by a single curve independent of speed [3]. When the turbine is linked to the remaining engine components, the whole operating range shown is not utilized and normally, both the mass flow rate and pressure ratio of the turbine will increase at the same time as the spool speed is increased, as shown by the dashed line in Fig. 1. In fact, a detailed turbine characteristic is seldom made available. Thus, representing the turbine operating characteristics by a single line is a very good approximation when predicting the off-design performance of the engine.

The efficiency curve rises very steeply at very low pressure ratios to a nearly constant value at high pressure ratios at constant speed. Note that the efficiency of the turbine is nearly constant over a wide range of speed and pressure ratio. This is a property of reaction blades. The accelerating nature of the flow allows such blades to operate over a wide range of incidence without much increase in loss coefficient [3]. The degree of reaction normally varies over the span of the blade, increasing from a low value at the hub.

### 2.2 Causes of Performance Degradation

There are several causes of loss in turbine performance, regardless of the nature of the cause, the cause will manifest itself either as a change in turbine flow passage area, or isentropic efficiency, or both. A change in flow passage area is caused by a change in blade profile or shape brought about by the build up of salt and ash deposits on the blades and also by bowing of blades caused by overtemperature, thereby reducing the metal cross-section non-uniformly. Damaged blading

---

3 Turbine ‘blading’ or ‘blade’ refers to either nozzle vane or rotor blade. Stationary blades will be referred to specifically as nozzle vanes, and rotating blades, rotor blades.
could be caused by failure of nozzle vanes by creep rupture, or thermal fatigue of rotor blades, or excessive bowing, or even by foreign objects passing through the turbine. A change in flow passage area due to a change in blade profile may cause a loss in turbine efficiency due to the fact that there is a slight re-match of the turbine and compressor, which then results in the turbine operating away from its peak efficiency point. Damaged turbine blading could cause the same effect but results in a larger drop in turbine efficiency.

The materials used for turbine blading have always imposed a limit on the performance of gas turbines, as the maximum usable TIT is limited by available materials and cooling technology. The stator vane material is usually nickel or cobalt base alloy, whilst nickel alloys are favoured for rotor blades. Chromium is usually present in these alloys to improve their corrosion resistance. The hot environment in which turbine blades operate can cause severe corrosion, erosion, thermal fatigue, or even local melting.

2.2.1 Corrosion

The effect of blade corrosion is that the resulting decrease in turbine efficiency causes a drop in useful output. In order to maintain power or thrust, fuel flow is increased thereby increasing TIT, and this leads to a shorter blade life. Land based gas turbines are more susceptible to corrosion than aircraft engines, partly because the surrounding atmosphere is more contaminated, compared with the cleaner atmosphere at altitude, and partly because land based engines burn a lower grade of fuel whereas aviation fuel is of much higher quality.

Corrosion of turbine blading occurs when salt or ash deposits on such blading break down the protective oxide layer of combined nickel and chromium, thereby exposing the parent material to chemical attack. Since turbine blades operate in a very hot environment, they are therefore subjected to the phenomenon of hot corrosion or sulphidation. Hot corrosion of turbine blading occurs when the engine is operating in an atmosphere in which alkali metals such as sodium are present with a fuel that contains small traces of sulphur. The sodium sulphate formed gets deposited on stator vanes in particular, and can proceed to the extent of corroding deep holes in the blading, and eventually, breakage. Traces of vanadium or lead in the fuel cause the same effect by depositing vanadium pentoxide or lead sulphate respectively, on the blades. To complete this section, it should be mentioned in passing that blade erosion due to ingested sand and dust particles does occur on turbine blades but is not so pronounced as it is in compressors.
2.2.2 Creep and Thermal Fatigue

Turbine blading breakage can occur as a result of creep rupture and thermal fatigue. Creep is a phenomenon that occurs at elevated temperatures when a material is subjected to very high steady tensile stresses. Excessive elongation of the blades can occur and this may lead to rupture and eventual failure.

In order to prolong creep life and keep the oxidation rate of the blading material low, it has become an acceptable practice amongst gas turbine designers to cool the first stage turbine blade row with small quantities of air. The metal temperature can be reduced by as much as 300 K by using about 2 - 4 per cent of the engine airflow. Note that blade cooling can result in improved engine performance due to the fact that the allowable turbine inlet temperature can be increased, resulting in increased specific thrust or power and reduced SFC.

Rotor blades can be lost by thermal fatigue which results from sudden changes of gas temperature during starting and engine transient operation. The material at the trailing and leading edges encounters temperatures higher than those experienced by the material at the central portion and therefore experiences severe strain as it is restrained from moving freely by the material at the central portion. When this cyclic strain, compressive during start up and acceleration and tensile during shut down, is repeated many times, fatigue cracks are formed, initially in line with the combustion outlet hot spots.

Thermal fatigue cracking of stator vanes can occur in nickel and cobalt base alloys. The presence of highly reactive elements such as titanium and aluminum in these alloys can contribute to rapid oxidation along the grain boundaries and this may lead to inter-granular cracking under operating conditions. So it is seen that thermal fatigue and creep affect the performance of the turbine though they are of a mechanical nature. It will be shown in section 2.4 that poor thermodynamic health may also indicate poor mechanical health.

2.3 Effect of Turbine Performance on Engine Performance

The unique relationship existing between stator inlet and exit areas, in order to efficiently convert pressure energy into kinetic energy, makes the design of the stator vane area a critical part of the engine design. Making the stator vane area too small or too large would cause the turbine to operate away from its point of best efficiency.

The effect of having a larger stator area is that there is an increase in specific fuel consumption.
due to a lower compressor delivery pressure and a significant loss of thrust, although there is a faster engine acceleration with less tendency of compressor stalling [1]. A small stator vane area greatly affects the acceleration of the engine in two ways. Firstly, it could cause the compressor to stall whilst the turbine is choking. A small area restricts the airflow through the engine causing the pressure ratio across the compressor to rise. The compressor operating point then moves closer to the surge line. And as noted in Fig. 1, the turbine nozzle is designed to be choked for most of its operating range. Secondly, a small nozzle area would cause a slower acceleration of the engine as the compressor will be forced to work against a higher back pressure.

A degradation in turbine performance results in a loss of turbine efficiency. A given drop in turbine efficiency affects the cycle efficiency of the engine more than an equal drop in compressor efficiency. For example, the analyses in Ref. 6 for a shaft power cycle show that a 1% decrease in compressor efficiency causes a 0.33% decrease in cycle efficiency whereas a 0.79% decrease in cycle efficiency occurs when the turbine efficiency drops by 1%, Fig. 3. This indicates that the turbine efficiency can be twice as critical as the compressor efficiency when computing cycle efficiency. The author claims that the fuel consumption increases by 0.88% for each decrement of 0.2% in cycle efficiency. Thus a small decrease in turbine efficiency will turn out to be uneconomical, in airline and industrial applications, due to the cost of the extra fuel used, while loss of thrust is unacceptable in military applications. So it is essential that an optimum operating efficiency of all components be maintained, and in particular, the turbine.

2.4 The Need for Engine Health Monitoring (EHM)

The primary reason for monitoring the health of a gas turbine is to obtain measurements which will be used as inputs to the decision making process of ensuring safety and economical operation of the engine. Gas turbines are costly (running into a few million dollars) and are usually employed in roles where engine operational reliability is of paramount importance. An hour of shutdown due to malfunction or a catastrophic failure giving rise to engine replacement can result in disastrous consequences and high costs when used in process industries. In airline application, passenger safety is at stake, whereas the fighting capability of a force can be drastically reduced in military application. A loss in operating revenue and cost savings can be substantial in the case of engines operating in continuous duty, not forgetting the serious social consequences, say, that may result if there is a power failure when the gas turbine is used to generate electricity.

In the past, the philosophy of all engine operations was that maximum life should be obtained
from the engine without incurring a catastrophic failure. In order to reduce the number of spare engines and parts inventory, users of gas turbines have dropped the concept of fixed times between overhauls in favour of overhauls on condition and where possible, overhauls on a convenient schedule [7]. This has come about due to the greatly increased operating reliability experienced with gas turbines. Since the degradation of a component is gradual, there is usually sufficient time for the user to take corrective action if he can be warned pending a degradation. This has been the basis of the concept of engine health monitoring schemes.

The health of an engine can be classified under mechanical health and thermodynamic health. Poor mechanical health leads to failure of an accessory or a rotating component whilst poor thermodynamic health results in performance degradation of one or more gas path components and may even lead to failure of one or more components.

In a gas path analysis, two of the most critical parameters are airflow and turbine inlet temperature. The pumping capacity of a compressor decreases when the compressor is fouled. The output power or thrust will decrease if there is a drop in airflow, and to maintain the level of power or thrust fuel flow increases, the net result is an increase in TIT and hence, a rapid drop in turbine blade life. These two parameters are not usually measured when the engine is in operation, but can be deduced with a fairly high level of confidence. Thus, the engine's health is predicated on several measurements which only give an indirect indication [8].

At any steady operating conditions of an healthy engine, each gas path component will have a set of parameter values at inlet and exit. Some of the parameter values in any set can only be changed by a fault of significant enough, and since each fault displays a unique pattern in a set, it is possible to identify that particular fault if the health of the engine is monitored [9]. Therefore, gas path analysis can be a great asset to users of gas turbines.

Gas path analysis will be used to analyse the performance of the engine. Since this is an analytical technique, the limitation is that it can only find implicitly detectable faults (i.e. implied from their effects on the measurable parameters) which cause observable changes in the gas containment sections of the engine as opposed to non-analytical techniques, such as radiography, visual inspection, etc, which will detect faults such as fatigue cracks that do not affect the geometry of the flow passages.
Chapter 3

MODEL DESCRIPTION

Mathematical modelling of the static performance of gas turbines is a well established discipline. All of the previously developed successful models have made use of empirical maps for describing the major engine components, provided these maps are accurate, an accurate definition of overall engine performance can be obtained [5]. A change in performance of any of the engine components will definitely cause a change in engine performance; and if it is possible to represent changes in component performance on the component performance characteristics, then a degraded component can be easily identified.

Simple as it may sound, there are several problems associated with applying this technique. The most frustrating of all is the complete lack of data. Therefore, the engine performance analyst is left in a situation where he cannot readily synthesize the performance of a degraded engine. The complete set of data can be obtained by inputting measurement data to thermodynamic models of the engine gas path components. This is made possible by the fact that a valid thermodynamic cycle which matches a set of measurement data satisfies the laws of physics governing the operation of the engine. This powerful technique can be used successfully only if the performance analyst understands the thermodynamics governing these mathematical models.

3.1 Engine Configuration

There are several configurations of a twin-spool gas turbine. The common feature of all, is that there is a high pressure turbine and a low pressure turbine, each on a separate shaft, driving a load which may be a combination of a compressor and compressor, or propeller, or fan, or rotor. The software that will be developed to analyse the performance of a gas turbine will be applied to a twin-spool non-afterburning turbojet engine only. Henceforth, reference will be made only to
this type of gas turbine.

The layout of the basic twin-spool non-afterburning turbine is shown in Fig. 4. It is comprised of an intake, low pressure compressor, high pressure compressor, combustion chamber, high pressure turbine, low pressure turbine, and an exhaust system which is made up of a jet pipe and a propelling nozzle. A description of the station numbering that will be used for cycle notation, as shown in Fig. 4, can be found in Table 4.

3.2 Gas Path Analysis

It may not be possible to measure some variables on an operational gas turbine. This is so either by nature of their positions in the gas stream or by the fact that instruments are not readily made available to measure them. These variables can be inferred from the measured data by using a technique known as Gas Path Analysis. The unmeasured parameters usually include the turbine inlet temperature and engine airflow while the measured parameters are usually the various temperatures and pressures at stations other than 4 and 5, fuel flow, thrust, and rotational speeds of the shafts.

The concept of gas path analysis, a means of obtaining additional insight into engine condition by mathematical analysis of measurement data, is relatively new in the area of engine health monitoring. Though this technique has the potential to indicate problems quite early in their development, it is poorly understood by gas turbine users, and so has not yet been successful as a valuable maintenance tool.

If enough measurements are recorded to satisfy compatibility of mass flow and work of the engine, gas path analysis can provide a means of estimating component performance in addition to overall engine performance. The unmeasured pressures and temperatures at the different engine stations can be estimated. These estimates can be used to calculate component efficiencies which then give an insight into engine performance and isolate faults to a particular component.

The ability of gas path analysis to detect problems quite early in their initial stages lies in the fact that any detectable fault may be viewed as affecting one or more components in one or more of their basic performance parameters [10]. Compressor faults will manifest themselves as changes in either the air pumping capacity, or isentropic efficiency, or both; a change in the effective turbine nozzle area or isentropic efficiency is indicative of problems in the turbine, whereas variations in propelling nozzle area which may cause the engine match point to change, are indicative of.
faults in the exhaust system. Such physical engine faults may be referred to as the primary independent variables and are not practically measurable. The measurable parameters, such as pressure and temperature, are treated as the dependent variables whose absolute values depend on the absolute levels of all primary independent variables. Hence, any gas containment parts that are in distress or have deviated from their initial or expected condition will have values of one or more of their dependent variables different from their expected baseline values, thus indicating faults. These baseline values are the nominal values the various performance variables of a healthy engine are expected to have when the engine is running at a particular steady state condition. This does not mean that a change in any of the dependent variables of a particular component will always indicate that there are faults in that component. For example, a decrease in compressor air pumping capacity due to compressor fouling yields lower turbine inlet temperatures. Thus, if gas path analysis is used correctly, single or simultaneous multiple engine faults that cause a gas turbine component to degrade can be detected before failure of any component occurs.

3.3 Engine Instrumentation and Data Storage

The computer program to analyse the performance of a twin-spool non-afterburning turbojet requires some measurement data for its support. These data, classified as primary performance measurements and gas path measurements, will be stored in a two-dimensional matrix, nineteen columns wide. Since the input data will be read from a file, it is absolutely necessary that the data be input in a certain order. This will be explained in subsequent paragraphs.

The engine should be instrumented to record the measurements in Tables 1 and 2. It is suggested that the measurements be input in the order as shown in Table 3. \( \delta_1 \) is the inlet pressure corrected to standard day and \( \sqrt{\delta_1} \) is the square root of inlet temperature corrected to standard day. If any of these parameters are not measured, they should be set to zero. Note that the format statement on line 289 of the main program on page 165 requires that the input data be read on two lines. The first 10 on the first line followed by the next 9 on the second line, and so on. The data for design point performance calculations should be input first.

1 As will be explained in the developed software, some of these measurements are not required to support the program. Since engine instrumentation may differ from user to user, it is the author's intention to make the program as flexible as possible.

2 If the reader wishes to input the measurements in a different order, the necessary corrections are to be made in the initialization section of the main program. If a different set of units are to be used, then the subroutine CCTAB has to be re-written using the appropriate constants from Ref. 11.
3.4 The Computer Program

The computer program is a thermodynamic analysis program that will compute those cycle parameters that are not usually measured on a twin-spool gas turbine. By using the technique of gas path analysis, the unmeasured variables can be inferred from the measured variables. The equations of compatibility of mass flow and work of the engine describe the physics of the operation of the engine. The various engine components are represented by mathematical models which describe the thermodynamics of the components, and if these models do represent a valid thermodynamic cycle, then the compatibility equations will be satisfied. Hence, the unmeasured parameters can be obtained provided there are enough measurement data to support the program. By suitably combining the variables at the different stations, the performance characteristics of the various components can be obtained.

The program performs design point and off-design calculations in accordance with the wishes of the user. The term "design performance" as used in this context refers to the performance calculations that are done to obtain those parameters that are assumed fixed for the engine in question, from the given design point data. These parameters are the mechanical efficiency of both spools, \( \eta_m \), combustion chamber efficiency, \( \eta_{cc} \), propelling nozzle efficiency, \( \eta_f \), turbine blade cooling bleed flow as a fixed percentage of engine airflow, \( W_{cb} \), combustion chamber pressure loss, \( \Delta P_{cc} \), and jet pipe pressure loss, \( \Delta P_{jp} \). Once these are obtained, they are used in determining the performance of the engine over the complete range of speed and thrust – off-design performance. The off-design performance calculations yield the characteristics of the HP and LP turbines, the HP and LP compressor running lines, and the nozzle characteristic.

3.4.1 Thermodynamic Equations

As was mentioned in the previous section, the physics of engine operation are described by the equations of compatibility of mass flow and work. The equations of compatibility of mass flow yield the mass flow balance throughout the engine whereas the equations of work balance give an estimate of the temperatures that were not measured at some engine stations. There is an additional equation to describe the process taking place in the combustor, which gives the combustor temperature rise.
From the abovediagrammatic representation of the engine configuration, the compatibility equations are as follows

**Mass**

\[ W_2 = W_1 - W_{0a} \]
\[ W_3 = W_4 - W_{e5} \]
\[ W_4 = W_3 + W_f \]
\[ W_5 = W_4 + W_{e6} \]
\[ W_s = W_5 - W_t \]

**Energy**

**LP Spool**

\[ W_1(h_1 - h_0) = \eta_m W_5(h_5 - h_0) \]

**HP Spool**

\[ W_2(h_1 - h_2) = \eta_m W_4(h_4 - h_3) \]

The combustor temperature rise is given by

\[ f = \frac{W_f}{W_3} = \frac{h_{a4} - h_{a3}}{\eta_m[E C V_4 + (h_f - h_R)]} \]

The enthalpy change of the fuel, \( h_f - h_R \), is however neglected.

The combustor temperature rise gives the turbine inlet temperature. When the program is in the design point performance mode, the inter-turbine temperature is obtained from both the HP and LP spool energy equations, but when the off-design performance calculations are being done, the HP spool energy balance yields the inter-turbine temperature while the exhaust gas temperature is obtained from the LP spool energy balance.

### 3.5 Program Hierarchy

The program will be written in modular form, with each module analyzing a particular component of the engine or carrying out some specific operation. The program starts off with arranging the corrected input data in a two-dimensional array and ends with printing out all engine data. The design point performance calculations are done first. All the parameters that are fixed for the particular engine in question are printed out, and these are used to analyse the engine in the off-design mode immediately, or at some later time. The operational hierarchy of the
program is shown in Fig. 5, and the program module hierarchy is shown in Fig. 6. A description of the functions of the various subroutines can be found in the Glossary.

3.6 Software Specification

The program is written in FORTRAN 77 language and as a result, extensive use is made of EQUIVALENCE statements which allow variables to have names corresponding to engineering symbols. The main program is supported by fourteen subprograms and in order to facilitate the transfer of data between functional modules, the data is made to reside in specified areas which form a data base structure. The equivalence statements allow access to these variables by their location in the data base. Common areas are reserved within the data base for variables of the same nature. The data base is described in detail in appendix A.

In order to apply gas path analysis to analyze the engine, several assumptions were made, and these include,

1) The air or combustion products flow is essentially one-dimensional, that is, it has substantially the same pressures and temperatures at every point in a plane normal to the gas flow.

2) The engine is in steady state conditions. This implies that all engine parameters and the distribution of fluid properties do not vary with time.

3) The gas flow through the engine is adiabatic. Heat addition occurs only in the combustion chamber.

4) The polytropic efficiencies of the compression and expansion processes in the compressors and turbines respectively, are constant.

5) The value of the ratio of specific heats, $\gamma$, is constant for any component and is equal to the value at inlet.

6) The fluid properties vary with temperature only.

7) The spools have the same mechanical efficiency, $\eta_m$.

8) The enthalpy change of the fuel is negligible.
3.6.1 Main Program and Thermodynamic Data

The main program is divided into four sections, viz.,

a) Data input,
b) Design point performance analysis,
c) Off - design performance calculations, and
d) Data output

The data are read from an input file, as explained in section 3.3, and then stored in a two-dimensional array. The elements in the array are then assigned to their respective performance parameters which are then transformed to actual values to be stored in the database in a common area labelled MPARS (Measured PARAmeterS).

When I takes the value 1 in the DO loop, the reader has the choice of performing either design point or off - design performance calculations. The former has to be done first in order to obtain the fixed engine parameters or engine constants which will be used as input to the off-design calculations in addition to the measured data. The required sub-program, DESIGN or OFFDSGN is then invoked to perform the necessary calculations. If the subroutine DESIGN is invoked, the calculated engine constants are printed in an output file as they are calculated, and the program ends after the last constant is printed. The component characteristics are computed if the sub-program OFFDSGN is invoked, followed by the printing out in an output file, of all measured and calculated engine performance parameters and component characteristics data, in their corrected forms. Since a lot of iterative techniques is employed in the program, the reader will find himself in constant conversation with the computer terminal. The module is described in Fig. 7.

The thermodynamic data used in this program are those found in Ref. 11. The subroutine CCTAB calculates \( C_p \), \( \Theta_C \), \( h_a \), \( \Theta_a \), \( \psi_a \), \( \Theta_y \), and ECV when given a value of temperature as an argument. This subroutine uses polynomial expressions for these properties as described in section 3 of Ref. 11, and the polynomial coefficients found in appendix D of these tables.

3.6.2 Sub - Program Module Structures

1. Design Performance

Since some subroutines are required to support certain subroutines, the reader is advised to follow the module hierarchy, Fig. 6, when going through the description of any of the program modules, as this will facilitate the understanding of how most of the subroutines work.
The sub-program DESIGN performs the design point calculations to obtain the engine constants for the engine in question. These parameters are $\eta_m$, $\eta_{ce}$, $\eta_j$, $W_{eb}$, $\Delta P_{ce}$, and $\Delta P_p$. The module is described in Fig. 8. It is worth mentioning that the reader should have a high degree of confidence in the data used for design point performance calculations.

The output file will contain a print out of all engine constants $W_{eb}$ will be in percentage of engine airflow, $W_1$, while $\eta_m$ and $\eta_{ce}$ will be in percentages. The values of thrust for six different values of nozzle efficiency, $\eta_j$, are also printed, and so is the actual measured thrust. The calculated thrust values are to be compared with the measured thrust, to choose a suitable value for nozzle efficiency. The design choking mass flow and $\gamma$ of the nozzle are also made available for generating the nozzle characteristic. Provision is made for choosing combustor and jet pipe pressure losses either as a fixed percentage of the pressure at inlet to the component in question, or they can be assumed to be proportional to the square of the non-dimensional mass flow at inlet to their respective components. The constants of proportionality for various values of combustor and jet pipe pressure losses are also printed out.

2. Off-Design Performance

The off-design performance of the engine is done when the subroutine OFFDSGN is invoked. The engine parameters that are not measured are estimated from the compatibility of mass and work equations. The module is described in Fig. 9.

Some engines may incorporate a blow-off valve that vents air overboard at low engine speeds in order to enable the engine to accelerate to full power in cases where the compressor running line intersects the surge line. When this surge bleed flow is not measured, it has to be deduced or estimated from a reliable source. The value $AF$ in step 2 of Fig. 9 represents the bleed port area factor ($A_1/A_2$) when the surge bleed flow is estimated from a graph giving surge bleed flow as a function of LP compressor pressure ratio. $A_1$ is the bleed port area of the engine in question, and $A_2$, the bleed port area of a similar engine for which the above mentioned graph is available. This factor should be set to zero if there is no such bleed port on the engine, and should be made equal to 1 if the graph for the test engine is available. It will be shown in Chapter 4 that this is the best method of estimating the surge bleed flow when it is not measured, and if the graph for the test engine is not available.

3. Inter-Compressor Temperature

If the pressure and not the temperature at LP compressor exit is measured, the LP compressor delivery temperature can be estimated from the overall compressor pressure and temperature ratios.
and the LP compressor delivery pressure by assuming that the polytropic efficiencies for both compressors are equal. The module, ICT, that computes this temperature is described in Fig. 10, and its supporting sub-program COMP is described in the following sub-section.

4. Determining Temperature from Entropy Function, $\Psi$

The subroutine ICT determines the inter-compressor temperature by calculating the entropy function $\Psi_2$, from which an interpolation for $T_2$ is performed. The author has developed a program that will calculate temperature from the entropy function, $\Psi$, to within 0.1 K using the data in Ref. 11. This was made possible by fitting a quadratic equation of $T$ as a function of $\Psi$ to the temperature range compressors are likely to fall within, and then using a 'hill-climbing' technique to iterate for $T$ from an assumed value. The module COMP, described in Fig. 11, performs this iteration. Rapid convergence is attained.

5. Turbine Temperatures

The module INTERT determines TIT, the inter-turbine temperature, ITT, and the exhaust gas temperature, EGT. This is made possible by computing mass flow and energy balances. This subroutine is supported by the subroutines HTT and TIT. A detailed description of the procedure is shown in Fig. 12.

6. Conversion of Enthalpy into Temperature

The module HTT converts enthalpy into temperature. The procedure, described in Fig. 13, was developed by the author and it determines temperature to within 0.1 K by using the data in Ref. 11. Convergence is rapid.

7. Turbine Inlet Temperature

The module TIT calculates the turbine inlet temperature from the fuel/air ratio to within 1 K by an iterative technique. The specific heat capacity at constant pressure, $C_p$, specific enthalpy and entropy functions, $h$ and $\Psi$ respectively, which will be used to compute turbine performance are also calculated. The module is described in Fig. 14.

8. Nozzle Conditions

The module NOZZLE determines whether or not the nozzle is choked and then invokes one of its supporting subroutines, CHOKED and UNCHOKED, to calculate the thrust developed by the engine. An iterative technique is used to determine the critical jet temperature from nozzle $\gamma$ and total temperature, $T_t$. The module is described in Fig. 15.
9. **Exhaust Flow with Nozzle Choked**

The subroutine CHOKED calculates the engine thrust when the nozzle is choked. Fig. 16 is a detailed description of the procedure.

10. **Exhaust Flow with Nozzle Unchoked**

Fig. 17 is a detailed description of the module UNCHOKED which calculates the jet thrust for an unchoked nozzle. The jet velocity is obtained by an iterative technique.

11. **Determination of Nozzle Efficiency**

The subroutine THRUST calculates engine thrust for various values of propelling nozzle efficiency. The measured thrust will be compared with calculated thrust values for a choked nozzle in order to determine the efficiency of the nozzle. The procedure is described in Fig. 18.

12. **Nozzle Characteristic**

The subroutine NOZZCHAR predicts the nozzle characteristic, given the design nozzle choking mass flow and \( \gamma \). The procedure is described in Fig. 19.

13. **Turbine Pressures**

The pressure at inlet to the HP turbine can be obtained from the HP compressor delivery pressure and the combustor pressure loss, if this is known. Likewise, the pressure at nozzle inlet can be found from the pressure at LP turbine exit and the jet pipe pressure loss, and vice versa. The combustor or jet pipe pressure losses can be chosen either as a fixed percentage of the pressure at inlet to the component in question or they may be assumed to be proportional to the square of the non-dimensional mass flow at inlet to their respective components. The inter-turbine pressure can be obtained by assuming that the polytropic efficiencies of both turbines are equal. The module TURB describes the procedure, Fig. 20. It is assumed that \( P_2 \) is measured. This can be easily modified if \( P_3 \) is measured instead of \( P_2 \).
Chapter 4

APPLICATION TO PRATT AND WHITNEY
J57 ENGINE SERIES

The developed software described in Chapter 3 is applicable to modelling any twin - spool non - afterburning turbojet. As is typical of all development models, experiments or tests have to be conducted on the model to find out how well the model describes the full scale or actual engine. Modifications are usually made to a model several times before the final form is adopted, the developed model was no exception. In this chapter, the adopted software will be used to model a Pratt and Whitney J57 engine. Efforts will be made to explain why certain aspects of the model were chosen over other choices.

4.1 Survey on the J57 Family of Engines

The Pratt and Whitney military designated J57 family of engines (commercial designation - JT3C) is one of the most successful forerunners of jet propulsion in North America. Basic design of this engine series began in 1947, the final design was adopted in 1949 and production started in 1953. About 21000 of these engines were produced up to 1985 when production ceased.

The J57 is an axial - flow twin - spool turbojet with a sixteen - stage compressor and a three - stage turbine. The second- and third - stage low pressure turbines drive a nine - stage low pressure compressor through a through - shaft while the first - stage high pressure turbine drives a seven - stage high pressure compressor through a hollow shaft. An inter-compressor bleed discharges air overboard through a bleed port during starting and low power operation. The combustor is of the annular type with six fuel nozzles in each of eight cans. The various versions, both military and commercial, differ only in minor details, and can be equipped with an afterburner or water injection system for thrust augmentation, the former being applicable to all versions for fighter aircraft. The compression ratio varies from about 12.5 to 14, the mass flow, from about 77 to

18
90 kg/s, and the thrust, from about 45 to 80 KN. The J57 powered aircraft such as the USAF Boeing B-52 G bomber, the North American F-100, and the Northrop SM-62 Snark long-range missile. The JT3C powers the Boeing 720 and 707-120 series, and the McDonnell Douglas DC-8 commercial aircraft, though most of these aircraft have been re-engined with the more fuel efficient JT3D turbofan engines. A cutaway view of the J57 is shown in Fig. 21 while the arrangement of the components is shown in Fig. 4.

From what has just been said, the reader may be wondering why an interest was taken in the J57 which is somewhat an obsolete engine. The National Research Council of Canada has identified the need for improved EHM procedures for military jet engines. The Department of National Defence, Government of Canada, provided a J57 engine to be devoted to research in a number of areas of interest to DND. This engine provided an opportunity to investigate EHM concepts and to provide much needed data on the effects of various common problems with the components of the engine.

4.2 Data Acquisition

The software developed in Chapter 3 requires certain data for its support, which implies that a test engine has to be instrumented adequately to obtain the necessary data. Test data were obtained from two J57 engines of the same version, and these were used to generate the turbine characteristics for the engines, by using the developed software. The engines were instrumented to record, at least, all the parameters in Table 3. The data for both engines can be found in Figs 22a - b, and a plot of these data can be found in Figs 50 - 61. For security reasons, most of the data have been normalized to a reference point.

4.3 Program - Aided Performance Evaluation

In order to generate the turbine characteristics of the two engines, the fixed engine parameters were first obtained from the design point calculations. The method of starting the program depends upon the system on which the program operates. The program, CYCLE, was run on the Honeywell CP-6 computer system at Carleton University, and since it was written in Fortran 77, the necessary files had to be set to their respective units. The procedure is as follows:

a) Fortran CYCLE.
b) Link

c) Set unit 5 to input (data) file
d) Set unit 108 to terminal
e) Set unit 105 to terminal
f) Set unit 0 to output file
g) Run

The program then prompts the following demands (a sample of the responses are shown)

Read test engine number (1-100)
Response  1

Read number of data sets
18

Read heating value of fuel
43195

Data set point = 1

Are you going to do design point calculations? Y/N

The response will be either 'Y' for yes or 'N' for no, and the program continues to run in either the design or off-design mode, accordingly.

4.3.1 Design Performance

As was mentioned in Chapter 3, the design point performance calculations are done to obtain those parameters that are assumed fixed for the engine in question, from the given design point data. In performing design point calculations, \( \eta_m \), \( \eta_{cc} \), and \( W_{eb} \) are the fixed engine parameters that are to be modified in order to satisfy the compatibility of mass and work equations. Compatibility of mass yields the combustor airflow. The fuel/air ratio, together with \( T_3 \) and \( \eta_{cc} \), determines the turbine inlet temperature to be used in the HP rotor energy balance. It is probable that a certain combination of these three parameters will cause the work required to drive the compressors and accessories, and to overcome friction, to differ from the work developed by the turbines. It can be
foreseen that finding values of the above mentioned parameters that satisfy the compatibility of mass and work equations can be a lengthy process.

To prevent the user from the boredom of going through such a lengthy process, the program is incorporated with a method that will detect if a set of $\eta_m$ and $\eta_{ec}$ will first of all satisfy the energy balance, before an attempt is made to find $W_{eb}$. The model for the turbine bleed flow extracts some air at the rear of the HP compressor to cool the HP turbine disc and stator vanes and then mixes with the exhaust gases. It is assumed that this airflow does not contribute to the airflow through the HP turbine to satisfy mass balance and so does not contribute to the HP turbine work. This may sound like a very severe assumption. A very detailed and more accurate analysis of the energy balance for the HP spool is not justified under these circumstances where only changes in performance are sought. In fact, it is quite difficult to quantify the effects of such an analysis on turbine performance.

The turbine cooling bleed flow is expressed as a percentage of inlet airflow. An investigation was carried out to find out what effect this airflow has on turbine performance when expressed as a percentage of the HP compressor airflow since this does not equal the inlet airflow when the bleed port is open. It was found that there is no noticeable change in the performance of the two turbines when $W_{eb}$ was expressed in terms of $W_2$. This is rather surprising as one would expect no change in the turbine characteristics in the region where the bleed port is closed since $W_1$ equals $W_2$, and a slight change, when the bleed port is open. The author suspects that the effect of an increase in HP turbine mass flow, $W_A$, due to extracting less turbine cooling bleed flow when this is expressed in terms of $W_2$, was more or less offset by a decrease in $\sqrt{T_A}$, thereby keeping the parameter $W_A\sqrt{T_A}/P_A$ almost constant.

When values of $\eta_m$, $\eta_{ec}$, and $W_{eb}$ are assumed, $W_{eb}$ determines the airflow through the combustor. The turbine inlet temperature can then be iterated for from the fuel/air ratio, $\eta_{ec}$, and $T_3$. Once the TIT is established, the inter-turbine temperature is then obtained from both HP and LP rotor work balances. Provision is made to use either $T_6$ or $T_7$ as the jet pipe or LP turbine exit temperature in the LP rotor energy balance. Ideally, these two temperatures should be the same since the process going on in the jet pipe should be adiabatic. But due to heat loss in the jet pipe, $T_6$ should be a bit higher than $T_7$. Also, a distinction is made between the two measurements to provide for flexibility of the computer program since engine instrumentation may differ from user to user. The following question is then asked.

Are you going to use $T_6$ or $T_7$ as jet pipe temperature?

Type '6' or '7' as appropriate.
The user responds accordingly. The equations of energy balance will give two values of $h_2$ from which $T_3$ can be obtained. It is intended to calculate $T_3$ to within 1 K accuracy, hence, if the absolute value of $dh_3$ (i.e., $h_{3 LP} - h_{3 HP}$) is greater than 1 KJ/Kg, the user is prompted for a new set of values of $\eta_m$, $\eta_{cc}$, and $W_{cb}$.

In order to save some time in finding a suitable set of values of the three parameters, $\eta_m$ and $\eta_{cc}$ are first assumed and a check is made to find out if this combination represents a real cycle. The program sets $W_{cb}$ to 0 % of $W_1$, and an iteration is carried out for TIT. This value of TIT then gives a value for $dh_3$ when used in the energy balance equations. $W_{cb}$ is then set to 1 % of $W_1$, and the procedure is repeated to obtain another value of $dh_3$. It was observed from hand calculations that a suitable combination of $\eta_m$ and $\eta_{cc}$ will give a decreasing absolute value of $dh_3$ as $W_{cb}$ is increased. This criterion was used in the program. If the absolute value of $dh_3$ when $W_{cb}$ is equal to 0 % of $W_1$ is greater than that of $dh_3$ when $W_{cb}$ is equal to 1 % of $W_1$ the user is told:

Combination of ETAM = (chosen value) and ETACC = (chosen value) cannot find $T_3$ to within accuracy set. So try a new combination.

Otherwise, the user is told:

Combination of ETAM = (chosen value) and ETACC = (chosen value) may calculate $T_3$ to within accuracy set. Now find out if these values do give reasonable bleed flows.

The instructions are straightforward and the user proceeds accordingly. In the former case, the user guesses a new set of values of $\eta_m$ and $\eta_{cc}$ and the procedure is repeated. In the latter case, the user goes on to find the actual turbine cooling bleed flow. Though the values of $\eta_m$ and $\eta_{cc}$, as found above, may represent a real cycle, it is possible that the turbine cooling bleed flow is too large and so unacceptable. If this is the case, a new set of values of $\eta_m$ and $\eta_{cc}$ is to be assumed and the procedure explained in the immediately preceding paragraph will have to be repeated. A limit of 6 % is set on $W_{cb}$ in the program. When this limit is exceeded, the user is told:

Cooling bleed flow = (value chosen) %. This is too much, so try another combination of ETAM and ETACC.

The process of finding a suitable value of $W_{cb}$ may be a long one. In fact, there is a small range of values of $W_{cb}$ that determines TIT to within 1 K. Iterating for TIT involves guessing a value for $T_4$ and then using this value together with $T_3$ and $\eta_{cc}$ to find the fuel/air ratio. This ratio is compared with the measured fuel/air ratio and if the two values are within 0.1 % of each other, the assumed value of $T_4$ is acceptable as the turbine inlet temperature. The inter-turbine
enthalpy, \( h_3 \), is then obtained from the LP and HP rotor work balances and if the magnitude of the difference is less than 1 KJ/Kg, the assumed value of \( W_{cb} \) is acceptable. Otherwise, a new value for \( W_{cb} \) is guessed, and the procedure repeated.

When a value for \( W_{cb} \) is guessed, the user is prompted to guess a value for TIT. If the assumed value does not calculate the fuel/air ratio, \( f \), to within 0.1% of the measured value, \( DF \) \((-\text{frac}{f_{mea}}{f_{cal}} - 1)\) is written on the terminal and the user is prompted to guess another value for TIT. The value of DF is either negative or positive, depending on which side of the acceptable range of TITs the assumed value of \( T_4 \) lies. A higher value of TIT gives a positive value of DF, while a lower TIT gives negative DF. It was observed that for a particular assumed value of \( W_{cb} \), the minimum temperature in the acceptable range of turbine inlet temperatures gives the largest value of \( dh_3 \), taking into consideration the minus or plus sign. If \( dh_3 \) is positive with a magnitude greater than the limit, 1 KJ/Kg in this case, then the temperature has to be increased in order to find out if the assumed value of \( W_{cb} \) is satisfactory. If it is, \( dh_3 \) goes below 1 KJ/Kg, and if not, DF goes positive. If \( dh_3 \) is negative, the minimum satisfactory value of TIT will indicate whether or not the assumed value of \( W_{cb} \) is satisfactory, as further increase in TIT will give a lower value for \( dh_3 \). This was used as a rule of thumb and was found to save a lot of time when the design point performance of the two engines were being sought. Table 5 verifies this.

When \( W_{cb} \) is 0.98% of \( W_1 \), a temperature of 1108.2 K gives a value of DF equal to -0.00113. The minimum temperature in the acceptable range of TITs is 1108.3 K and this gives a value of \( dh_3 \) equal to +2.01 KJ/Kg. The temperature was increased further until a positive value of DF was obtained, indicating that this value of \( W_{cb} \) is unsatisfactory. A similar trend is seen when the cooling bleed flow is 1.88% of \( W_1 \). The minimum TIT of 1112.5 K gives the maximum value of \( dh_3 \) equal to -1.05 KJ/Kg, and from what was said in the previous paragraph, this value of \( W_{cb} \) is unsatisfactory. But when \( W_{cb} \) is 0.99% of \( W_1 \), \( dh_3 \) goes positive at a TIT of 1108.4 K and on increasing the temperature further, a value of \( dh_3 \) equal to +0.97 KJ/Kg was obtained, indicating a satisfactory value of \( W_{cb} \). When \( W_{cb} \) is 1.87% of \( W_1 \), \( dh_3 \) is equal to -0.95 KJ/Kg at the onset of the range of satisfactory TITs, indicating that this value of cooling bleed flow is satisfactory. At first, it is difficult understanding this trend, but once it is understood the time spent on doing design point performance calculations can be cut by about half. It was found out that Engine 1 has a satisfactory value of \( W_{cb} \) in the range 0.99 - 1.87% of \( W_1 \) with \( \eta_m \) and \( \eta_{cc} \) equal to 99% and 98% respectively, when \( T_7 \) is used as LP turbine exit temperature. If \( T_6 \) is used as jet pipe temperature, the values are 4.32 - 5.04% of \( W_1 \) for \( W_{cb} \), 99% and 100% for \( \eta_m \) and \( \eta_{cc} \) respectively. For Engine 2, the values of \( W_{cb} \), \( \eta_m \), and \( \eta_{cc} \) are 0.1 - 0.97% of \( W_1 \), 98% and 98% respectively, when \( T_7 \) is used as jet pipe temperature. When \( T_6 \) is used as jet pipe temperature,
the values are 147 - 2.32 % \( W_1 \), 99 % and 100 % for \( W_{eb} \), \( \eta_m \), and \( \eta_{re} \) respectively.

When a satisfactory value of \( W_{eb} \) is found, the user is asked:

"Are you satisfied with the value of cooling bleed - (value chosen) % of \( W_1 \) is OK? Y/N"

If the user answers 'Y', the program proceeds to calculating the thrust of the engine for six different values of \( \eta_j \), starting with a value of 0.95, with increments of 0.01. Next, the constant \( K_{re} \) in the expression

\[
P_5 = P_5(1 - K_{re} Q_{re}^{\alpha})
\]

is calculated for combustor pressure loss of 2 - 7 % of \( P_5 \), in steps of 1 %. This is followed by calculating \( K_{jp} \) in the expression

\[
P_5 = P_5/(1 - K_{jp} Q_{re}^{\alpha})
\]

for jet pipe pressure loss ranging from 2.5 - 8 % of \( P_5 \) in steps of 0.5 %. These constants are provided in case the user may wish to use variable instead of constant pressure drop in either the combustor or jet pipe. The program then ends by saying:

"Design point calculations are over!"

The output contains a print out of all fixed engine parameters, Figs 23 - 26. Figs 23a and b are the design point data for Engine 1 when the minimum and maximum values in the range of values of \( W_{eb} \) that satisfies the equations of compatibility of mass and work are used, when \( T_j \) is used as the jet pipe temperature, while Figs 24a and b are for the case when \( T_0 \) is used as jet pipe temperature. Figs 25 - 26 are the corresponding data for Engine 2. It will be shown in the off-design calculations that the value of \( W_{eb} \) chosen slightly affects the turbine characteristics. In measuring the data for the two test engines, \( T_0 \) was measured more accurately than \( T_0 \), and so the design point data obtained when \( T_0 \) was used as jet pipe temperature will be discarded.

The values of \( W_{eb} \), \( \eta_m \), and \( \eta_{re} \) that are printed out are those found from the iteration process. To determine the nozzle efficiency, the values of thrust as calculated for the chosen values of nozzle efficiency, 95 - 100 %, are to be compared with the measured thrust. It is seen that the nozzle efficiency is just about 95 % for Engine 1, Figs 23 - 24, whereas it is about 98 % for Engine 2, Figs 25 - 26. The values for the nozzle's design corrected mass flow and ratio of specific heats, \( \gamma_N \), which will be used to generate the nozzle characteristic are also made available. The respective values are about 54.5 Kg/s and 1.35 for both engines. As far as the pressure drop in the combustor..."
is concerned, it is up to the user's discretion to choose a suitable value. It will be shown later on
that it does not matter if constant or variable pressure drop is used, but the value of the pressure
loss chosen affects the level of the turbine characteristics. The value of the pressure drop in the
jet pipe has to be estimated somehow. Since $P_6$ and $P_7$ were measured at the design point for
both engines, the pressure drop in the jet pipe at the design point was readily found. It was noted
that in the case of the jet pipe, variable pressure drop should be used instead of constant pressure
drop. A 7 per cent combustor pressure drop will be used for both engines. This value was decided
on with the help of the technical data for two other engines of entirely different designs, and one
of them is of the same vintage as the J57. The pressure drop in the jet pipe at the design point is
about 4.5% for both engines. Hence, the value of $K_{\text{dp}}$ corresponding to 4.5% pressure loss will
be used for both engines.

4.3.2 Off - Design Performance

Once the design point data for the engine is found, the fixed engine parameters affect the
performance of the engine when the engine is operating away from its design point. It is now
necessary to find the range of possible operating conditions for the respective engine components.
Since it is not possible to record enough data to determine the complete range of operating
conditions, only the equilibrium running line of the various components can be established. Hence,
the non-dimensional mass flow through the compressors, turbines, and nozzle can be obtained at
any pressure ratio across the component in question.

When the program is running in the off - design mode, the only iteration that is performed is
that for turbine inlet temperature. When I takes the value 1, the following command is issued:

Read percent ETAJ, ETAM, ETACC, WCB, AF

The values for these parameters are read in percentages with the exception of AF, which is read
as a fraction. The next question is

Is bleed port open? Y/N

If the answer is 'Y', the LP compressor pressure ratio is displayed and the user is prompted to

Read percent overboard bleed.

This is obtained from a graph giving surge bleed flow, in percentage of inlet airflow, as a function
of LP compressor pressure ratio. The user then iterates for TIT. But if the answer to the above
question was 'N', the program continues by asking the user to iterate for TIT. When TIT is found,
the user is asked

Do you wish to use constant or variable pressure drop across combustor? Type ’1’ for former or ’2’ for latter.

If the response is ’1’, the user is asked to

Choose percent pressure drop across combustor

If the response is ’2’, the user is asked to

Choose percent pressure drop across combustor and the equivalent K Ec

The program continues by asking

Do you want to get P a from P e or use measured value of P a? Type ’6’ or ’7’ as appropriate.

If the response is ’7’, the user is told to

Choose pressure drop in jet pipe and equivalent K j,p

and I is then set to 2. If the response was ’6’ I is set to 2. From hereon, the user iterates only for TIT for each data set point. After the last data set point has been evaluated, the user is told to.

Read GAMMAN and Q7D from design point calculation.

These two parameters are used to generate the nozzle characteristic. A sample run of the procedure is shown in appendix B.

The output data contains the data for generating the nozzle characteristic, and a print out of the rotor speeds, the temperatures and pressures at all stations, inlet airflow, fuel flow, surge bleed flow, calculated and measured values of thrust, the performance data for each component, and the engine constants, Figs 27a-d. The corresponding data for Engine 2 can be found in Figs 71a-d. All performance parameters are corrected to standard day.

Before leaving this subsection, it is worth mentioning why certain decisions were taken in choosing a particular method of obtaining certain parameters, such as TIT, over other possible choices.

There are two methods of obtaining the turbine inlet temperature. These are the fuel/air ratio and the compressor/turbine work balance. The fuel/air ratio is related to T a by the expression

\[ f = \frac{h_{at} - h_{a3}}{n_{ec} ECV_i} \]
$h_{a1}$ is a function of $T_3$, and $h_{a4}$ and $E CV_4$ are functions of the assumed $T_4$. By using a suitable combustor efficiency with these parameters, the fuel/air ratio can be found and if this value agrees with the measured fuel/air ratio to within the limit set, the turbine inlet temperature is then obtained.

Since the mass flow through the compressors and turbines are known, as are $T_1$, $T_3$, and $T_6$, the compressor work can be equated to the turbine work to find $T_4$. If the whole arrangement is considered as a single spool, the work balance gives

$$h_t = h_6 + \frac{W_1(h_3 - h_1)}{\eta_m W_t}$$

At low speeds when the bleed port is open, the compressor work can be split into the individual IP and HP compressor work. $T_4$ can then be obtained from $h_t$ and the fuel/air ratio by an inverse function, using the data in Ref. 11.

Fig. 28 is a comparison of the turbine inlet temperatures for Engine 1 on as obtained by both methods. $T_j$ was used as the jet pipe temperature. When the bleed port is closed, the temperatures agree to within 1 K, but when it is open, the temperatures differ ranging from 0 - 20 K. This can be attributed to incorrectly estimating the surge bleed flow as will be explained later. However, the turbine inlet temperature was obtained from the fuel/air ratio, as explained earlier, as this is a better method of obtaining this parameter as it involves usage of fewer measured parameters than the work balance method.

The test engines have a left bleed port that vents air overboard in order to prevent the IP compressor running line from intersecting the surge line at low engine speeds. This airflow was not measured and so had to be inferred from another source. Three methods were investigated to find out which method gives the best estimate of the surge bleed flow.

The first method involves using the measured thrust. An iteration was done by assuming a surge bleed equal to a certain percentage of the inlet airflow, and then calculating the engine thrust until a value was obtained to within 0.5% of the measured value. The method was found to give very high values of surge bleed flow. The second method involves adjusting the surge bleed flow until the turbine inlet temperature obtained from both the fuel/air ratio and compressor/turbine work balance agreed to within 1 K. This method gave negative values for surge bleed flow at quite low speeds, i.e., air was flowing into the engine through the bleed port. The third method involves estimating the overboard bleed from a graph supplied by the engine manufacturer which gives

1 Since the results for both engines are identical, reference will be made to Engine 1 only when explaining any sample results. Wherever there is a discrepancy in the results for both engines, the result for Engine 2 will be shown as well. The generalised results for Engine 2 will be included at the end.
this airflow as a function of LP compressor pressure ratio. This graph was not available for the bleed port size (3.25 in diameter) that was used, but was available for a J57 engine with a left and right bleed port of diameters 2.2 in and 6 in respectively, Fig. 29. The surge bleed flow was then obtained by scaling the values from Fig. 29 in proportion to the ratio of the port areas. This was made possible by assuming that the mass flow rate at the point of extraction is proportional to the bleed port area. The ratio of the two areas is 0.25883, this is the value of AF that was used for both engines. See step 2 of Fig. 9.

The reason for choosing the third method over the other two is that this is the only method that gives reasonable estimates of the surge bleed flow. Table 3 is a comparison of the surge bleed flows as obtained from the three methods. Fig. 30 shows plots of the HP compressor running line as obtained from the three methods. The first two methods cause the running line to move towards the surge line whereas the third method moves the running line slightly away from the surge line. In fact, there should be no discontinuity in the shape of the HP compressor running line [12]. Also, only the third method gives a nozzle characteristic close enough to that predicted from the design point performance data, Fig. 31.

4.3.3 Turbine Characteristics Data

As mentioned in Chapter 2, turbine performance is always presented as plots of non-dimensional mass flow at inlet to the turbine, and turbine isentropic efficiency against the pressure ratio across the turbine.

As noted in section 4.3.1, there is a range of values of $W_{eb}$ that satisfies the compatibility of mass and work equations. The minimum and maximum values in this range, i.e. 0.99 and 1.87 \% $W_1$, were used to find out how the chosen value of $W_{eb}$ will affect the turbine's performance. Fig. 32 compares the mass flow functions of the HP turbine, while Fig. 33 does the same for the LP turbine, for these two values of $W_{eb}$. The difference in the values of Q at any pressure ratio is negligible; only the second place after the decimal point is affected. Figs 34 - 35 compare the efficiencies for the HP and LP turbines respectively, for the two chosen values of $W_{eb}$. The difference in turbine efficiencies at any pressure ratio is about 0.2 \% on average, for each turbine. Hence, practically speaking, the turbines do not 'know' which value of bleed flow was used. So, it is recommended that only value in the acceptable range of values of $W_{eb}$ be used. In this case, the maximum value of $W_{eb}$ will be used for both engines, i.e. 1.87 and 0.97 \% $W_1$ for engines 1 and 2 respectively.

As far as the pressure drop in the combustor is concerned, the user has the choice of using...
constant or variable pressure drop as explained earlier. Fig 36 shows how the HP turbine mass flows obtained with constant and variable pressure drop in the combustor compare. Fig 37 is the corresponding curves for the LP turbine. The difference in the values of \( Q \) for each turbine is barely noticeable, so it does not matter whichever method is used. However, constant pressure drop will be used here.

The pressure drop in the jet pipe is assumed to be proportional to the square of the actual non-dimensional mass flow at station 7. Though the pressure at station 6 was measured, this was not used as the LP turbine exit pressure due to lack of confidence in this measurement. \( P_6 \) was therefore inferred from \( P_7, Q_{7a}, \) and \( K_{fp} \). Tables 7 and 8 are a comparison of the measured and calculated pressure drop in the jet pipe for both engines.

Finally, the predicted HP turbine characteristics for Engine 1 are shown in Figs 38a - b, and those for the LP turbine are shown in Figs 39a - b. The corresponding curves for Engine 2 can be found in Figs 40 and 41, and a comparison of the two engines can be found in Figs 42 and 43. The maps for the compressors and nozzle are shown in Figs 44 - 49 for both engines.
Chapter 5

APPLICATION TO ENGINE HEALTH MONITORING

When the complete engine data has been generated, a decision has to be taken as to what state the engine is in. Once this is determined, the necessary corrective actions are to be taken in the case where the engine is found to be in a state of poor health. But before this is attempted, the user has to be confident that the generated data represent a credible description of engine condition. In this chapter, an attempt will be made to address the subject of user confidence in the generated data. An attempt will also be made to predict engine health based on a diagnosis of the generated data. Suggestions are also made on ways of effecting performance reliability of a degraded engine or component.

5.1 General Discussion

The computer program developed in Chapter 3 requires some data for its support. The accuracy of the generated data is strongly dependent on the accuracy of the input data, which in turn depends greatly on the accuracy of the engine instrumentation. The idea of validating a calculation or a measurement suggests that a comparison has to be made with some known and trustworthy information, or that some logical conclusions can be drawn from the data themselves [4]. By satisfying mass flow and energy balance in the engine, gas path analysis as explained in Chapter 2, has the capability to relate each of the measurements to all other measurements through the physical laws governing the operation of the engine, and thus permits the calculation of additional parameters such as turbine inlet temperature. Therefore if the program is supplied with reliable data, it should provide credible results. Agrawal et al [4] have provided guidelines for validating performance measurements of gas turbines.

The developed software is intended to be used to estimate the performance of an aircraft
or aero-derivative industrial gas turbine on a test rig. This restriction has been placed on the program, as an operational gas turbine would not normally be instrumented to record the necessary measurements that are required to support the program. Establishments that are involved with gas turbine testing would be expected to have developed the capability to obtain a high level of confidence in engine instrumentation through experience and also by regular checks against known standards, and hence can obtain high-quality data. The serious element of error would be expected to be position error where a probe may be situated in a position that would give a reading inconsistent with the average radial or circumferential reading, and this will have an impact on the engine performance parameters especially when such parameters are computed rather than measured. Hence, when all the data, computed as well as measured, are compared with their baseline values, a decision concerning the current health of the engine can be made with confidence.

Moreover, hand calculations were done to verify whether or not the components do match. The method of matching the components of a twin-spool turbojet as explained in Ref. 3 was slightly modified to take into account variable fluid properties. These calculations were performed at four test points on Engine 1. Matching of the components was obtained accurately at the two test points in the high-power region where the overboard bleed port is closed, but there was a discrepancy in the values of Q₂ where the calculations were carried out at the two chosen test points in the low-power region. Gastrax Ltd., under contract to the government of Canada, has developed a performance analysis program for the J57 engine. Provision is made in this program for checking measurements by defining an error function as the root mean square error (RMSE) between each proposed measurement and the nearest valid thermodynamic cycle [5]. This program was run to check the measurements for Engine 1. An unacceptable value of the error function was obtained for some of the data sets at low power settings, whereas almost all the data sets at high power gave an acceptable value for the error function. This indicated that some of the measurements at low power settings may not have been accurate enough though this was not reflected in any of the plots of Figs. 50–60. The components not matching at low power settings may have been caused by the surge bleed flow not being obtained accurately. The need now arises to provide guidelines for predicting the performance of an engine.

5.2 Program Usage

As mentioned earlier, the decision taken on an engine’s health is predicated on a comparison of the engine data, calculated and measured, with baseline values, or on logical deductions from
engine data. These baseline values are usually supplied by the manufacturer when the engine is bought and are normally generalized for that particular engine design. But due to manufacturing tolerances and assembly variations, the baseline values for the various component variables will vary slightly from engine to engine. Since it is not possible to perform a detailed check on engine performance, especially at the component level, when the engine is in a production test bed, gas turbine operators should devote the first couple of runs of a new engine to gathering data in the useful power region which will be used to establish the baseline values for the engine in question. These baseline values are of prime importance when estimating the remaining life of a component or the entire engine. The computer program can be used to obtain those baseline values that cannot be measured, provided the engine is instrumented to record the supporting data.

At any point in time after the engine has been used, measurements of the performance variables can be recorded, and a comparison of the baseline values coupled with other established engine health monitoring techniques will give a rough indication of engine health. Once it is decided that an overhaul of the engine should take place, the program can then be put to use to determine the health of the turbines and the other gas path components. This level of analysis is most needed for future modular engines where a degraded component can be easily separated from the main engine for repair work.

The approach to all engine health monitoring techniques is to determine differential changes in state and not absolute levels. Therefore, when the present state and baseline values of a parameter are compared at the value of baseline abscissa parameter, the interpretation of the data within the allowable tolerance limits will produce one of four possible results.

1) The plant and the instruments are in an acceptable state of health.

2) An instrument has failed or degraded

3) The gas turbine has changed

4) The gas turbine has changed and an instrument has degraded

If the result is any other than the first, then the data has to be analysed further to find out if the engine operating point has changed.

5.3 Data Interpretation and Engine Performance Prediction

The art of predicting the performance of a gas turbine involves interpreting a large number
of data. Diagnosing engine faults is a very delicate subject and so should be handled with care lest a misleading judgement be given. This can only be done wisely by experts with a sound understanding of gas turbine performance, and such a discipline can only be acquired by past experience. Gas turbine operations and maintenance personnel do not usually have such skills that would permit them to deliver a good judgement on the state of an engine's health. Therefore, if gas path analysis is to become a useful maintenance technique to such people, then simple analytical tools are to be provided that will aid them in interpreting the data correctly. The task of interrelating the performance variables to give meaningful conclusions on engine condition is quite difficult and complex. This can be simplified by the use of a Performance Analysis Matrix such as Table 9, which gives a cause-effect relationship between various engine health states and key engine parameters.

Table 9 clearly shows that any change in the health state of an engine will produce an observable change in the measured fuel flow, HP compressor discharge pressure, and exhaust gas temperature and pressure. Also, a real change in any one of these measurements was found to reflect itself as a change in all other measurements [4]. Therefore, these four variables are to be treated as key engine variables, a change in any one will definitively lead to a change in the turbine inlet temperature, the most important single parameter that is a measure of overall engine health. It is therefore logical to conclude that it is not possible for an unhealthy engine to indicate an unacceptable deviation from baseline values in only one measurement.

If all the data, both measured and calculated, deviate from their respective baselines outside acceptable limits, then it is logical to assume that the engine operating point has changed. This change in operating point was brought about by a rematch of the operating point of one or more deteriorated components. A detailed analysis of the data at the component level will then yield the degraded component. This involves comparisons of the generated component maps with their as installed performance maps.

A degraded turbine or compressor will reflect itself as a deterioration in the mass flow parameter, Q, or component efficiency, η, or both, and will ultimately give rise to an increase in turbine inlet temperature in order to maintain thrust or gas generator speeds. A decrease in the swallowing capacity of any of the turbines suggests that the first stage nozzle area has decreased due to coking, whereas an increase in the swallowing capacity is due to vane erosion or corrosion resulting in an increase in stator area. Since it is not well known whether or not thermal bowing increases the flow passage area of a stage, it cannot be established whether this will increase or decrease the swallowing capacity of a turbine. Some gas turbine performance analysts do argue that bowing will reduce the cross sectional area of a blade or vane and will therefore increase the
flow passage area. Urban [10] states that bowing of first stage HP turbine nozzle will increase the flow passage area and will result in a loss in HP turbine efficiency. A loss in turbine efficiency can also occur as a result of mechanical imbalance caused by rotor blade failure, worn turbine seals, or foreign object damage such as a piece of combustor liner breaking loose.

By nature of its position in the gas path, the HP turbine is more susceptible to deterioration than its LP counterpart. A deterioration in the swallowing capacity of the compressors is indicative of compressor fouling whereas a loss in compressor efficiency is indicative of foreign object damage. These are more likely to happen to the LP compressor by virtue of its proximity to the engine intake. A change in the swallowing capacity of any of the components will cause a rematch of the affected components and will either lower or raise the appropriate compressor operating line.

Table 10 is a summary of the effect of turbine and compressor faults on TIT, thrust, fuel flow, and compressor pressure ratio for a single spool gas turbine. The pertinent diagnostic messages are also shown. This should hold true if the whole arrangement of a twin spool gas turbine is considered as a single spool.

5.4 Some Performance Reliability Measures

Once the engine has been proclaimed faulty, corrective actions are to be taken to effect performance reliability if the exact causes of the faults are known. Any gas turbine can be viewed as being comprised of accessory equipment, rotational mechanical equipment, and the thermodynamic gas path elements. The accessory equipment includes such items as fuel control and lubrication system, the rotational mechanical equipment includes the various main engine bearings, rotors, and gear trains, while the gas path elements include the compressors, turbines, combustor, and the gas containment path such as the intake and exhaust system. There may be problems in any one of these general areas, and therefore a complete integrated diagnostic system must have a proper balance of emphasis on all of them, with the measured data from the three areas serving in a mutually complementary fashion to lead to proper diagnoses [10]. Diagnosing the mechanical health of a gas turbine has been well investigated and the corrective measures to be taken to effect performance reliability of accessory and rotational mechanical equipment can be found in literature on gas turbine performance analysis and therefore, will not be addressed here.

Repairing a degraded compressor or turbine is just a matter of replacing damaged blading and/or cleaning the deteriorated component. Work on the turbine can only be done when the unit is shut down whereas a compressor wash can be carried out while the engine is in operation.
Methods of replacing blading are normally given in the engine operation and maintenance manual supplied by the manufacturer whereas instructions on compressor or turbine wash can be readily found in literature such as Ref. 13. Combustor distress will manifest itself as an unevenness in the circumferential variation of exhaust gas temperature. This is indicative of plugged fuel nozzles caused by dirt-contaminated fuel. This would require some cleaning and a thorough check on the fuel-filtering system. Propelling nozzle damage, though expected to be a rare problem, will affect the engine operating point by causing a rematch of the turbines and compressors brought about by a change in the swallowing capacity of these components. The necessary course of action, i.e., repair, is to be taken.

5.5 Analysis of the Turbine Health States of the J57 Test Engines

Since it was not possible to obtain baseline values of the performance variables and component maps of the two engines, no absolute conclusions can be made about the current health of the engines. What can be done is to compare the data for both engines and then give an assessment of the health states of the engines relative to one another since it is quite unlikely that if both engines have degraded, the deteriorations were of the same manner and to the same extent.

Figs 50-60 clearly tell us that the two engines have almost identical performance. Only the LP turbine exit temperatures, $T_b$, are in disagreement. It can be concluded from the measurement data that Engine 2 is of a higher thrust rating. Since the instrumentation on both engines was basically the same, it can also be concluded that repeatability of measurements was obtained indicating that one should have confidence in the particular engine instrumentation and hence, data. Figs 66-69 show how the computed variables, i.e., $T_2$, $T_1$, $T_3/P_3$, and ITT for both engines compare. Again, the comparisons are quite close indicating that the program computes such parameters consistent with the measured data.

As can be noted from Figs 56 and 57, there is a discrepancy in the values for $T_6$ and $T_7$ for both engines, with the curves for Engine 1 lying at a higher level. The calculated $T_6$ for Engine 1 is compared with the measured $T_6$ and $T_7$ in Fig. 62, while the corresponding curves for Engine 2 can be found in Fig. 64. In the case of Engine 1, the calculated values of $T_6$ agree very well with the measured values of $T_7$ when the bleed port is closed, but when the port is open, there is a discrepancy. At around idle speed, the calculated $T_6$ is greater than $T_7$ and then decreases to lesser values of $T_7$ as speed increases. The measured $T_6$ agrees very well with $T_7$ at low speeds, but gets higher at higher speeds. The pattern is quite different with Engine 2 however. The temperature
profiles of $T_6$ and $T_7$ do agree very well over a wide range of speeds, the discrepancies occurring at speeds from idle to about 55% $N_1$. Fig. 70 shows that the values for the computed $T_6$ for both engines are very close in agreement. One would suspect that Fig. 62 gives a better description of the distribution of $T_6$ and $T_7$. $T_7$ should be expected to be slightly lower than $T_6$ due to heat transfer in the jet pipe. At high speeds, the heat loss to the surroundings is greater than that at low speeds. Thus $T_6$ is almost equal to $T_7$ at low speeds. This is not so in the case of Engine 2. The measured $T_6$ is greater than $T_7$ only at speeds greater than about 87% $N_1$. When Engine 2 was being tested, it was noticed that there was a cold spot in both the radial and circumferential temperature distributions at station 7. It was therefore concluded that one of the burner cans was in distress, and since $T_7$ was obtained from an average of thirty-six thermocouple readings weighted in proportion to their annulus areas in comparison to obtaining $T_6$ from an average of five readings, the inconsistency in the comparisons of $T_6$ and $T_7$ for both engines can be attributed to a malfunction of one of the burner cans in Engine 2.

Figs 63 and 65 show how the calculated and measured values of thrust on Engines 1 and 2 compare. When the bleed port is closed, the computed and measured thrust values of both engines are the same. But at low speeds when the bleed port is open, the calculated values are a bit higher than the measured values. This is so for both engines, and can be attributed to the fact that the overboard bleed flow was not accurately obtained. More air should have been bled off through the bleed port so as to reduce the thrust. This being the case, the nozzle characteristic would be displaced further away from the predicted characteristic, see Figs 44 and 47. However, gas turbine users are not interested in operating their units at very low speeds as Fig. 61 may suggest, and so a serious error will not be committed if the overboard bleed flow is estimated as was done.

A comparison of the HP and LP turbine maps and efficiency contours for both engines are shown in Figs 42 and 43. Fig. 42a basically says that the HP turbine of both engines is choked throughout the speed range at a value of $Q$ about 14 Kg/s. The slight increase in the mass flow parameter when the bleed port is open is due to the fact that the surge bleed flow was not correctly obtained as was mentioned earlier. Fig. 42b clearly shows that the HP turbine efficiency is slightly greater for Engine 1. Also, the efficiency is almost constant as was explained in Chapter 2. Fig. 43a does not contradict Fig. 42a as far as the comparison of the LP turbine maps for both engines are concerned, only that the LP turbines are not choked throughout the speed range. The LP turbine efficiencies of both engines are about equal and constant when the bleed port is closed, Fig. 43b. The efficiencies are, however, lower when the bleed port is open in the case of Engine 2.

Since the difference in both LP and HP turbine efficiencies of both engines are only marginal, it can be concluded that the HP turbines in both engines are in a similar state of health, and so
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<thead>
<tr>
<th>$N_1$ (%)</th>
<th>Measured</th>
<th>Calculated</th>
</tr>
</thead>
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<td>4.51</td>
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Table 8 Comparison of Jet Pipe Pressure Drop in Engine 2
Chapter 6

CONCLUSIONS

1. In order to ensure safety and economical operation of a gas turbine, the health of gas turbines has to be monitored. Gas path analysis has the potential to compute cycle parameters that cannot usually be measured in service. As a result, this technique can yield information that cannot be obtained in any other way, and when combined with accessory diagnosis and vibration analysis, it can provide a gas turbine user with direct and timely knowledge of engine condition. By comparing values of engine performance parameters, calculated as well as measured, with their nominal expected values, a decision can be made on the current health of an engine, and by interrelating changes in engine variables to changes in component performance parameters, engine faults can be isolated to the various components. The nature of these faults can also be described.

2. Due to the lack of information on methods of obtaining turbine performance characteristics for purposes of engine health monitoring, there is a need for providing a means of generating turbine data. A computer program has been developed that will compute those cycle parameters that cannot be measured on an operational twin-spool non-afterburning turbojet engine. By a suitable combination of some of the engine variables, the HP and LP turbine characteristics are generated. The HP and LP compressor running lines and nozzle characteristic are also obtained.

3. To verify that the data generated by the computer program give a credible description of engine condition, the program was validated by using test data from two Pratt & Whitney J57 engines. Within the limits of the accuracy of the data, the generated characteristics of the compressors, turbines, and nozzle were found to conform to general performance characteristics of these components. Matching of components was also obtained indicating that the mathematical models of the various engine components do represent a valid thermodynamic cycle.

4. The execution of the developed program requires minimal computer memory. If this program is used by gas turbine operations and maintenance groups, it will prove itself to be a useful
maintenance tool
REFERENCES


BIBLIOGRAPHY


## GLOSSARY

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<tr>
<td>$N_1$</td>
<td>LP Rotor Speed</td>
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<tr>
<td>$N_2$</td>
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<tr>
<td>$W_f$</td>
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<td>$F$</td>
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Table 1 Primary Performance Measurements

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<td>Inlet Pressure*</td>
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<td>$T_1$</td>
<td>Inlet Temperature</td>
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<tr>
<td>$W_1$</td>
<td>Inlet Air Flow Rate</td>
</tr>
<tr>
<td>$P_2$</td>
<td>LP Compressor Delivery Pressure</td>
</tr>
<tr>
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<td>LP Compressor Delivery Temperature</td>
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<tr>
<td>$W_{sb}$</td>
<td>Compressor Surge Bleed</td>
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<td>HP Compressor Exit Temperature</td>
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<td>$P_6$</td>
<td>LP Turbine Exit Pressure</td>
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<tr>
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<td>Nozzle Entry Pressure</td>
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<tr>
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<td>Nozzle Entry Temperature</td>
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* All Pressures and Temperatures are Total.

Table 2 Gas Path Measurements
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<td>G/S</td>
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<td>$F_f$</td>
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Table 3 Data Input Hierarchy
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Table 4 Station Numbering Description
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contd...
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Table 5: Sample Results of TIT Iteration

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Table 6: Comparison of Surge Bleed Flow

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<th>Calculated</th>
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<td>94.7</td>
<td>4.73</td>
<td>4.48</td>
</tr>
<tr>
<td>93.1</td>
<td>4.59</td>
<td>4.51</td>
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<tr>
<td>90.6</td>
<td>4.76</td>
<td>4.45</td>
</tr>
<tr>
<td>89.2</td>
<td>4.79</td>
<td>4.37</td>
</tr>
<tr>
<td>88.7</td>
<td>4.57</td>
<td>4.27</td>
</tr>
<tr>
<td>84.8</td>
<td>4.62</td>
<td>4.25</td>
</tr>
<tr>
<td>80.9</td>
<td>4.56</td>
<td>4.05</td>
</tr>
<tr>
<td>79.9</td>
<td>4.19</td>
<td>3.96</td>
</tr>
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<td>76.0</td>
<td>3.83</td>
<td>3.77</td>
</tr>
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<td>67.6</td>
<td>3.42</td>
<td>3.21</td>
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<td>60.3</td>
<td>3.44</td>
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<td>53.9</td>
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</tr>
<tr>
<td>48.5</td>
<td>2.65</td>
<td>1.81</td>
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<td>2.20</td>
<td>1.51</td>
</tr>
<tr>
<td>39.8</td>
<td>1.63</td>
<td>1.27</td>
</tr>
<tr>
<td>36.4</td>
<td>1.47</td>
<td>1.11</td>
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<tr>
<td>33.2</td>
<td>1.12</td>
<td>0.94</td>
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</table>

Table 8 Comparison of Jet Pipe Pressure Drop in Engine 2
### Measured vs. Calc.

<table>
<thead>
<tr>
<th>Plant Health State</th>
<th>$P_1$</th>
<th>$T_1$</th>
<th>$P_2$</th>
<th>$T_2$</th>
<th>$M_f$</th>
<th>$W$</th>
<th>$T_4$</th>
<th>$h_1$</th>
<th>$h_2$</th>
<th>$SFC$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G.G. Comp Flow Reduced</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>G.G. Comp Effcy Reduced</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Comp. Flow and Effcy Reduced</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>G.G. Turbine Effcy Reduced</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Comp Flow, Effcy and G.G. Turbine Effcy Reduced</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>Comp. Flow and G.G. Turbine Efficiency Reduced</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>Comp Flow Improved</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Comp. Effcy Improved</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
</tbody>
</table>

*Gas generator performance analysis matrix (constant gas generator speed.)*

Table 9

---

### Table 10

**Engine Fault Matrix**

(at constant gas generator speed)

<table>
<thead>
<tr>
<th>Fault</th>
<th>TIT</th>
<th>T</th>
<th>P</th>
<th>m_f</th>
<th>CPR</th>
<th>Vibration</th>
<th>LEAP Indication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Generator Turbine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Rotor damage</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>Yes</td>
<td>$P_{1 \text{ low}}$</td>
</tr>
<tr>
<td>2. Nozzle erosion</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↓</td>
<td>↓</td>
<td>No</td>
<td>$W \sqrt{T/P}$ high</td>
</tr>
<tr>
<td>3. Nozzle coking</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>No</td>
<td>$W \sqrt{T/P}$ low</td>
</tr>
<tr>
<td>Compressor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. F.O.D.</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↓</td>
<td>↓</td>
<td>Yes</td>
<td>$\eta_c$ low, $W$ low</td>
</tr>
<tr>
<td>2. Dirty</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>No</td>
<td>$\eta_c$ low, $W$ normal or slightly reduced</td>
</tr>
</tbody>
</table>

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FIGURES
FIG. 1 Turbine characteristics

Fig. 2 Turbine Characteristics
FIGURE 3 Effect of Compressor and Turbine Efficiency on the Cycle Efficiency
Fig. 4 Engine Station Numbering
MAIN

ARRANGE INPUT DATA IN AN ARRAY

ASSIGN ELEMENTS OF ARRAY TO PERFORMANCE VARIABLES

TRANSFORM CORRECTED DATA INTO ACTUAL VALUES

DESIGN POINT PERFORMANCE

CALCULATION OF FIXED ENGINE PARAMETERS

OUTPUT

OFF-DESIGN PERFORMANCE

INPUT FIXED ENGINE PARAMETERS FROM DESIGN POINT CALCULATIONS

CALCULATION OF PERFORMANCE PARAMETERS

CALCULATION OF COMPONENT PERFORMANCE VARIABLES

STANDARDIZATION OF ALL ENGINE DATA

OUTPUT

Fig. 6 Operational Hierarchy
Fig. 6 Module Hierarchy
1) DECLARE NUMBER OF DATA POINTS
   READ N

2) ARRANGE DATA IN A TWO-DIMENSIONAL ARRAY
   READ ((A(I,J),J=1,19),I=1,N)

3) REPEAT 4) to 16) FOR I=1,2,...,N

4) ASSIGN ELEMENTS OF ARRAY TO PERFORMANCE VARIABLES

5) TRANSFORM CORRECTED DATA INTO ACTUAL VALUES

6) IF I ≠ 1 GOTO 8

7) IS DESIGN POINT PERFORMANCE REQUIRED? Y/N
   IF 'N' GOTO 8
   IF 'Y' CALL DESIGN
   GOTO 20

8) CALL OFFDSGN

9) DETERMINE PRESSURE RATIO ACROSS LPC, HPC, HPT, and LPT

   \[ PR_{LPC} = \frac{P_2}{P_1} \]
   \[ PR_{HPC} = \frac{P_3}{P_2} \]
   \[ PR_{HPT} = \frac{P_4}{P_3} \]
   \[ PR_{LPT} = \frac{P_5}{P_4} \]

10) DETERMINE CORRECTED MASS FLOWS THROUGH COMPRESSORS, TURBINES, AND NOZZLE

   \[ Q_J = W_J \sqrt{T_J/288}/(P_J/101325) \quad FOR \quad J = 1, 2, 4, 5, 7 \]

11) DO 12 to 15 FOR J = 5,6

12) CALCULATE HP and LP TURBINE EFFICIENCIES

   \[ \eta_J = 1/(1 - R_{J-1}/C_{P(J-1)}) \]
   \[ \epsilon_J = 1 - 1/\eta_{J-1} \]
13) DETERMINE HPT and LPT EXIT ISENTROPIc TEMPERATURES

\[ T_{JS} = T_{J_{-1}} / PR^{n-1} \]

\[ PR = \text{Pressure Ratio Across Turbine} \]

14) GET \( h_a \) and \( \theta_h \) from CCTAB for \( T_{JS} \)

15) \[ h_{JS} = h_a + f/(1 + f) \theta_h \]

16) \[ \eta_{HPT} = (h_4 - h_3)/(h_4 - h_{JS}) \]

\[ \eta_{LPT} = (h_5 - h_4)/(h_5 - h_{JS}) \]

17) CORRECT ALL ENGINE DATA TO STANDARD DAY

18) GENERATE AND PRINT NOZZLE CHARACTERISTIC

CALL NOZZLE

19) PRINT ENGINE DATA

20) END

Fig. 7 MODULE MAIN
1) Determine Inter - Compressor Temperature if not measured
   IF (T2 = 0) CALL ICT
   GOTO 3

2) Get h1, h2, and h3 from CCTAB

3) Guess η_m and η_cc and check whether these values will satisfy the equations of compatibility of work
   READ η_m, η_cc

4) DO 5 TO 6 FOR J = 1,2

5) Set turbine cooling bleed flow
   Wcb = (J - 1)/100 W1

6) Find the difference in the values of h3 calculated from each value of T3 obtained from energy balance for both LP and HP spools
   Δh_j ← CALL INTERT

7) IF
   |Δh2| > |Δh1|
   GOTO 3

8) Determine turbine cooling bleed flow
   GUESS Wcb

9) Find the difference in the values of h3 calculated from each value of T3 obtained from energy balance for both LP and HP spools
   Δh3 ← CALL INTERT

10) IF
    |Δh3| > 1
    GOTO 8

11) Is value of Wcb reasonable? Y/N
    IF 'Y' GOTO 13
    IF 'N' CONTINUE

12) Do you wish to calculate new values for η_m and η_cc? Y/N
    IF 'Y' GOTO 3
    IF 'N' GOTO 8

13) Calculate thrust for η_j = 0.95, 0.96, ..., 1
    CALL THRUST

14) Obtain constants for combustor and jet pipe pressure losses
    CALL TURB

15) RETURN

Fig. 8 MODULE DESIGN
1) If (I $\neq$ 1) GOTO 3

2) Input engine constants
   \[ \text{READ } \eta_j, \eta_m, \eta_{ce}, W_{cb}, \text{ and AF} \]

3) If (T_2 = 0) CALL ICT
   \[ \text{GOTO 6} \]

4) Get h_1, h_2, and h_3 from CCTAB

5) Find compressor polytropic efficiency
   \[ \eta_{coe} = \frac{\log_{10} P_3/P_1}{\psi_3 - \psi_1} \]

6) Is bleed port open? Y/N
   If 'Y' READ W_{cb}
   If 'N' W_{cb} = 0

7) Determine TIT, ITT, and EGT
   CALL INTERT

8) Determine condition of nozzle and calculate thrust
   CALL NOZZLE

9) Determine HP turbine inlet and exit pressures
   CALL TURB

9) RETURN

Fig. 9 MODULE OFFDSGN

\[ \text{CPARS} \]
\[ \frac{T_2, W_{ob}}{T_1, T_3} \]
\[ \text{FPARS} \]
\[ \eta_{cc}, \eta_{mr}, \eta_j, W_{cb} \]
\[ \text{DUMMY} \]
\[ \frac{I}{I} \]
\[ \text{TRVARS} \]
\[ \text{AF} \]

\[ \text{TRVARS} \]
\[ h_1, h_2, h_3 \]

\[ \text{ANS} \]
\[ \text{ANS2} \]
1) Get $\psi_1$ and $\psi_3$ from CCTAB

2) Calculate compressor polytropic efficiency

$$\eta_{oee} = \frac{\log_{10} P_3/P_1}{\psi_3 - \psi_1}$$

3)

$$\psi_2 = \psi_1 + \frac{1}{\eta_{oee}} \log_{10} P_2/P_1$$

4) Determine $T_2$ from $\psi_2$

CALL COMP

Fig. 10 MODULE ICT

1) Initialize $\psi$

$$\psi = \psi_{a2}$$

2) Guess a value for temperature

$$T_2 = 11\psi^2 - 844$$

3) Get $\psi_2$ from CCTAB

4) Check if $\psi_2$ has converged

$$\Delta \psi = \psi_{a2} - \psi_2$$

If

$$|\Delta \psi| < 0.0004$$

GOTO 6

5) Guess a new value for $\psi$

$$\psi = \psi + \Delta \psi$$

GOTO 2

6)

$$T_2 = T_2$$

$$h_2 = h_{a2}$$

7) RETURN

Fig. 11 MODULE COMP
1) Determine flow breakdown

\[ W_2 = W_1 (1 - W_{16}/100) \]
\[ W_5 = W_2 - W_{16} W_1 \]
\[ W_4 = W_3 + W_f \]
\[ W_f = W_4 + W_{16} W_1 \]
\[ W_6 = W_f \]
\[ f = W_f/W_3 \]

2) Determine turbine inlet temperature

\[ \text{CALL TIT} \]

3) If main program is in off - design mode GOTO 9

4) Establish which of \( T_6 \) and \( T_7 \) is being used for jet pipe temperature in design performance

\[ \text{READ ANS3} \]

5)

If 'ANS3' = 5
Jet Pipe Temperature = \( T_6 \)
If (\( T_7 = 0 \)) \( T_7 = T_6 \)
If 'ANS3' = 7
Jet Pipe Temperature = \( T_7 \)

6) Get \( h_{16}, \theta_{16}, \Psi_{16}, \phi_{16} \) from CCTAB and jet pipe temperature

7)

\[ h_{16} = h_{16} + f(1 + f) \theta_{16} \]
\[ \Psi_{16} = \Psi_{16} + f(1 + f) \phi_{16} \]

8) Find \( h_s \) values from energy balance for both LP and HP spools

\[ h_{SH} = h_4 - W_2(h_3 - h_2)/\eta_m W_4 \]
\[ h_{SL} = h_6 + W_1(h_2 - h_1)/\eta_m W_5 \]
\[ \Delta h = h_{SL} - h_{SH} \]

\[ \text{GOTO 13} \]

9) HP spool energy balance

\[ h_s = h_4 - W_2(h_3 - h_2)/\eta_m W_4 \]

10) Find \( T_6 \) from \( h_s \)

\[ \text{CALL HTT} \]

\[ T_6 = T \]

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11) LP spool energy balance

\[ h_8 = h_6 - W_1 (h_2 - h_1) / \eta_m W_6 \]

12) Find \( T_6 \) from \( h_8 \)

CALL HTT

\[ T_6 = T \]

\[ \psi_6 = \psi \]

13) RETURN

Fig. 12 MODULE INTERT
1) Initialize \( \Delta h \) and \( T \)

\[
\Delta h = 0 \\
T = h_0 
\]

2) Guess a value for temperature

\[ T = T - \Delta h \]

3) Get \( h_a \) and \( \theta_a \) from Cctab and \( T \)

4) \[
h = h_a + f/(1+f) \theta_a \]

5) Check if \( h \) has converged and exit from loop if necessary

\[ \Delta h = h - h_0 \]

If

\[ |\Delta h| > 0.01 \]

GOTO 2

6) \[
C_p = C_{pa} + f/(1+f) \theta_{cp} \\
\psi = \psi_a + f/(1+f) \theta_{\psi} \]

7) RETURN

**Fig. 13 MODUHE HTT**
1) Guess a value for TIT

READ $T_4$

2) Get $h_{a4}$ and ECV$_4$ from CCTAB

3) Compute fuel/air ratio

$$f_a = (h_{a4} - h_{a3})/\eta_{cc}ECV_4$$

4) Compare measured and calculated fuel/air ratios

$$df = f_a/f - 1$$

If

$$|df| > 0.1\%$$

GOTO 1

5) $h_4 = h_{a4} + f/(1 + f)\theta_h$

$C_{p4} = C_{p4} + f/(1 + f)\theta_{c4}$

$$\Psi_4 = \Psi_{a4} + f/(1 + f)\theta_{\Psi}$$

6) RETURN

Fig. 14 MODULE TIT
1) \[ R = 0.286 \]

2) First guess for \( \gamma_N \)

\[ \gamma_N = 4/3 \]

3) Find critical jet temperature

\[ T_{je} = \frac{2}{\gamma_N + 1} T_7 \]

4) \[ T_{av} = (T_7 + T_{je})/2 \]

5) \[ T_{e1} = T_{je} \]

6) Get \( C_{p ej} \) and \( \theta_{spj} \) from CCTAB and \( T_{av} \)

7) \[ C_{ji} = C_{p ej} + \frac{f}{(1 + f) \theta_{spj}} \]

8) Find new value for \( \gamma_N \)

\[ \gamma_N = 1/(1 - R/C_{pji}) \]

9) \[ T_{je} = \frac{2}{\gamma_N + 1} T_7 \]

10) Check if \( T_{je} \) has converged

\[ DT_e = T_{e1}/T_{je} - 1 \]

If

\[ |DT_e| > 0.5\% \]

GOTO 4

11) Find nozzle critical pressure ratio

\[ PR_e = \frac{1}{\left(1 - \frac{\gamma_n - 1}{\gamma_n \gamma + 1}\right)^{\frac{\gamma - 1}{\gamma + 1}}} \]

12) Check condition of nozzle and calculate engine thrust

If \( PR_e > PR_a \) GOTO 14

13) Find unchoked thrust

CALL UNCHOKED

GOTO 15

14) Find choked thrust

CALL CHOKED

15) RETURN

Fig. 15 MODULE NOZZLE
1) \[ R = 0.286 \]

2) \[ P_e = P_t / P_R \]

3) Calculate critical jet density and velocity, and nozzle area

4) \[ \rho_e = P_e / RT_e \]

5) \[ C_{je} = \sqrt{\gamma NRT_e} \times 1000 \]

6) \[ A_j = W_t / \rho_e C_{je} \]

7) Calculate engine thrust

\[ F_j = W_t C_{je} / 1000 + A_j (P_e - P_a) \]

8) RETURN

Fig. 16 MODULE CHOKED
1) \[ R = .285 \]

2) First guess of jet velocity
\[ T_j = T_1(1 - \eta_j(1 - 1/PR_e^{1.4})) \]
where \[ \epsilon_\gamma = 1 - 1/\gamma N \]

3) \[ T_1 = T_j \]

4) \[ T_{av} = (T_{j1} + T_1)/2 \]

5) Get \( C_{p, ej} \) and \( \theta_{C_{pj}} \) from CCTAB and \( T_{av} \)

6) \[ C_{pj} = C_{p, ej} + f/(1 + f) \theta_{C_{pj}} \]

7) \[ \gamma N = 1/(1 - R/C_{pj}) \]

8) \[ \epsilon_\gamma = 1 - 1/\gamma N \]

9) Calculate new value of jet velocity
\[ T_j = T_1(1 - \eta_j(1 - 1/PR_e^{1.4})) \]

10) Check if \( T_j \) has converged
\[ \Delta T_j = T_j/T_{j1} - 1 \]

If \[ |\Delta T_j| > 0.5\% \]

GOTO 3

11) \[ C_j = \sqrt{2}C_p(T_1 - T_j) 1000 \]

12) \[ F_j = W_j C_j/1000 \]

Fig. 17 MODULE UNCHOKED
1) Initialize nozzle efficiency
   \[ \eta_j = 0.95 \]

2) Do 3 to 5 for \( j = 1, 2, ..., 6 \)

3) Calculate thrust for chosen nozzle efficiency
   \[
   \text{CALL NOZZLE}
   \]

4) \( F_{jd}(J) = F_j \)

5) \[ \eta_j = \eta_j + 0.01 \]

6) Write \( F_{jd}(J) \) for \( j = 1, 2, ..., 6 \) in output file

7) Calculate nozzle choking mass flow
   \[
   Q_{7d} = \frac{W_7 \sqrt{T_7/288}}{P_{7}/101.325}
   \]

8) RETURN

Fig. 18 MODULE THRUST
1) READ $\gamma_N$ and $Q_{7d}$

2) Find nozzle critical pressure ratio

$$PR_c = \frac{1}{\left(1 - \frac{\gamma_N - 1}{\gamma_N + 1}\right)^{\frac{\gamma_N}{\gamma_N - 1}}}$$

3) Find nozzle constant

$$K_N = \frac{Q_{7d}}{\sqrt{1/PR_c^{\frac{1}{\gamma_N}} - 1/PR_c^{\frac{1}{\gamma_N}}}}$$

4) Initialize nozzle pressure ratio

$$PR_N = 0.98$$

5) Repeat 6 to 8 for $PR_N < PR_c$

6) Set step increase in $PR_N$

$$\text{IF } (PR_N < 1.08) \text{ THEN}$$
$$PR_N = PR_N + 0.02$$
$$\text{ELSE}$$
$$PR_N = PR_N + 0.05$$

7) Define maximum value of $PR_N$

$$\text{IF } PR_N > PR_c \text{ THEN}$$
$$\text{WRITE } PR_c \text{ and } Q_{7d}$$
$$\text{GOTO 9}$$

8)

$$Q_7 = K_N \sqrt{1/PR_N^{\frac{1}{\gamma_N}} - 1/PR_N^{\frac{1}{\gamma_N}}}$$

9) RETURN

Fig. 19 MODULE NOZZCHAR
1) Check mode of main program
   IF (I = 1) THEN
     IF program is in design mode  GOTO 2
     ELSE  GOTO 14
   END
   Q_{3a} = W_3 \sqrt{T_3}/P_3
   Q_{7a} = W_7 \sqrt{T_7}/P_7
   \Delta P_{jp} = 2\%
   5) Do 6 to 11 for J = 1, 2, ..., 5
   6) Choose combustor pressure loss
      \Delta P_{ae} = J + 1
   7) P_i = (1 - \Delta P_{ae}/100) P_5
   8) Determine combustor pressure loss constant
      K_{ae} = (1 - P_i/P_5)/Q_{7a}^2
   9) \Delta P_{jp} = \Delta P_{jp} + 0.5
   10) P_6 = P_i/(1 - \Delta P_{jp}/100)
   11) Determine jet pipe pressure loss constant
      K_{jp} = (1 - P_i/P_6)/Q_{7a}^2
   12) Write K_{ae} and K_{jp} for J = 1, 2, ..., 5 in output file
      GOTO 28
   13) Do you want to use constant or variable pressure drop in combustor? 1/2
      READ ANSS
      IF ('ANSS' = 1) THEN
        IF (I \neq 1)  GOTO 16
      END
      15) Choose percent pressure drop in combustor
          \\READ \Delta P_{ae}
          \\K_{ae} = 0
          16) P_i = P_5(1 - \Delta P_{ae}/100)
          17) IF ('ANSS' = 2) THEN
              IF (I \neq 1)  GOTO 19
          END
          18) Choose percent pressure drop in combustor and equivalent pressure loss constant
              \\READ \Delta P_{ae} and K_{ae}
              19) Q_{3a} = W_3 \sqrt{T_3}/P_3
                  P_4 = P_5(1 - K_{ae}Q_{3a}^2)
20) If \((I \neq 1)\) GOTO 22

21) Do you want to obtain \(P_6\) from \(P_7\) or use measured value of \(P_6^*\)? 6/7
   READ ANS4

22) If ('ANSA' = 6) THEN
    \(K_{jp} = 0\)
    \(P_6 = P_6\)

23) If ('ANSA' = 7) THEN
    If \((I \neq 1)\) GOTO 25

24) Choose percent pressure drop and equivalent pressure loss constant in jet pipe
   READ \(\Delta P_{pp}\) and \(K_{jp}\)

25) \[Q_{7a} = W_f \sqrt{T_f} / P_f\]
    \[P_6 = P_f / (1 - K_{jp} Q_{7a}^2)\]

26) Find turbine polytropic efficiency
    \[\eta_{opt} = \frac{\eta_1-\eta_2}{\ln P_6/P_6}\]

27) Find inter-turbine pressure
    \[P_b = \frac{P_6 - W_f}{10^{\eta_{opt}}}\]

28) RETURN

Fig. 20 MODULE TURB

72
Figure 21 Pratt & Whitney J57 turbojet engine.
<table>
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<tr>
<th>TR2</th>
<th>FA</th>
<th>U1</th>
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Fig. 22b J57 TEST DATA FOR ENGINE 2
TEST ENGINE NUMBER = 1

DESIGN POINT PERFORMANCE

JET PIPE TEMPERATURE USED = .77
WCB = .99 KN  ETAM = 99.00 %  ETACC = 98.00 %

ACTUAL MEASURED THRUST = 40.571 KN

<table>
<thead>
<tr>
<th>ETAJ</th>
<th>95%</th>
<th>96%</th>
<th>97%</th>
<th>98%</th>
<th>99%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40.698</td>
<td>40.875</td>
<td>41.047</td>
<td>41.213</td>
<td>41.378</td>
<td>41.533</td>
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Q7D = 54.4996 KG/S  GAMMA = 1.3461

DPcc = 2%  3%  4%  5%  6%  7%
KCC = .007768  .011852  .015537  .019421  .023305  .027189
[XG/S K**1/2 /KPA]**(-1)

DPJP = 2.5%  3%  3.5%  4%  4.5%  5%
KJP = .000300  .000360  .000420  .000480  .000540  .000600
[XG/S K**1/2 /KPA]**(-1)

Fig. 23a Fixed Engine Parameters for Engine 1
TEST ENGINE NUMBER = 1

DESIGN POINT PERFORMANCE

JET PIPE TEMPERATURE USED = T7
WCB = 1.87 \%  \quad ETAM = 99.00 \%  \quad ETACC = 99.00 \%

ACTUAL MEASURED THRUST = 40.671 KN

\begin{center}
\begin{tabular}{ccccccc}
ETAJ & 95\% & 96\% & 97\% & 98\% & 99\% & 100\% \\
40.660 & 40.875 & 41.047 & 41.214 & 41.376 & 41.533 & \\
\end{tabular}
\end{center}

\( C7D = 54.496 \text{ KG/s} \quad \text{GAMMA} = 1.3461 \)

DPcc = 2\%  \quad 3\%  \quad 4\%  \quad 5\%  \quad 6\%  \quad 7\%

\begin{center}
\begin{tabular}{cccccccc}
KCC & \text{0.007008} & \text{0.011883} & \text{0.015816} & \text{0.019771} & \text{0.023725} & \text{0.027679} & \\
(KG/s K=1/2 /KPA) \text{**(-1)} & \\
\end{tabular}
\end{center}

DPJP = 2.5\%  \quad 3\%  \quad 3.5\%  \quad 4\%  \quad 4.5\%  \quad 5\%

\begin{center}
\begin{tabular}{cccccccc}
KJP & \text{0.000300} & \text{0.000360} & \text{0.000420} & \text{0.000480} & \text{0.000540} & \text{0.000600} & \\
(KG/s K=1/2 /KPA) \text{**(-1)} & \\
\end{tabular}
\end{center}

Fig. 23b Fixed Engine Parameters for Engine 1
TEST ENGINE NUMBER = 1

DESIGN POINT PERFORMANCE

JET PIPE TEMPERATURE USED = T6
WCB = 4.22 N1 ETAN= 99.00 % ETACC = 100.00 %

ACTUAL MEASURED THRUST = 40.671 KN

ETAJ = 95% 96% 97% 98% 99% 100%
40.699 40.875 41.046 41.215 41.377 41.534

Q7D = 54.4926 KG/S GAMMA = 1.3458

DPcc = 2% 3% 4% 5% 6% 7%
KCC [.008301 .012452 .016602 .020753 .024903 .029054
[KG/S K**1/2 /KPA]**(-1)

DPJP = 2.5% 3% 3.5% 4% 4.5% 5%
KJP [.000300 .000380 .000420 .000480 .000540 .000600
[KG/S K**1/2 /KPA]**(-1)

Fig. 24a Fixed Engine Parameters for Engine 1

78
TEST ENGINE NUMBER = 1

DESIGN POINT PERFORMANCE

JET PIPE TEMPERATURE USED = 76

Ucb = 5 047 W1  EtaM = 99 00 %  EtaCc = 100 00 %

ACTUAL MEASURED THRUST = 40 671 KN

<table>
<thead>
<tr>
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<th>95%</th>
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<th>97%</th>
<th>98%</th>
<th>99%</th>
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<td>41 048</td>
<td>41 215</td>
<td>41 377</td>
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Q7D = 64 4996 KG/S  GAMMN = 1 3457

DPcc = 2% 3% 4% 5% 6% 7%

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<th>008445</th>
<th>012668</th>
<th>016890</th>
<th>021113</th>
<th>025335</th>
<th>029558</th>
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<td>[KG/S K<strong>1/2 /KPA]</strong>(-1)</td>
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DPjp = 2 5% 3% 3 5% 4% 4 5% 5%

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<td>[KG/S K<strong>1/2 /KPA]</strong>(-1)</td>
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Fig 24b Fixed Engine Parameters for Engine 1
TEST ENGINE NUMBER = 2

DESIGN POINT PERFORMANCE

JET PIPE TEMPERATURE USED = 77

VCB = 10 KNUETAM = 98.00% ETACC = 98.00%

ACTUAL MEASURED THRUST = 43 207 KN

<table>
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<th>98%</th>
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<tr>
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<td>42 699</td>
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<td>43 044</td>
<td>43 209</td>
<td>43 359</td>
<td>43 524</td>
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Q7D = 54 4358 KG/S GAMMA = 1 3452

DPcc = 2% 3% 4% 5% 6% 7%

KCC 007999 011863 015817 019772 023726 027680

[KG/S K**1/2 /KPA]**(-1)

DPJP = 2.5% 3% 3.5% 4% 4.5% 5%

KJP 000301 000361 000421 000481 000541 000602

[KG/S K**1/2 /KPA]**(-1)

Fig 25a Fixed Engine Parameters for Engine 2
TEST ENGINE NUMBER = 2

DESIGN POINT PERFORMANCE

JET PIPE TEMPERATURE USED = T7

\[ T \]

\[ W_{CB} = 97 \text{ KV1} \quad \text{ETAM} = 98.00\% \quad \text{ETACC} = 98.00\% \]

ACTUAL MEASURED THRUST = 43 207 KN

<table>
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<th>ETAJ</th>
<th>95%</th>
<th>96%</th>
<th>97%</th>
<th>98%</th>
<th>99%</th>
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<td>43 525</td>
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Q7D = 64 4358 KG/S \quad \text{GAMMN} = 1.3452

DPcc = 2% 3% 4% 5% 6% 7%

\[
\begin{array}{ccccccc}
\text{KGC} & 008048 & 012072 & 016096 & 020121 & 024145 & 028169 \\
[\text{KG/S K**1/2 /KPA]**(-1)]
\end{array}
\]

DPJP = 2.5% 3% 3.5% 4% 4.5% 5%

\[
\begin{array}{ccccccc}
\text{KJP} & 000301 & 000381 & 000421 & 000481 & 000541 & 000602 \\
[\text{KG/S K**1/2 /KPA]**(-1)]
\end{array}
\]

Fig. 25b Fixed Engine Parameters for Engine 2
TEST ENGINE NUMBER = 2

DESIGN POINT PERFORMANCE

JET PIPE TEMPERATURE USED = TC

UCB = 1 47
ETAM = 99 00 %
ETACC = 100 00 %

ACTUAL MEASURED THRUST = 43 207 KN

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Q7D = 64 4358 KG/S

GAMMA = 1 3451

DPcc = 2% 3% 4% 5% 6% 7%

KCC

[KG/S K**1/2 /KPA]**(-1)

DPJP = 2.5% 3% 3.5% 4% 4.5% 5%

KJP

[KG/S K**1/2 /KPA]**(-1)

Fig 26a Fixed Engine Parameters for Engine 2
TEST ENGINE NUMBER = 2

DESIGN POINT PERFORMANCE

JET PIPE TEMPERATURE USED = 76

WCB = 2 32 %

ETAM = 90 00 %

ETACC = 100 00 %

ACTUAL MEASURED THRUST = 43 207 KN

ETAJ = 95% 96% 97% 98% 99% 100%

42 700 42 875 43 046 43 210 43 370 43 525

Q7D = 54 4358 KG/S

GAMMN = 1 3450

DPcc = 2% 3% 4% 6% 6% 7%

KCC = 008272 012408 016544 020681 024817 028963

[KG/S K**1/2 /KPA]**(-1)

DPJP = 2 6% 3% 3 5% 4%...

KIP = 000301 000361 000421 000481 000541 000602

[KG/S K**1/2 /KPA]**(-1)

Fig 26b  Fixed Engine Parameters for Engine 2
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<th>PA</th>
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**PRESSURE DROP ACROSS COMBUSTOR = 7.0 %**

**NOZZLE EFFICIENCY = .950**

**COMBUSTOR EFFICIENCY = .980**

**PRESSURE DROP ACROSS JET PIPE = 4.50 %**

**MECHANICAL EFFICIENCY = .990**

**COOLING BLEED FLOW = .0187**

**KCC = .000600 (KG/S K**1/2 /KPA)**(-1)**

**KJP = .000540 (KG/S K**1/2 /KPA)**(-1)**

FIG. 27 Complete Engine Data for Engine 1
FIG. 28 COMPARISON OF T1T

N1 PERCENT

T4 (K)

◊ - FUEL/AIR RATIO  × - WORK BALANCE
PRATT & WHITNEY AIRCRAFT
J57 TURBOJET ENGINES
ESTIMATED AUTOMATIC INTERCOMPRESSOR BLEED FLOW
LEFT BLEED STD 6" DIA
RIGHT BLEED 2.2" DIA ADAPTER

FIGURE 29
FIG. 31 COMPARISON OF NOZZLE CHIC

\[ Q_7 \text{ (KG/S)} \]

\[ \frac{P_7}{P_A} \]

- PREDICTED
- THRUST
- WORK
- GRAPH
FIG. 32  EFFECT OF WCB ON HPT CHIC

P4/P5

- WCB/W1 = .0099  x - WCB/W1 = .0187
FIG. 33 EFFECT OF WCB ON LPT CHIC

\[
\begin{align*}
Q_5 \quad \text{(KG/S)} \\
24.2 & \quad 41.1 & \quad 49.6 & \quad 62.3 & \quad 78.6
\end{align*}
\]

- WCB/W1 = .0099
- WCB/W1 = .0187
FIG. 34 EFFECT OF WCB ON HPT EFFY

ETA ISEN.

P4/P5

v - WCB/W1 = 0.0099  x - WCB/W1 = 0.0187
FIG. 35  EFFECT OF WCB ON LPT EFFY

P5/P6

\[ \text{WCB/V1} = 0.0099 \quad \text{×} \quad \text{WCB/V1} = 0.0187 \]
FIG. 36 EFFECT OF VARIABLE AND CONSTANT COMBUSTOR PRESSURE LOSS ON HPT MAP

Q₄ (KG/S)

N₄ > 78.6

P₄/P₅

▼ VARIABLE × CONSTANT
FIG. 38A HPT MAP FOR ENGINE 1

Q4 (KG/S)

P4/P5
FIG. 38B HPT EFFY FOR ENGINE 1

ETA ISEN.

3.4.2 41.1 49.6 62.3 N> 78.6

P4/P5
FIG. 39A. LPT MAP FOR ENGINE 1

Q5 (KG/S)

P5/P6

N > 78.6
FIG. 39B LPT EFFY FØR ENGINE 1
FIG. 40A HPT MAP FOR ENGINE 2

Q4 (KG/S)

P4/P5

N₁ > 76
FIG. 40B HPT EFFY FOR ENGINE 2

ETR ISEN

P4/P5

N1 > 80

33.2  39.8  48.5  60.3
FIG. 41A LPT MAP FOR ENGINE 2

$Q_5$ (KG/S)

P5/P6
FIG. 41B LPT EFFY FOR ENGINE 2

ETA ISEN.

P5/P6
FIG. 42A COMPARISON OF HPT MAPS

Q4 (KG/S)

P4/P5

- ENGINE 1  - ENGINE 2
FIG. 42B COMPARISON OF HPT EFFY

ETR ISEN.

P4/P5

v - ENGINE 1  x - ENGINE 2
FIG. 43A COMPARISON OF LPT MAPS

$Q_5 \text{ (KG/S)}$

P5/P6

\[
\begin{align*}
\text{v - ENGINE 1} & \quad \text{x - ENGINE 2}
\end{align*}
\]
FIG. 43B COMPARISON OF LPT EFFY

P5/P6

v - ENGINE 1  x - ENGINE 2
FIG. 44 NOZZLE CHIC FOR ENGINE 1

Q7 (KG/S)

P7/PA

x - PREDICTED  v - MEASURED
FIG. 45 LPC RUNNING LINE FOR ENGINE 1
FIG. 46 HPC RUNNING LINE FOR ENGINE 1
FIG. 47 NOZZLE CHIC FOR ENGINE 2

Q7 (KG/S)

P7/PA

x - PREDICTED  v - MEASURED
FIG. 48  LPC RUNNING LINE FOR ENGINE 2
FIG. 49 HPC RUNNING LINE FOR ENGINE 2
FIG. 50 VARIATION OF N2 WITH N1

N2 PERCENT

N1 PERCENT

ENGINE 1 • ENGINE 2
FIG. 51 VARIATION OF P2/P1 WITH N1

N1 PERCENT

P2/P1

v - ENGINE 1  ■ - ENGINE 2
FIG. 52 VARIATION OF OPR WITH N1

N1 PERCENT

P3/P1

v - ENGINE 1  ■ - ENGINE 2
FIG. 53 VARIATION OF P6/P1 WITH N1

- ENGINE 1
- ENGINE 2
FIG. 54 VARIATION OF P7/P1 WITH N1

\[ \frac{P7}{P1} \]

\[ \text{N1 PERCENT} \]

\[ \text{▼ - ENGINE 1 ▼ - ENGINE 2} \]
FIG. 55 COMPRESSOR DELIVERY TEMP.

T3 (K)

N1 PERCENT

- ENGINE 1  - ENGINE 2
FIG. 56 EXHAUST GAS TEMPERATURE

T6 (K)

30  40  50  60  70  80  90  100

N1 PERCENT

- ENGINE 1  - ENGINE 2

50
FIG. 57 VARIATION OF T7 WITH N1

N0ZZLE ENTRY TEMP. (K)

N1 PERCENT

v - ENGINE 1  x - ENGINE 2
FIG. 59 VARIATION OF FUEL FLOW WITH N1

FUEL FLOW (G/S)

N1 PERCENT

- ENGINE 1  - ENGINE 2

30  40  50  60  70  80  90  100
FIG. 60 COMPARISON OF ENGINE THRUST

V - ENGINE 1  X - ENGINE 2
FIG. 62 JET PIPE TEMP. FOR ENGINE 1

JET PIPE TEMP. (K)

N1 PERCENT

- T6-MEA  - T6-CALC  ▲ T7
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(71a)
FIG. 64. JET PIPE TEMP. FOR ENG. 2

N1 PERCENT

JET PIPE TEMP. (K)

• T6-MEA   ○ T6-CALC   ▲ T7
FIG. 65 COMPARISON OF THRUST OF ENG. 2

Percent Thrust

N1 Percent

- Calculated  x - Measured
FIG. 66 COMPARISON OF T2

\[ T2 \] (K)

\[ N1\ \text{PERCENT} \]

\( \text{v - ENGINE 1} \quad \text{x - ENGINE 2} \)
FIG. 67 COMPARISON OF TIT

- ENGINE 1
- ENGINE 2
FIG. 68 COMPARISON OF P5/P1

\[ \text{P5/P1} \]

\[ \text{N1 PERCENT} \]

\( \text{v - ENGINE 1 } \times \text{ ENGINE 2} \)
FIG. 69 COMPARISON OF ITT

![Graph showing comparison of ITT for Engine 1 and Engine 2.](image-url)

- Engine 1
- Engine 2

N1 Percent

T5
FIG. 70 COMPUTED EXHAUST GAS TEMP.

N1 PERCENT

T6 (K)

- ENGINE 1  x - ENGINE 2
TEST ENGINE NUMBER = 2

****NOZZLE CHARACTERISTICS****

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Pressure Drop Across Combustor = 7.0 %

Nozzle Efficiency = .980

Combustor Efficiency = .980

Pressure Drop Across Jet Pipe = 4.50 %

Mechanical Efficiency = .980

Cooling Bleed Flow = .009/KW

KCC = .000000 (KG/S K**1/2 /KPA)**(-1)

KJP = .000541 (KG/S K**1/2 /KPA)**(-1)

Fig. 71 Complete Engine Data for Engine 2
APPENDICES
Variables in COMMON Block POLY

COMMON/POLY/ ETAPT (18)

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Variables in COMMON Block EFF

COMMON/EFF/ ETAPC (18)

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The program was written in FORTRAN 77 language and as a result, extensive use was made of Equivalence statements which allowed variables to have names corresponding to engineering symbols. In order to minimize computer memory, the data were made to reside in specified areas; the use of Equivalence statements provided easy access to the data in their bases and also easy transfer of the data between functional modules. The data bases are defined in labelled COMMON program segments which were chosen to describe the origin of the data. The labelled COMMON areas are defined as follows;

CONST contains the assumed fixed engine parameters (FPARS) or engine constants.

OUTPUT contains all calculated parameters (CPARS) that are required to complement the measured data in forming a complete data set that fully describes the engine.

TEMP contains the temporary or transient variables (TRVARS) that are calculated in the process of finding key engine parameters.

DATA contains all measured parameters (MPARS).

POLY contains the turbine polytropic efficiencies (ETAPT) evaluated at the various data set points.

EFF contains the compressor polytropic efficiencies (ETAPC) evaluated at the various data set points.

ALPHA contains all the alphanumeric inputs, i.e. 'Y' and 'N'.

ITGR contains the value of the counter I in the DO loop.
Variables in COMMON Block CONST

COMMON/CONST/ FPARS (8)

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### Variables in COMMON Block OUTPUT

**COMMON/OUTPUT/ CPARS (14)**

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Variables in COMMON Block TEMP

COMMON/TEMP/ TRVARS.(25)

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<td>( h_0 )</td>
<td>Enthalpy from which Temperature is Sought</td>
<td>22</td>
</tr>
<tr>
<td>( C_{p5} )</td>
<td>Sp. Ht Capacity at Const. Pressure of Gas at Sta. 5</td>
<td>23</td>
</tr>
<tr>
<td>( C_p )</td>
<td>Sp. Ht Capacity at Const. Pressure of Gas at Temp. T</td>
<td>24</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Entropy Function of Gas at Temp. T</td>
<td>25</td>
</tr>
</tbody>
</table>
Variables in COMMON Block DATA

COMMON/DATA/ MPARS (20)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Position in Data Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$</td>
<td>Low Pressure Compressor Inlet Temperature</td>
<td>1</td>
</tr>
<tr>
<td>$P_1$</td>
<td>Low Pressure Compressor Inlet Pressure</td>
<td>2</td>
</tr>
<tr>
<td>$W_1$</td>
<td>Inlet Airflow</td>
<td>3</td>
</tr>
<tr>
<td>$PR_{21}$</td>
<td>Overall Pressure Ratio</td>
<td>4</td>
</tr>
<tr>
<td>$PR_{21}$</td>
<td>Low Pressure Compressor Ratio</td>
<td>5</td>
</tr>
<tr>
<td>$W_f$</td>
<td>Fuel Flow</td>
<td>6</td>
</tr>
<tr>
<td>$N_2$</td>
<td>HP Rotor Speed</td>
<td>7</td>
</tr>
<tr>
<td>$PR_{11}$</td>
<td>Ratio of Nozzle Inlet Pressure to LPC Inlet Pressure</td>
<td>8</td>
</tr>
<tr>
<td>$T_3$</td>
<td>High Pressure Compressor Discharge Temperature</td>
<td>9</td>
</tr>
<tr>
<td>$P_3$</td>
<td>High Pressure Compressor Discharge Pressure</td>
<td>10</td>
</tr>
<tr>
<td>$P_2$</td>
<td>Low Pressure,Compressor Discharge Pressure</td>
<td>11</td>
</tr>
<tr>
<td>$T_7$</td>
<td>Nozzle Inlet Temperature</td>
<td>12</td>
</tr>
<tr>
<td>$P_7$</td>
<td>Nozzle Inlet Pressure</td>
<td>13</td>
</tr>
<tr>
<td>$F_{JM}$</td>
<td>Measured Thrust</td>
<td>14</td>
</tr>
<tr>
<td>$\delta_1$</td>
<td>Corrected Inlet Pressure</td>
<td>15</td>
</tr>
<tr>
<td>$\sqrt{\delta_1}$</td>
<td>Corrected LPC Inlet Temperature</td>
<td>16</td>
</tr>
<tr>
<td>$N_1$</td>
<td>LP Rotor Speed</td>
<td>17</td>
</tr>
<tr>
<td>$T_o$</td>
<td>Low Pressure Turbine Exit Temperature</td>
<td>18</td>
</tr>
<tr>
<td>$P_e$</td>
<td>Free Stream Static Pressure</td>
<td>19</td>
</tr>
<tr>
<td>$PR_{IA}$</td>
<td>Ratio of Nozzle Inlet Pressure to Ambient Static Pressure</td>
<td>20</td>
</tr>
</tbody>
</table>
Variables in COMMON Block POLY

COMMON/POLY/ ETAPT (18)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Position in Data Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Turbine Polytropic Efficiency at Data Set Point I</td>
<td>1 - 18</td>
</tr>
</tbody>
</table>

Variables in COMMON Block EFF

COMMON/EFF/ ETAPC (18)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Position in Data Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Compressor Polytropic Efficiency at Data Set Point I</td>
<td>1 - 18</td>
</tr>
</tbody>
</table>
DF = 00288

GUESS TIT
?882

UNCHOKED THRUST = 20.183 KN

DATA SET POINT = 18

T2 = 307.4 K

IS BLEED PORT OPEN? Y/N
?Y

LP COMPRESSOR PRESSURE RATIO = 1.1573

READ PER CENT OVERBOARD BLEED
?5 38

DF = 00000

GUESS TIT
?660

DF = -00588

GUESS TIT
?651

DF = -.00204

GUESS TIT
?652

DF = .00181

GUESS TIT
?651.5

UNCHOKED THRUST = 2.703 KN

READ IN GAMMA, Q7D, FROM DSGM PT CALC
?1.3461 54.4996

*STOP*
APPENDIX B

PROGRAM SAMPLE RUNS
DESIGN POINT CALCULATIONS
!XEQ J02  COMP

$ECBO
$ORES MEM=84
$LINK *G OVER *GU RUN
* SHARED COMMON SYS (Shared Library) associated
* No linking errors
* Total program size = 13K
$SET 6 UETD1,FUN=IN
$SET 126 ME
$SET 106 ME
$SET 6 CYCLE1 OUT,CTG=YES,EXIST=NEWFILE,FUN=CREATE
$GU RUN

READ TEST ENGINE NUMBER (1-100)
"1"

READ NUMBER OF DATA SETS
"18"

READ IN HEATING VALUE OF FUEL
"43105"

DATA SET POINT = 1

ARE YOU GOING TO DO DESIGN POINT CALCULATIONS? Y/N
"Y"

T2 = 405.6 K

THE EFFICIENCIES YOU PREVIOUSLY CHOSE WERE ETAM = 00% ETACC = 00%

GUESS PER CENT ETAM, ETACC
"GG 100"

CHECKING IF CHOSEN VALUES OF ETAM AND ETACC ARE REASONABLE FOR CYCLE

COOLING BLEED FLOW IS NOW .0001

DF = .0000

GUESS TIT
"11110"

DF = -.00750

GUESS TIT
"11114"

DF = .00123

GUESS TIT
"11113"

ARE YOU GOING TO USE T6 OR T7 AS JET PIPE TEMP?

TYPE '6' OR '7' AS APPROPRIATE
"7"

DR6 = -5 82 KJ/KG

COOLING BLEED FLOW IS NOW .0015
DF = 00000
GUESS TIT
?1116
DF = -00446
GUESS TIT
?1118
DB5 = -0.47 KJ/KG

COMBINATION OF ETAM = 999 AND ETACC = 1000 CANNOT FIND T5 WITHIN ACCURACY SET SO TRY A NEW COMBINATION

GUESS PERCENT ETAM, ETACC
?99 99

CHECKING IF CHOSEN VALUES OF ETAM AND ETACC ARE REASONABLE FOR CYCLE

COOLING BLEED FLOW IS NOW 00W1

DF = 00000
GUESS TIT
?1110
DF = .01275
GUESS TIT
?1106
DF = .00164
GUESS TIT
?1104
DB5 = 5.06 KJ/KG

COOLING BLEED FLOW IS NOW .01W1

DF = .00000
GUESS TIT
?1110
DF = .00263
GUESS TIT
?1109
DB5 = 1.22 KJ/KG

COMBINATION OF ETAM = 99900% AND ETACC = 9800% MAY CALCULATE T5 WITHIN ACCURACY SET!
NOW FIND IF THESE VALUES GIVE REASONABLE BLEED FLOWS

PREVIOUS BLEED FLOW = .000%

GUESS PERCENT COOLING BLEED FLOW
?2
DF = 00000
GUESS TIT 71112
DF = -00314
GUESS TIT 71113

\[ DH5 = -1.30 \text{ KJ/kg} \]

PREVIOUS BLEED FLOW = 2.000%

GUESS PERCENT COOLING BLEED FLOW
71.5

DF = 00000
GUESS TIT 71114
DF = 00634
GUESS TIT 71112
DF = 00196
GUESS TIT 71111

\[ DH5 = -0.09 \text{ KJ/kg} \]

ARE YOU SATISFIED VALUE OF COOLING BLEED = 1.60% OF W1 IS OK? Y/N

DO YOU WANT TO CHANGE ETAM AND ETACC? Y/N

PREVIOUS BLEED FLOW = 1.500%

GUESS PERCENT COOLING BLEED FLOW
71.87

DF = 00000
GUESS TIT 71112
DF = -00181
GUESS TIT 71113

\[ DH5 = -1.67 \text{ KJ/kg} \]

PREVIOUS BLEED FLOW = 1.670%

GUESS PERCENT COOLING BLEED FLOW
71.87

DF = 00000
GUESS TIT
71112 5

DH5 = -1.07 KJ/KG

PREVIOUS BLEED FLOW = 1.870 %

GUESS PERCENT COOLING BLEED FLOW
71 87

DF = .0000

GUESS TIT
71112 4

DH6 = 95 KJ/KG

ARE YOU SATISFIED VALUE OF COOLING BLEED = 1.87 % OF W1 IS OK ? Y/N

Y

CHOKED THRUST = 40.698 KN

CHOKED THRUST = 40.875 KN

CHOKED THRUST = 41.047 KN

CHOKED THRUST = 41.214 KN

CHOKED THRUST = 41.378 KN

CHOKED THRUST = 41.533 KN

DESIGN POINT CALCULATIONS ARE OVER !!!

*STOP*
!XEQ JOE CUMP
$ECHO
$ORES WFM=64
$LINK *G OVER *OU RUN
  * SHARED COMMON :SYS (Shared Library) associated
  * No linking errors
  * Total program size = 13K
$SET 5 UETD1,FUM=IN
$SET 106 ME
$SET 105 ME
$SET 6 CYCLE1 OUT,CTG=YES,EXIST=NEWFILE,FUN=CREATE
$*OU RUN
READ TEST ENGINE NUMBER (1-100)
?1
READ NUMBER OF DATA SETS
?18
READ IN HEATING VALUE OF FUEL
*43195
DATA SET POINT = 1
ARE YOU GOING TO DO DESIGN POINT CALCULATIONS? Y/N
?N
READ PERCENT ETAJ, ETAM, ETACC, WCB, AF
?95 99 08 1.87 25843
T2 = 405.8 K
IS BLEED PORT OPEN? Y/N
?N
DF = OOOOO
GUESS TIT
?1112
DF = -.00181
GUESS TIT
?1113
CHOOED THRUST = 40.596 KN
DO YOU WISH TO USE CONSTANT OR VARIABLE PRESSURE DROP ACROSS COMBUSTOR?
TYPE '1' FOR FORMER OR '2' FOR LATTER
?1
CHOOSE PERCENT PRESSURE DROP ACROSS COMBUSTOR
?7
DO YOU WANT TO GET P6 FROM P7 OR USE MEASURED VALUE OF P6?
TYPE 6 OR 7 AS APPROPRIATE
?7
/ CHOOSE PRESSURE DROP IN JET PIPE AND EQUIVALENT KJP
DATA SET POINT = 9
T2 = 383.1 K
IS BLEED PORT OPEN? Y/N
N
DF = 00000
GUESS TIT
?040
DF = 01033
GUESS TIT
?047
DF = 00926
GUESS TIT
?045
DF = .00365
GUESS TIT
?044
UNCHOKED THRUST = 23.174 KN
DATA SET POINT = 10
T2 = 388.0 K
IS BLEED PORT OPEN? Y/N
Y
LP COMPRESSOR PRESSURE RATIO = 2.0702
READ PER CENT OVERBOARD BLEED
?8.18
DF = .00000
GUESS TIT
?890
DF = .02445
GUESS TIT
?870
DF = .03704
GUESS TIT
?880
DF = .00635
GUESS TIT
?883
DF = 00288
GUESS TIT
"882
UNCHOKED THRUST = 20 183 KN
DATA SET POINT = 18
T2 = 307 4 K
IS BLEED PORT OPEN? Y/N
"Y
LP COMPRESSOR PRESSURE RATIO = 1 1573
READ PER CENT OVERBOARD BLEED
"S 38
DF = 00000
GUESS TIT
"650
DF = -00588
GUESS TIT
"651
DF = -00204
GUESS TIT
"652
DF = 00181
GUESS TIT
"651.6
UNCHOKED THRUST = 2.703 KW
READ IN GAMMA, Q7D, FROM DSGM PT CALC
"1.3461 54.4996
*STOP*
APPENDIX C

PROGRAM LISTINGS
PROGRAM MAIN

THIS PROGRAM IS CALLED CYCLE AND IS THE MAIN PROGRAM TO
TO ANALYZE THE PERFORMANCE OF A TWIN-SPOOLED NON-AFTERBURNING
TURBOJET ENGINE. THE COMPONENT CHARACTERISTICS ARE ALSO
GENERATED. IT IS SUPPORTED BY FOURTEEN SUBROUTINES

DEFINE COMMON AREAS IN DATA BASES

COMMON/ALPHA/ ANS
COMMON/ITGR/ DUMMY
COMMON/CONST/ FPARS
COMMON/OUTPUT/ CPAES
COMMON/TEMP/ TVARAS
COMMON/DATA/ MPARS
COMMON/POLY/ ETAFT
COMMON/EFF/ ETAFC
COMMON/M1C,M2C,PRLPC,PRIHC,PBHT,PRLPT,Q1,Q2,Q4,Q5, ETAHPC
1, ETAHTP,P1C,T1C,T2C,PB31C,T3C,PR41,T4C,PS11,T5C,PS61
1, PB71C,T7C,W1A,WFF,WOBG,FJC,FJMEA,DELTAC1C,RTH1C

INTEGER DUMMY
CHARACTER ANS:*1
CHARACTER ANS(2)

THE MATRICES USED IN THIS PROGRAM ARE 18 ROWS LONG
TO OCCUPY 18 DATA SET POINTS. THIS SHOULD BE MODIFIED
TO SUIT THE USER.

REAL FPARS(8), TVARAS(14), CPAES(14), A(18, 19), MPARS(20), ETAFT(18)
REAL M1C(18), M2C(18), PRLPC(18), PRIHC(18), PBHT(18), PRLPT(18), KCC
REAL Q1(18), Q2(18), Q4(18), Q5(18), ETAHPC(18), ETAHTP(18), P1C(18)
REAL T1C(18), T2C(18), PB31C(18), T3C(18), PR41(18), T4C(18), T5C(18)
REAL PS61(18), PB71C(18), WOBG(18), T7C(18), W1A(18), WFF(18), Q7(18)
REAL WOBG(18), FJC(18), FJMEA(18), DELTAC1C(18), RTH1C(18), W1, W2
REAL T8C(18), JIP, PAC(18), ETAFC(18)

EQUIVALENCE (ANS1, ANS(1))
EQUIVALENCE (PR21, MPARS(5))
EQUIVALENCE (T1, MPARS(1))
EQUIVALENCE (P1, MPARS(2))
EQUIVALENCE (PA, MPARS(19))
EQUIVALENCE (PB31, MPARS(4))
EQUIVALENCE (W1, MPARS(3))
EQUIVALENCE (PB71, MPARS(8))
EQUIVALENCE (PB7A, MPARS(20))
EQUIVALENCE (DELTAC1, MPARS(15))
EQUIVALENCE (RTH1, MPARS(16))
EQUIVALENCE (T3, MPARS(9))
EQUIVALENCE (P3, MPARS(10))
EQUIVALENCE (P2, MPARS(11))
EQUIVALENCE (T7, MPARS(12))
EQUIVALENCE (T6, MPARS(18))
EQUIVALENCE (P7, MPARS(13))
EQUIVALENCE (FJ4, MPARS(14))
EQUIVALENCE (WF, MPARS(6))
EQUIVALENCE (I, DUMMY)
EQUIVALENCE (P4, CPAES(10))
EQUIVALENCE (P5, CPAES(14))
EQUIVALENCE (P6, CPAES(13))
EQUIVALENCE (T2, CPAES(11))
EQUIVALENCE (W4, CPAES(7))
EQUIVALENCE (W5,CPARS(12))
EQUIVALENCE (T4,CPARS(3))
EQUIVALENCE (W7,CPARS(8))
EQUIVALENCE (T5,CPARS(5))
EQUIVALENCE (CP4,TRVARS(17))
EQUIVALENCE (CP6,TRVARS(23))
EQUIVALENCE (W2,MPARS(7))
EQUIVALENCE (W1,MPARS(17))
EQUIVALENCE (WCB,FPARS(3))
EQUIVALENCE (FJ,CPARS(11))
EQUIVALENCE (W2,CPARS(6))
EQUIVALENCE (W1,CPARS(4))
EQUIVALENCE (ETACC,FPARS(1))
EQUIVALENCE (ETAM,FPARS(2))
EQUIVALENCE (ETAJ,FPARS(4))
EQUIVALENCE (DPJPP,FPARS(6))
EQUIVALENCE (DPCC,FPARS(8))
EQUIVALENCE (KCC,FPARS(7))
EQUIVALENCE (KJPF,FPARS(6))
EQUIVALENCE (H5,TRVARS(6))
EQUIVALENCE (H5,TRVARS(6))
EQUIVALENCE (F,TRVARS(4))
EQUIVALENCE (H4,TRVARS(10))
IDENTIFY TEST ENGINE (CHOOSE ANY NUMBER FROM 0 - 100)
WRITE(108,98)
READ(105,*) W
WRITE(6,99) W
DECLARE NUMBER OF DATA POINTS
WRITE(108,4)
READ(106,*) W
ARRANGE INPUT DATA IN A 2-D ARRAY.!!! NOTE - THE DATA IN THE
INPUT FILE SHOULD BE READ IN TWO LINES. THE FIRST 10 ON
THE FIRST LINE AND THE NEXT 9 ON THE SECOND LINE, AND 80 ON
SEE FORMAT ON LINE 289
*** IMPORTANT *** THE DATA FOR DESIGN POINT PERFORMANCE
SHOULD OCCUPY THE FIRST TWO LINES IN THE DATA FILE.
READ(6,10) ((A(I,J),J=1,19),I=1,W)
WRITE(108,30)
READ HEATING VALUE OF FUEL IF NECESSARY. OTHERWISE
THIS SECTION SHOULD BE MODIFIED TO SUIT USER'S DATA.
SEE LINES 153-166
READ(105,*) HV
DO PERFORMANCE CALCULATIONS FOR NO. OF DATA POINTS
DO 5 I=1,W
WRITE(108,70) I
ASSIGN ELEMENTS OF ARRAY TO PERFORMANCE VARIABLES
M1=A(I,1)
M2=A(I,2)
W1C=A(I,12)
WFC=A(I,13)
T1 = A(I, 17)  
P1 = A(I, 16)  
TB1 = A(I, 6)  
PB1 = A(I, 7)  
PR21 = A(I, 9)  
TB21 = A(I, 10)  
TB71 = A(I, 4)  
PB71 = A(I, 5)  
PB81 = A(I, 8)  
PA = A(I, 11)  
FJMC = A(I, 14)  
DELTA1 = A(I, 18)  
RTH1 = A(I, 19)  

TRANSFORM CORRECTED DATA INTO ACTUAL VALUES

T2 = TB21 * T1  
T3 = P1 * TR31  
P3 = P1 * PB31  
P2 = P1 * PB21  
T7 = T1 * T71  
P7 = P1 * PB71  
T6 = A(I, 15) * RTH1**2  
A1 = P1 * PB61  

THE FOLLOWING STATEMENT SHOULD BE MODIFIED ACCORDING TO THE METHOD THE USER HAS USED TO CORRECT FUEL FLOW

WF = WFC * DELTA1 * RTH1 * 42.98 / H
FJMC = FJMC * DELTA1  
PB7A = P7 / P1

IF (I, EQ. 1) THEN
    1 CONTINUE

FIND OUT WHETHER DESIGN POINT PERFORMANCE IS REQUIRED

WRITE (108, 50)
READ (105, 'G') AS1
IF (AS1, EQ. 'Y') GOTO 2
IF (AS1, EQ. 'N') GOTO 3
GOTO 1
ELSE
GOTO 3
END IF

2 CONTINUE
CALL DESIGN
GOTO 5

3 CONTINUE
CALL OFFDSGN

CORRECT COMPONENT PERFORMANCE VARIABLES TO STANDARD DAY

R = .286
PB1PC(I) = PR21
PB1PC(I) = PR31 / PR21
PREPT(I) = P4 / P5
PB1PT(I) = P5 / P6
Q1(I) = W1 * SQRT(TI(288) / (P1 / 101.326))
Q2(I) = W2 * SQRT(TI(288) / (P2 / 101.326))
Q4(I) = W4 * SQRT(TI(288) / (P4 / 101.326))
Q5(I) = W5 * SQRT(TI(288) / (P5 / 101.326))
190 Q7(I)=W7*SQRT(T7/288)/(F7/101 326)
191 C CALCULATE TURBINE EFFICIENCIES
192 C
193 C G4M4=1/(1-1/B/CP4)
194 G4M5=1/(1-1/B/CP5)
195 E4=1-1/G4M4
196 E5=1-1/G4M5
197 C
198 C DETERMINE TURBINE ISENTROPIC TEMPERATURE DROP
199 C
200 C T618=T4/PHB(1)**E4
201 CALL CCTAB(T618,CPA,TMCP,HA,THB,PSIA,THPSI,ECV)
202 T618=HA+F/(1+F)*THB
203 CALL CCTAB(T618,CPA,TMCP,HA,THB,PSIA,THPSI,ECV)
204 H618=HA+F/(1+F)*THB
205 ETAHPT(I)=(H4-H6)/H4-H618
206 ETAHPT(I)=(H5-H6)/H5-H618
207 C
208 C CORRECT ENGINE DATA TO STANDARD DAY
209 C
210 C W1C(I)=W1
211 C W2C(I)=W2
212 C P1C(I)=P1
213 C PAC(I)=PA
214 C T1C(I)=T1
215 C
216 C RTH1C(I)=TH1
217 C DELTA1C(I)=DELTA1
218 C TH1=TH1**2
219 C T2C(I)=T2/TH1
220 C PR31C(I)=PR31
221 C T3C(I)=T3/TH1
222 C PR41C(I)=P4/P1
223 C T4C(I)=T4/TH1
224 C PR51C(I)=P5/P1
225 C T5C(I)=T5/TH1
226 C T6C(I)=T6/TH1
227 C PR61C(I)=P6/P1
228 C PR7AC(I)=PR7A
229 C T7C(I)=T7/TH1
230 C W1C(I)=W1C
231 C WFF(I)=WFC
232 C WGB(I)=WGB
233 C FJIC(I)=FJ/DELTA1C(I)
234 C FJWCA(I)=FJMC
235 C
236 5 CONTINUE
237 C
238 C GENERATE AND PRINT NOZZLE CHARACTERISTICS
239 C
240 C CALL MUZZCHAR
241 C
242 C PRINT ENGINE DATA
243 C
244 C WRITE(6,60)
245 C WRITE(6,300)
246 C WRITE(6,600)
247 C WRITE(6,100) (W1C(I),W2C(I),P1C(I),T1C(I),PR31C(I),T2C(I)
248 C 1,PR31C(I),T3C(I),PR41C(I),T4C(I),PR51C(I),T6C(I),I=1,18)
249 C WRITE(6,60)
250 C WRITE(6,400)
251 C WRITE(6,600)
252 C WRITE(6,200) (PAC(I),T6C(I),PR61C(I),PR7AC(I),T7C(I),W1C(I)
253 C
254 C
1.WFF(I),WBC(1),FJCI),FJME(1),DELTA1C(1),RTHC(1),I=1,18
2.WFIE(6,700)
3.WFIE(6,800)
4.WFIE(6,900)
5.WFIE(6,950) (PRLP(I),Q1(I),PBP(C),Q2(I),PBPI(I),Q4(I)
6.WFPEP(I),Q5(I),ETAEP(I),ETALP(I),Q7(I),ETA(I),ETAPC(I)
7.1.I=1,18
8.WFIE(6,40) DFCC
9.WFIE(6,80) ETAJ
10.WFIE(6,90) ETACC
11.WFIE(6,95) DPJP
12.WFIE(6,85) ETAM
13.WFIE(6,75) WCB
14.WFIE(6,95) KCC
15.WFIE(6,97) KJP
4 FORMAT(/' READ NUMBER OF DATA SETS'/)
10 FORMAT(18(10G9.9) )
30 FORMAT(/' READ IN HEATING VALUE OF FUEL '
40 FORMAT(///.I0X,'PRESSURE DROP ACROSS COMBUSTOR = ',F4.1,'%')
50 FORMAT(///.I0X,'ARE YOU GOING TO DO DESIGN POINT CALCULATIONS? Y/N')
60 FORMAT(///.I0X,'************ENGINE PERFORMANCE************')
1  PARAMETER************
70 FORMAT(///.I0X,'DATA SET POINT = ',I2)
75 FORMAT(///.I0X,'COOLING BLEED FLOW = ',F5.4,'W1')
80 FORMAT(///.I0X,'NOZZLE EFFICIENCY = ',F5.3)
85 FORMAT(///.I0X,'MECHANICAL EFFICIENCY = ',F5.3)
90 FORMAT(///.I0X,'COMBUSTOR EFFICIENCY = ',F5.3)
95 FORMAT(///.I0X,'PRESSURE DROP ACROSS JET PIPE = ',F4.2,'%')
96 FORMAT(///.I0X,'KCC = ',F9.6,' KG/S K**1/2 /KPA**(1)')
97 FORMAT(///.I0X,'KJP = ',F9.6,' KG/S K**1/2 /KPA**(1)')
98 FORMAT(///.I0X,'READ TEST ENGINE NUMBER (1-100)'
99 FORMAT(///.I0X,'TEST ENGINE NUMBER = ',I3)
100 FORMAT(///.I0X,'T5,F5.1,T14,F5.1,T24,F7.3,T34,F5.3,T46,F5.3,T56,F5.1
200 FORMAT(///.I0X,'T2,F7.3,T14,F5.1,T24,F5.3,T34,F6.3,T44,F5.3,T54,F5.2
1.1,T64,F7.2,T75,F5.2,T85,F6.3,T96,F6.3,T107,F6.4,T118,F6.4)
300 FORMAT(///.I0X,'T6, W1,T15 W2,T26,P1,T37,T48,P2,P1,T67
1.1,T26,P3,P1,T78,T3',T87,'F4/P1,T100,'T4
1.1,T100,'P5/P1,T120,'T6')
400 FORMAT(///.I0X,'T6,PA,T16,T6,T24,P6/P1',T34,P7/PA
1.1,T45,'T7',T65,'W1',T66,'WF',T77,'WGB'
200,'T85,'THUST',T97,'FJME',T108,'DELTA1',T118,'BTETA1')
500 FORMAT(T6, W1,T16, W2,T26,'KPA',T37,'K',T78, 'K',T100, 'K
1.1,T120,'K')
600 FORMAT(T5,'KPA',T15,'K',T45,'K',T64,'KG/S',T65,'G/S
1.1,T77,'W1',T87,'KW',T98,'KW')
700 FORMAT(///.4DX,'********COMPONENT PERFORMANCE*********')
800 FORMAT(///.6X,'P2/P1',.6X,'Q1',.7X,'P3/P2',.6X,'Q2',.7X,'P4/P3'
1.6X,'Q4',.7X,'P5/P6',.6X,'Q5',.6X,'ETA',.3X,'ETAPL'
1.6X,'Q7',.6X,'ETA',.3X,'ETAPOLY'
303 FORMAT(14X,'KG/S',.16X,'KG/S',.16X,'KG/S',.16X,'KG/S',.16X,'25X','KG/S')
304 FORMAT(///.4(6X,F5.3,4X,F5.3,4X,F5.3,4X,F5.3,4X,F5.3,4X,F5.3)
305 1.6X,F5.3)
306 RETURN
307 END
SUBROUTINE DESIGN

THIS SUBROUTINE FINDS THOSE PARAMETERS THAT ARE ASSUMED FIXED FOR THE ENGINE FROM THE GIVEN DESIGN POINT DATA

COMMON/OUTPUT/ CPARS
COMMON/TEMP/ TRVARS
COMMON/CONST/ FPARS
COMMON/DATA/ MPARS

REAL DBT(2), CPARS(14), FPARS(8), TRVARS(14), MPARS(20)
CHARACTER ANS*1

EQUIVALENCE (T2, CPARS(1))
EQUIVALENCE (ETACC, FPARS(1))
EQUIVALENCE (ETAM, FPARS(2))
EQUIVALENCE (WCB, FPARS(3))
EQUIVALENCE (WOB, CPARS(4))
EQUIVALENCE (DB, TRVARS(13))
EQUIVALENCE (T1, MPARS(1))
EQUIVALENCE (T3, MPARS(9))
EQUIVALENCE (H1, H1, TRVARS(2))
EQUIVALENCE (H3, H1, TRVARS(3))
EQUIVALENCE (H2, H2, TRVARS(1))

Determine inter-compessor temperature if not measured

IF(T2.NE.0) GOTO 4
CALL ICT
GOTO 12

4 CONTINUE

Determine H1, H2, and H3

CALL CCTAB(T1, CPA1, THCP1, HA1, THH1, PSHA1, THEP11, ECV1)
CALL CCTAB(T3, CPA3, THCP3, HA3, THH3, PSHA3, THEP13, ECV3)
CALL CCTAB(T2, CPA2, THCP2, HA2, THH2, PSHA2, THEP12, ECV2)

12 CONTINUE

WCBP=0
ETAMP=0
ETACC=0
WRITE(108,100) ETAMP, ETACC
CONTINUE

Guess mechanical and combustor efficiencies and check whether these values satisfy the compatibility of work equations

WRITE(108,65)
READ(106,*), ETAMP, ETACC.
ETAMP=ETAMP/100
ETACC=ETACC/100
DHS=0
WRITE(108,30)

Cooling bleed flow is automatically assumed to check mechanical and combustor efficiencies

DO 7 J=1,2
WCB=(J-1)/100
WOB=0
WRITE(108,60) WCB
CALL IINTERT
DHT(J)=DB
7 CONTINUE
IF(ABS(DHT(2)) GT ABS(DHT(1))) GOTO 3
C
C IF THE ABOVE STATEMENT IS TRUE, THE ASSUMED VALUES OF MECHANICAL
C AND COMBUSTOR EFFICIENCIES SATISFY THE COMPATIBILITY OF WORK
C EQUATIONS AND THE PROGRAM CONTINUES. OTHERWISE, NEW VALUES OF
C THESE PARAMETERS ARE TO BE GUESSED TO REPEAT THE PROCESS
C
WRITE(108,50) ETAMP,ETACC
WRITE(108,56)
GOTO 5
3 CONTINUE
WRITE(108,40) ETAM,ETACC
GOTO 6
5 CONTINUE
C
C DETERMINE COOLING BLEED FLOW
C
WRITE(108,120) WCBP
WRITE(108,70)
READ(105,*) WCBP
C
C SET LIMIT ON TURBINE COOLING BLEED
C
IF(WCBP.LT.6) GOTO 8
WRITE(108,80) WCBP
GOTO 6
8 CONTINUE
WCBP=WCBP/100
CALL INTERP
DB5=DB
IF(ABS(DB5).GT.1) GOTO 5
9 CONTINUE
WRITE(108,90) WCBP
READ(108,'(G1)') ANS
IF(ANS.EQ.'Y') GOTO 11
10 IF(ANS.NE.'N') GOTO 9
2 CONTINUE
WRITE(108,110)
READ(108,'(G1)') ANS
IF(ANS.EQ.'Y') GOTO 6
12 IF(ANS.NE.'N') GOTO 2
GOTO 6
11 CONTINUE
WRITE(6,200)
WRITE(6,10) WCBP,ETAMP,ETACC
100 WRITE(108,20)
10 FORMAT(///,6X,'WCBM='',F4.2,' kW1 ETAM=' ',F6.2
11 1.' DBC=' ',F6.2,' kS1)
20 FORMAT(//,' DESIGN POINT CALCULATIONS ARE OVER !!!')
26 100 FORMAT(//,' THE EFFICIENCIES YOU PREVIOUSLY CHOSE WERE ETAM = ')
127  1,F6.2,'% ETACC = ',F6.2,'%')
128   65 FORMAT(//,'GUESS PER CENT ETAM, ETACC')
129   30 FORMAT(//,'CHECKING IF CHOSEN VALUES OF ETAM AND ETACC ARE'
130      1,'REASONABLE FOR CYCLE')
131   60 FORMAT(//,'COOLING BLEED FLOW IS NOW ',F4.2,'W1')
132   60 FORMAT(//,'COMBINATION OF ETAM = ',F6.2,'% AND ETACC = ',F6.2
133      1,'% MAY CALCULATE TS WITHIN ACCURACY SET!')
134   66 FORMAT(//,'NOW FIND IF THESE VALUES GIVE REASONABLE BLEED FLOWS')
135   40 FORMAT(//,'COMBINATION OF ETAM = ',F6.3,'% AND ETACC = ',F6.3
136      1,'CANNOT FIND TS WITHIN ACCURACY SET. SO TRY A NEW COMBINATION')
137   200 FORMAT(///,10X,'GGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGGG
SUBROUTINE OFFDSGM

THIS SUBROUTINE PERFORMS THE OFF-DESIGN PERFORMANCE
CALCULATIONS OF THE ENGINE

COMMON/TEMP/ TRVARS
COMMON/OUTPUT/ CPARS
COMMON/CONST/ FPARS
COMMON/DATA/ MPARS
COMMON/ALPHA/ ANS
COMMON/ITGR/ DUMMY
COMMON/EFF/ ETAPC

INTEGER DUMMY
REAL CPARS(14), FPARS(8), TRVARS(14), MPARS(20), ETAPC(18)
CHARACTER ANS2*1
CHARACTER ANS(2)

EQUIVALENCE (I, DUMMY)
EQUIVALENCE (T2, CPARS(1))
EQUIVALENCE (ETACC, FPARS(1))
EQUIVALENCE (ETAM, FPARS(2))
EQUIVALENCE (WCB, FPARS(3))
EQUIVALENCE (WGB, CPARS(4))
EQUIVALENCE (ETAJ, FPARS(4))
EQUIVALENCE (AF, TRVARS(15))
EQUIVALENCE (AN2, ANS(2))
EQUIVALENCE (P2, MPARS(5))
EQUIVALENCE (PH3, MPARS(4))
EQUIVALENCE (T1, MPARS(1))
EQUIVALENCE (T3, MPARS(9))
EQUIVALENCE (B1, HPATR(2))
EQUIVALENCE (B3, HATS, TRVARS(3))
EQUIVALENCE (B2, HATR, TRVARS(1))

IF(I .NE. 1) GO TO 2
WRITE(108,10) ETAJP, ETAMP, ETACCP, WCB, AF
READ(105, *) ETAJP, ETAMP, ETACCP, WCB, AF

NOTE: THESE PARAMETERS WERE OBTAINED FROM DESIGN POINT
CALCULATIONS AND ARE FIXED FOR THE ENGINE. THE COOLING
BLEED IS ASSUMED TO BE A FIXED PERCENTAGE OF ENGINE AIRFLOW.

AF IS BLEED PORT AREA FACTOR FOR THE CASE WHERE THE SURGE BLEED
IS OBTAINED FROM A GRIPS FOR A SIMILAR ENGINE WITH A DIFFERENT
BLEED PORT AREA. THIS MAY BE SET TO ZERO OR ONE
ACCORDINGLY TO SUIT THE USER'S DATA

ETAJ=ETAJP/100
ETAM=ETAMP/100
ETACCP=ETACCP/100
WCB=WCB/100

CONTINUE
IF(T2 .NE. 0) GO TO 3
CALL ICT
GOTO 4

CONTINUE

DETERMINE B1, B2, AND B3

CALL CCTAB(T1, CPA1, TECP1, HA1, TEB1, PSIA1, TBP11, ECV1)
CALL CCTAB(T3, CPA3, TECP3, HA3, TEB3, PSIA3, TBP31, ECV3)
CALL CUCTAB(T2,CPA2,THCP2,HA2,THH2,PSIA2,THPS12,ECV2)
ETAPC(I) = ALOG10(PR31)/(PSIA3-PSIA1)
CONTINUE
WOBP=0
CONTINUE
WRITE(105,25)
READ(105,*(G)) ANS2
IF (ANS2 EQ 'Y') THEN
WRITE(108,40) PR21
WRITE(108,30)
READ(105,*) WOBP
IT IS ASSUMED THAT OVERBOARD BLEED IS A
FUNCTION OF LP COMPRESSOR PRESSURE RATIO
WOB=WOBP*AF
WOB IS OVERBOARD BLEED AS A PERCENTAGE OF W:
ELSE
IF(ANS2.GT.0) GOTO 1
WOB=0
END IF
DETERMINE TIT, ITT, AND EGT
CALL INTERT
DETERMINE NOZZLE CONDITION AND FIND THRUST
CALL NOZZLE
DETERMINE HP TURBINE INLET AND EXIT PRESSURES
CALL TURB
10 FORMAT(/[,' READ PERCENT ETAJ, ETAH, ETACC, WCB, AF']
25 FORMAT(/[,' IS BLEED PORT OPEN? Y/N']
30 FORMAT(/[,' READ PER CENT OVERBOARD BLEED']
40 FORMAT(/[,' LP COMPRESSOR PRESSURE RATIO = ',F6.4])
RETURN
END
SUBROUTINE ICT

THIS SUBROUTINE CALCULATES INTER-COMPRESSOR TEMPERATURE

COMMON/OUTPUT/ CPARS
COMMON/TEMP/ TRVARS
COMMON/DATA/ MPARS
COMMON/EFF/ ETAPC
COMMON/ITGR/ DUMMY

INTEGER DUMMY
REAL CPARS(14),TRVARS(14),MPARS(2),ETAPC(I)

EQUIVALENCE (I,DUMMY)
EQUIVALENCE (PB31,MPARS(4))
EQUIVALENCE (HA1,H1,TRVARS(2))
EQUIVALENCE (T2,CPARS(1))
EQUIVALENCE (HA3,H3,TRVARS(3))
EQUIVALENCE (T1,MPARS(1))
EQUIVALENCE (T3,MPARS(Q))
EQUIVALENCE (PB21,MPARS(5))
EQUIVALENCE (PSIA2,TRVARS(14))

DETERMINE PSI1 AND PSI3

CALL CCTAB(T1,CPA1,THCP1,HA1,THH1,PSIA1,THPSI1,ECV1)
CALL CCTAB(T3,CPA3,THCP3,HA3,THH3,PSIA3,THPSI3,ECV3)

FIND COMPRESSOR POLYTROPIC EFFICIENCY

ETAPC(I)=ALOG10(PB31)/(PSIA3-PSIA1)
PSIA2=PSIA1+ALOG10(PB21)/ETAPC(I)

FIND INTER-COMPRESSOR TEMPERATURE

CALL COMP
WRITE(108,30) T2

30 FORMAT(/' T2 = ',F5.1,' K')
RETURN
END
SUBROUTINE INTERT

THIS PROGRAM CALCULATES INTER-TURBINE TEMPERATURE
AND LP TURBINE EXIT TEMPERATURE

COMMON/OUTPUT/ CPARS
COMMON/TEMP/ TVARS
COMMON/CONST/ FPARS
COMMON/DATA/WFARS
COMMON/ALPHA/ ANS

REAL FPARS(6), CPARS(14), TVARS(4), WFARS(2), ANS(2)

CHARACTER ANS(2)
CHARACTER ANS1(1)

EQUIVALENCE (W2, CPARS(5))
EQUIVALENCE (W4, CPARS(7))
EQUIVALENCE (W5, CPARS(12))
EQUIVALENCE (W7, CPARS(8))
EQUIVALENCE (H3, TVARS(3))
EQUIVALENCE (PS10, TVARS(7))
EQUIVALENCE (H2, TVARS(1))
EQUIVALENCE (ETAM, FPARS(2))
EQUIVALENCE (F, TVARS(4))
EQUIVALENCE (H4, TVARS(10))
EQUIVALENCE (W1, WFARS(3))
EQUIVALENCE (W8, CPARS(4))
EQUIVALENCE (W3, CPARS(2))
EQUIVALENCE (W9, WFARS(6))
EQUIVALENCE (WCB, FPARS(3))
EQUIVALENCE (T5, WFARS(10))
EQUIVALENCE (H1, TVARS(2))
EQUIVALENCE (D8, TVARS(13))
EQUIVALENCE (TJPI, TVARS(16))
EQUIVALENCE (AMS3, TVARS(18))
EQUIVALENCE (T7, WFARS(12))
EQUIVALENCE (AMS1, ANS(1))
EQUIVALENCE (T, TVARS(21))
EQUIVALENCE (CP, TVARS(24))
EQUIVALENCE (BO, TVARS(32))
EQUIVALENCE (PSI, TVARS(25))
EQUIVALENCE (CP5, TVARS(23))
EQUIVALENCE (PS16, TVARS(12))
EQUIVALENCE (T5, CPARS(5))
EQUIVALENCE (H5, TVARS(6))
EQUIVALENCE (H6, TVARS(6))

DETERMINE FLOW BREAKDOWN

W2 = W1 * (1 - WOB/100)

WOB IS OVERBOARD BLEED AS A PERCENTAGE OF W1

W3 = W2 - WCB * W1
W4 = W3 + WF
W7 = W4 + WCB * W1
W6 = W7
F = WF/W3

DETERMINE TURBINE INLET TEMPERATURE

CALL TIT
64 TJPT=0
65 IF(ANS1 EQ 'N') GOTO 1
66 IF(ANS3 NE 0) GOTO 3
67 2 CONTINUE
68 C
69 C ESTABLISH WHICH OF T6 OR T7 IS USED AS JET PIPE TEMPERATURE
70 C
71 WRITE(108,20)
72 WRITE(108,30)
73 READ(105,*) ANS3
74 3 CONTINUE
75 IF (ANS3 EQ 6) THEN
76 TJPT=T6
77 IF (T7=0) T7=T6
78 ELSE
79 IF (ANS3 NE 7) GOTO 2
80 TJPT=T7
81 END IF
82 CALL CCTAB(TJPT,CPA6,THCP6,HA0,THB6,PSIA6,THPSI6,ECV6)
83 HS=HA0+F/(1+F)*THB6
84 PSI6=PSIA6+F/(1+F)*THPSI6
85 C
86 C FIND B5 FROM LP AND HP SPOOL WORK BALANCES
87 C
88 HS6=HS-H2*(H3-H2)/(ETAM*W4)
89 HS1=HS-H1*(H2-H1)/(ETAM*W5)
90 DH=HS6-H5
91 WRITE(108,10) DH
92 GOTO 4
93 1 CONTINUE
94 C
95 C FIND INTER-TURBINE TEMPERATURE
96 C
97 HS=H4-W2*(H3-H2)/(ETAM*W4)
98 HO=HS
99 CALL RTT
100 T5=T
101 PSI5=PSI
102 CP6=CP
103 C
104 C FIND LP TURBINE EXIT TEMPERATURE
105 C
106 HS=HS5-W1*(H2-H1)/(ETAM*W5)
107 HO=HS
108 CALL RTT
109 T6=T
110 PSI6=PSI
111 4 CONTINUE
112 10 FORMAT(/' , DH5 = ',F8.2,' KJ/KG')
113 20 FORMAT(/' ARE YOU GOING TO USE T6 OR T7 AS JET PIPE TEMP?')
114 30 FORMAT(/' TYPE 'S' OR 'T' AS APPROPRIATE')
115 RETURN
116 END
SUBROUTINE HTT

THIS SUBROUTINE FINDS TEMPERATURE FROM ENTHALPY

COMMON/TEMP/TRVARS

REAL TRVARS(14)

EQUIVALENCE (T,TRVARS(21))
EQUIVALENCE (H,TRVARS(22))
EQUIVALENCE (F,TRVARS(4))
EQUIVALENCE (CP,TRVARS(24))
EQUIVALENCE (PSI,TRVARS(25))

DH=0
T=BO

GUESS A VALUE FOR TEMPERATURE

T=T-DH
CALL CTAB(T,CPA,THCP,RA,THH,PSIA,THPSI,ECV)
H=RA+F/(1+F)*THH

CHECK FOR CONVERGENCE AND EXIT FROM LOOP

IF(ABS(DH).GT.0.01) GOTO 1

CP=CPA+F/(1+F)*THCP
PSI=PSIA+F/(1+F)*THPSI

RETURN

END
SUBROUTINE UNCHOKED

THIS SUBROUTINE CALCULATES THRUST OF AN UNCHOKED NOZZLE

COMMON/CONST/ FPARS
COMMON/TEMP/ TVARS
COMMON/OUTPUT/ CPARS
COMMON/DATA/ WPARS

REAL FPARS(8), TVARS(14), CPARS(14), WPARS(20)

EQUIVALENCE (FJ, CPARS(11))
EQUIVALENCE (T7, WPARS(12))
EQUIVALENCE (ETAJ, FPARS(4))
EQUIVALENCE (PB7A, WPARS(20))
EQUIVALENCE (F.TVARS(4))
EQUIVALENCE (GAMMN, CPARS(9))
EQUIVALENCE (W7, CPARS(8))

FIND JET VELOCITY BY ITERATING

R = 265
E7 = (GAMMN - 1) / GAMMN

FIRST GUESS OF JET VELOCITY

TJ = T7 * (1 - ETAJ * (1 - 1/PB7A**E7))

CONTINUE

TJ1 = TJ
TAV = (TJ1 + T7) / 2
CALL OUTFAB(TAV, CPAJ, THCPJ, HAJ, TBJ, PSIAJ, THPSIJ, ECVJ)
CPJ = CPAJ + F/(1 + F) * TECPJ
GAMMN = 1/(1 - R/CPJ)
E7 = (GAMMN - 1) / GAMMN
TJ = T7 * (1 - ETAJ * (1 - 1/PB7A**E7))

CHECK IF TJ HAS CONVERGED

DTJ = (TJ - TJ1) / TJ1
IF (ABS(DTJ) GT 0.005) GOTO 1
CJ = SQRT(2 * CPJ * (T7 - TJ) * 1000)
FJ = TJ - CJ / 1000
WRITE(108, 10) FJ

10 FORMAT (/ 'UNCHOKED THRUST = ', F8.3, ' KN')

RETURN
END
SUBROUTINE TIT
THIS SUBROUTINE CALCULATES TURBINE INLET TEMPERATURE
COMMON/ALPHA/ ANS
COMMON/OUTPUT/ CPARS
COMMON/TEMP/ TRVARS
COMMON/CONST/ FPARS
REAL CPARS(14),TRVARS(14),FPARS(8)
EQUIVALENCE (T4,CPARS(3))
EQUIVALENCE (F,TRVARS(4))
EQUIVALENCE (R3,TRVARS(3))
EQUIVALENCE (CP4,TRVARS(17))
EQUIVALENCE (R4,TRVARS(10))
EQUIVALENCE (ETACC,FPARS(1))
EQUIVALENCE (PSI4,TRVARS(8))
DF=0
1 CONTINUE
WRITE(108,20) DF
GUESS A VALUE FOR TIT
WRITE(108,10)
READ(105,*) T4
CALL CCTAB(T4,CP4,TCBP4,HA4,THB4,PSIA4,THPSI4,ECV4)
FC=(RA4-R3)/(ETACC*ECV4)
CHECK IF FUEL: AIR RATIOS ARE EQUAL AND EXIT FROM LOOP
DF=FC/F-1
IF(ABS(DF) .GT. .001) GOTO 1
H4=HA4+F/(1+F)*THB4
CP4=CPA4+F/(1+F)*TSCP4
PSI4=PSIA4+F/(1+F)*THPSI4
10 FORMAT(../' GUESS TIT')
20 FORMAT(../' DF = ',F7.6)
RETURN
END

SUBROUTINE THRUST

THIS PROGRAM CALCULATES THRUST FOR VARIOUS VALUES OF
NOZZLE EFFICIENCY AND JET PIPE PRESSURE LOSS. THE
MEASURED THRUST IS THEN COMPARED WITH THE CALCULATED
THRUST VALUES TO CHOOSE A SUITABLE NOZZLE EFFICIENCY

COMMON/OUTPUT/ CPABS
COMMON/CONST/ FPABS
COMMON/DATA/ MPABS
COMMON FJD

REAL CPABS(14),FPABS(8),MPABS(20)
REAL FJD(0)

EQUIVALENCE (FJ,FJ,FJ)
EQUIVALENCE (T7,MPABS(12))
EQUIVALENCE (P7,MPABS(13))
EQUIVALENCE (ETAJ,FPABS(4))
EQUIVALENCE (FJ,CPABS(11))
EQUIVALENCE (W7,CPABS(8))
EQUIVALENCE (GAMMW,CPABS(0))

WRITE(6,30) FJ
WRITE(6,40)
WRITE(6,50)
ETAJ=ETAJ+.01
DO 2 J=1,6
CALL NOZZLE
FJD(J)=FJ
ETAJ=ETAJ+.01
2 CONTINUE
WRITE(6,60) (FJD(J),J=1,6)

FIND CHOKING MASS FLOW

Q7D=W+SQRT(T7/288)/(P7/101.325)
WRITE(6,70) Q7D,GAMMW
FORMAT(//.1X,'ACTUAL MEASURED THRUST = ',F6.3,' KN')
FORMAT(//.25X,'***************THRUST**********'
1,'***************')
50 FORMAT(//.1X,'ETAJ = ',T30,'95%','T44','96%','T58','97%','T72','98%'
1,'98%','100%')
70 FORMAT(//.5X,'Q7D = ',F7.4,' KG/S','6X','GAMMW = ',F6.4)
80 FORMAT(//.T25.6(F7.3,7X))
RETURN
END
SUBROUTINE CHOKED

! THIS SUBROUTINE CALCULATES THE THRUST OF A CHOKED NOZZLE

COMMON/OUTPUT/ CPARS
COMMON/TEMP/ TVARS
COMMON/DATA/ MPARS

REAL CPARS(14), TVARS(14), MPARS(20)

EQUIVALENCE (FJ, CPARS(11))
EQUIVALENCE (PJC, TVARS(9))
EQUIVALENCE (TJC, TVARS(11))
EQUIVALENCE (P7, MPARS(13))
EQUIVALENCE (PA, MPARS(19))
EQUIVALENCE (GAMMN, CPARS(9))
EQUIVALENCE (W7, CPARS(8))

R = .286
PC = P7/PBC

CALCULATE CRITICAL JET DENSITY, VELOCITY, AND NOZZLE AREA

RHOC = PC/(R*TJC)
CJC = SQRT(GAMMN*R*TJC*1000)
AJ = W7/(RHOC*CJC)
FJ = W7*CJC/1000*AJ*(PC-PA)

WRITE (108, 10) FJ

10 FORMAT (' ' , ' CHOKED THRUST = ', F6.3, ' KN')

RETURN

END
SUBROUTINE UNCHOKED

THIS SUBROUTINE CALCULATES THRUST OF AN UNCHOKED NOZZLE

COMMON/CONST/ FPARS
COMMON/TEMP/ TBVARS
COMMON/OUTPUT/ CPARS
COMMON/DATA/ MPARS

REAL FPARS(8), TBVARS(14), CPARS(14), MPARS(20)

EQUIVALENCE (FJ, CPARS(11))
EQUIVALENCE (T7, MPARS(12))
EQUIVALENCE (ETAJ, FPARS(4))
EQUIVALENCE (PR7A, MPARS(20))
EQUIVALENCE (F, TBVARS(4))
EQUIVALENCE (GAMMN, CPARS(9))
EQUIVALENCE (W7, CPARS(8))

FIND JET VELOCITY BY ITERATING

R = 286
E7 = (GAMMN - 1)/GAMMN

FIRST GUESS OF JET VELOCITY

TJ = T7*(1-ETAJ*((1-1/PR7A)**E7))

1 CONTINUE

TJ1 = TJ
TAV = (TJ1 + T7)/2
CALL CCTAB(TAV, CPAJ, THCPJ, HAJ, THHJ, PSIAJ, THPSIJ, ECVJ)
CPJ = CPAJ + F/(1+F)*THCPJ
GAMMN = 1/(1-B/CPJ)
E7 = (GAMMN - 1)/GAMMN
TJ = T7*(1-ETAJ*((1-1/PR7A)**E7))

CHECK IF TJ HAS CONVERGED

DTJ = (TJ - TJ1)/TJ1
IF (ABS(DTJ) GT 0.005) GOTO 1
CJ = SQRT(2*CPJ*(T7 - TJ) + 1000)
FJ = W7*CJ/1000
WRITE(108, 10) FJ
10 FORMAT(1X, 'UNCHOKED THRUST = ', F6.3, ' KN')

RETURN
END
SUBROUTINE TURB

THIS SUBROUTINE CALCULATES COMBUSTOR PRESSURE LOSS CONSTANT.
JET PIPE PRESSURE LOSS CONSTANT AND INTER-TURBINE PRESSURE

COMMON/ITGR/ DUMMY
COMMON/CONST/ FPARS
COMMON/TEMP/ TVARS
COMMON/OUTPUT/ CPARS
COMMON/DATA/ MPARS
COMMON/POLY/ ETAFT
COMMON/ALPHA/ ANS

REAL FPARS(8), TVARS(14), CPARS(14), ETAFT(18), MPARS(20)
REAL KCC, KC(6), KP(6), KJP
INTEGER DUMMY
CHARACTER ANS(2)
CHARACTER ANS1:1

EQUIVALENCE (P7,MPARS(13))
EQUIVALENCE (DPCC,FPARS(8))
EQUIVALENCE (P4,CPARS(10))
EQUIVALENCE (K7,MPARS(12))
EQUIVALENCE (KCC,FPARS(7))
EQUIVALENCE (P6,CPARS(13))
EQUIVALENCE (P5,CPARS(14))
EQUIVALENCE (P3,MPARS(10))
EQUIVALENCE (W3,CPARS(2))
EQUIVALENCE (T3,CPARS(6))
EQUIVALENCE (KJP,FPARS(6))
EQUIVALENCE (DPJP,FPARS(6))
EQUIVALENCE (PS16,TVARS(7))
EQUIVALENCE (PS14,TVARS(8))
EQUIVALENCE (PS15,TVARS(12))
EQUIVALENCE (I,DUMMY)
EQUIVALENCE (ANS4,TVARS(19))
EQUIVALENCE (ANS5,TVARS(20))
EQUIVALENCE (W7,CPARS(8))
EQUIVALENCE (ANS1,ANS1)

IF (I.EQ.1) THEN
  IF(ANS1.EQ.'Y') GOTO 2
  IF(ANS1.EQ.'N') GOTO 3
ELSE
  GOTO 9
END IF

2 CONTINUE

Q3A=W3*SQRT(T3)/P3
Q7A=W7*SQRT(T7)/P7

52 C

INITIALIZE JET PIPE PRESSURE LOSS

DPP=2
DO 5 J=1,6
5 C

57 C

58 C

59 C

60 C

61 C

DETERMINE COMBUSTOR PRESSURE LOSS CONSTANT

180
KC(J)=(1-P4/P3)/Q3A**2
DPP=DPP+0.5
P6=P7/(1-DPP/100)

THE ABOVED LINE SHOULD BE MODIFIED TO SUIT USER'S DATA

DETERMINE JET PIPE PRESSURE LOSS CONSTANT

KP(J)=(1-P7/P6)/Q7A**2

5 CONTINUE
WRITE(6,40)
WRITE(6,30) (KC(J),J=1,6)
WRITE(6,110)
WRITE(6,120) (KP(J),J=1,6)
GOTO 4

3 CONTINUE
WRITE(108,90)
8 CONTINUE
WRITE(108,80)
READ(105,*) ANS5
9 CONTINUE
IF (ANS5.EQ.1) THEN
IF (I.NE.1) GOTO 11
WRITE(108,100)
READ(105,*) DPCC
KCC=0
11 P4=P3*(1-DPCC/100)
ELSE
IF (ANS5.NE.2) GOTO 9
IF (I.NE.1) GOTO 12
WRITE(108,20)
READ(105,*) DPCC,KCC
12 Q3A=W3*SQRT(T3)/P3
P4=P3*(1-KCC*Q3A**2)
END IF
IF (I.NE.1) GOTO 6
WRITE(108,60)
7 CONTINUE
WRITE(108,60)
READ(105,*) ANS4
6 CONTINUE
IF (ANS4.EQ.6) THEN
DPJPP=0
KJP=0
P6=P6
ELSE
IF (ANS4.NE.7) GOTO 11
IF (I.NE.1) GOTO 13
WRITE(108,70)
READ(105,*) DPJPP,KJP
13 Q7A=W7*SQRT(T7)/P7
P6=P7/(1-KJP*Q7A**2)
THE ABOVED LINE SHOULD BE MODIFIED TO SUIT THE USER'S DATA

END IF

FIND TURBINE POLYTROPIC EFFICIENCY

ETAPT(I)=(PS16-PS14)/ALOG10(P6/P4)
P5=P6/10**((PS16-PS15)/ETAPT(I))
4 CONTINUE
20 FORMAT(/' CHOOSE PERCENT PRESSURE DROP ACROSS COMBUSTOR' )
1 AND THE EQUIVALENCY KCC'/)
30 FORMAT(/' KCC KG/S X**1/2 /KPA**(-1)' ,T37,F7.5,(4X,F7.5))
40 FORMAT(/// T30,'DPcc = ',T40,'2%',T61,'3%',T62,'4%',T73,'5%'
1,T84,'6%',T96,'7%')
50 FORMAT(/' DO YOU WANT TO GET P0 FROM P7 OR USE MEASURED'
1 VALUE OF P6?')
60 FORMAT(/' TYPE 6'or 7 AS APPROPRIATE')
70 FORMAT(/' CHOOSE PRESSURE DROP IN JET PIPE AND EQUIVALENT KJP')
80 FORMAT(/' TYPE '1' FOR FORMER OR '2' FOR LATTER')
90 FORMAT(/' DO YOU WISH TO USE CONSTANT OR VARIABLE PRESSURE'
1 DROP ACROSS COMBUSTOR?')
100 FORMAT(/' CHOOSE PERCENT PRESSURE DROP ACROSS COMBUSTOR' )
110 FORMAT(/// T30,'DPJP = ',T39,'2.6%',T61,'3%',T61,'3.6%',T73,'4%
1,T83,'4.5%',T96,'6%')
120 FORMAT(/' KJP KG/S X**1/2 /KPA**(-1)' ,T37,F7.5,(4X,F7.5))
RETURN
END
SUBROUTINE NOZZCERM

THIS SUBROUTINE PREDICTS NOZZLE CHARACTERISTICS
FROM THE DESIGN POINT DATA

COMMON/CONST/ FPARS

REAL FPARS(8)

EQUIVALENCE (ETAJ,FPARS(4)) :

WRITE(6,50)
WRITE(6,20)
WRITE(6,40)
WRITE(108,10)
READ(106,** GAMMN, Q7D
PRC=1/(1-(GAMMN-1)/(GAMMN+1)/ETAJ)**(GAMMN/(GAMMN-1))

FIND NOZZLE CONSTANT

KN=Q7D/((1/PRC)**(2/GAMMN)-(1/PRC)**(1+1/GAMMN))**0.5

IF (PRN LT. 1.08) THEN
PRN=PRN+0.02
ELSE
PRN=PRN+0.06
END IF

IF (PRN GT. PRC) THEN
WRITE(6,30) PRC, Q7D
GOTO 3
ELSE
CONTINUE
END IF

Q7=KN*SQRT((1/PRN)**(2/GAMMN)-(1/PRN)**(1+1/GAMMN))
WRITE(6,30) PRN, Q7
GOTO 1

CONTINUE

FORMAT(/, 'READ IN GAMMN, Q7D, FROM DSGN PT CALC')
20 FORMAT(/, '10X, 'PRN10X, 'Q7')
30 FORMAT(/, '10X,F4.2,7X,F6.2)
40 FORMAT(2X, 'KG/B')
50 FORMAT(/, '6X, '*****NOZZLE CHARACTERISTICS*****')
RETURN
END
SUBROUTINE COMP
THIS SUBROUTINE CALCULATES ICT FROM PSI FUNCTION

COMMON/TEMP/ TVEARS
COMMON/OUTPUT/ CPARS

REAL TVEARS(14),CPARS(14)
EQUIVALENCE (PSIA2,TVEARS(14))
EQUIVALENCE (T2,CPARS(1))
EQUIVALENCE (H2,HA2,TVEARS(1))

PSI=PSIA2
1 CONTINUE

GUESS A VALUE FOR TEMPERATURE

T2=11*PSI**2-844
CALL CCTAB(T2,CPA2,THCP2,HA2,THB2,PSI2,THPSI2,ECV2)

CHECK IF PSI HAS CONVERGED

DPSI=PSIA2-PSI2
IF(ABS(DPSI).LT.0.0004) GOTO 2
PSI=PSI+DPSI
GOTO 1
2 CONTINUE
RETURN
END
SUBROUTINE CCTAB(T,CP,THCP,H,THH,PSI,THPSI,ECV)

THIS PROGRAM CALCULATES AIR AND COMBUSTION PRODUCTS PARAMETERS
FOR USE IN GAS TURBINE CYCLE CALCULATIONS

REAL ABRC(7,2),ABRCP(6,2),ABRH(6,2),ARBF(5,2)

DATA ABRC/O.24336328,-.329215418E-04,.4739514E-07,.10126885E+00
1,-.89683656E-13,-.405671,3.205009E,.19075549,.12762498E-03
2,.64661968E-07,.82378182E-11,0,.11317636E+02,.76344726/
3,.056863702,.001078728,.67154771E-06,.51850414E-08
4,.08521981E-11,.29292103E-14,.26004518,.33817793E-04
5,1.4574254E-06,.29619212E-09,7325274E-13,.62379544E-17/
6,.00000000,.79869910,.12835676,.78970103E-03,.5178609E-06
7,1.5959612E-10,.83337878E-13,.42237153E+02,.19980167
8,.87129123E-04,.66282756E-07,.29954469E-10,.39185699E-14/
9,.24830334,-.79968103E-03,.46828797E-04,.88952464E-07
10,.78009876E-10,-.28503319E-13,.44056245E+01,.01856879
11,.99426593E-06,.67149417E-08,.18514999E-11,2.43476933E-15/
12=R.188586/.28.926
13=J=1
14_IF(T.GT.800) J=2
15_CPC=ABRC(1,J)*T+ABRC(2,J)*T**2+ABRC(3,J)*T**3
16*ABRC(4,J)*T**4
17=CP=CPC*4.1868
18_TBCP=ABRCP(1,J)*T+ABRCP(2,J)*T**2+ABRCP(3,J)*T**3
19+ABRCP(4,J)*T**4+ABRCP(5,J)*T**5
20_THCP=THPCP*4.1868
21_H=E^T+T^3
22*ABRC(1,J)*T*(ABRC(2,J)/2+T*(ABRC(3,J)/3+T
23+1*(ABRC(4,J)/4+T*(ABRC(5,J)/6))))*ABRC(6,J)
24=E=HC*4.1868
25_THH=ABRH(1,J)*T+ABRH(2,J)*T**2+ABRH(3,J)*T**3
26+ABRH(4,J)*T**4+ABRH(5,J)*T**5
27=THB=THBB*4.1868
28_PSI=ALG(0.2,7182818)*(ABRC(1,J)*ALG(T)+ABRC(2,J)*T
29+ABRC(3,J)*T**2/2+ABRC(4,J)*T**3/3+ABRC(5,J)*T**4/4
30+ABRC(6,J)*T**5/5
31+THPSI=ALG(2,7182818)*(ARBF(1,J)*ARBF(2,J)*T+ARBF(3,J)
32+1*T**2=ARBF(4,J)*T***3+ARBF(5,J)*T**4+ARBF(6,J)*T**5
33+ECVC=10300-(8C-60.04)-(THFC-31.06)
34+ECV=ECVC*4.1868
35=RETURN
36
Note:- The Program 'CYCLE' was created in CP6 Account No. PNO42564,
ROYAIKINS, KODJO. It has been stored on tape by using the STOW
command.