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**POWER ASSURANCE FOR THE PT6/T400
ENGINE THROUGH THE USE OF A COMPUTER
MODEL**

by

RONALD J. HATTIE
B.Eng., Technical University of Nova Scotia, 1995

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

Department of Mechanical and Aerospace Engineering
Ottawa-Carleton Institute
for Mechanical and Aerospace Engineering

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The Faculty of Graduate Studies and Research
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the Use of a Computer Model**
submitted by
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in partial fulfillment of the requirements for
the degree of Master of Engineering

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June 26, 1997

Abstract

Recently, the Canadian Department of National Defence has purchased 100 Bell 412 helicopters. For these helicopters, a need has been expressed for improved engine health monitoring and power assurance testing. To achieve this, a steady state thermodynamic model has been developed for the T400 Twin Pac helicopter engine. This model brings the capability to predict the effects of typical engine faults on the measured performance to the end user.

A two step method has been developed to determine the maximum output power capability of an actual T400 engine without the requirement of operating the engine at full power. The first step involves matching the predicted performance of the thermodynamic T400 model to the measured engine performance through the scaling of the compressor and turbine component maps. In the second step, the maximum power test is performed using the T400 model with the scaled component characteristic data found in the first step.

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Pratt and Whitney Canada provided the compressor and turbine maps of the T400 helicopter engine. Also, they provided data from their thermodynamic performance model of this engine which played an important role in validating the work which was done. In addition, they provided considerable technical information on the T400 engine which greatly aided the work.

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Nomenclature

A	-	Area
c_p	-	Specific heat at constant pressure
H	-	Enthalpy
M	-	Mach number
N	-	Spool mechanical speed
P	-	Pressure
R	-	Gas constant
s	-	Entropy
T	-	Absolute or total temperature
W	-	Mass flow
δ	-	Corrected pressure = P/P_{ref} .
ρ	-	Density
Θ	-	Corrected temperature = T/T_{ref} .
η	-	Isentropic efficiency
γ	-	Specific heat ratio (1.40 for air, 1.333 for combustion products)
Δ	-	Difference
CDP	-	Compressor delivery pressure
CDT	-	Compressor delivery temperature
Corrected	-	Corrected to MSL, ISA conditions
ECV	-	Equivalent calorific value for combustion chamber calculations.
EGT	-	Exhaust gas temperature
FAR	-	Fuel/air ratio
HPC	-	PT6 centrifugal compressor section
HPT	-	High pressure turbine
ISA	-	International Standard Atmosphere
ITT	-	Inter turbine temperature

LPC	-	PT6 axial compressor section on same spool as HPC
MSL	-	Mean Sea Level conditions (T = 518.67°R, P=14.696 psia)
PT	-	Free power turbine
PR	-	Pressure ratio
PW	-	Power
SFC	-	Specific fuel consumption
SHP	-	Shaft Horsepower
TBO	-	Time between scheduled engine overhauls
TIT	-	Turbine inlet temperature
TRQ	-	Engine output torque
TSO	-	Time since the last engine overhaul
Relative	-	Normalized by design point value

$$\varepsilon = \left(\frac{\gamma - 1}{\gamma} \right)$$

Subscripts

0	-	Stagnation
a	-	Air
altitude	-	engine or component operating state at altitude
c	-	Compressor
cc	-	Combustion chamber
cl	-	Cooling
D	-	Design value
f	-	Fuel
g	-	Combustion products
gdb	-	Gas generator disk cooling bleed
gt	-	Gas generator turbine

hb	-	Compressor handling bleed
hp	-	Gas generator spool
i	-	Isentropic value
lk	-	Leakage from HPC exit to PT exit
lp	-	Power turbine spool
m	-	Mechanical
obd	-	Overboard or customer air bleed from station 3
pdb	-	Power turbine disk cooling bleed
po	-	Gas generator spool accessory power removed
PT	-	Power turbine
nb	-	HPT nozzle cooling bleed
ref	-	Conditions at MSL, ISA
so	-	Power turbine accessory power removed
s	-	Static conditions value
work	-	Constant work coefficient

Station Numbers

amb	-	Ambient conditions
1	-	Intake inlet
2	-	Compressor inlet
24	-	Exit of axial compressor section
25	-	Entry of centrifugal compressor section
3	-	Compressor exit before bleeds are extracted
31	-	Combustion chamber entry after bleeds are extracted
4	-	Combustion chamber exit
41	-	HPT nozzle row exit after mixing with NGV cooling
44	-	HPT exit
45	-	PT entry after mixing with HPT cooling bleed
49	-	PT exit
5	-	PT exit after mixing with PT cooling bleed
6	-	PT exit after mixing with leakage from HPC to PT
8	-	Exhaust nozzle exit

Chapter 1

INTRODUCTION

1.1 General

In the gas turbine industry, manufacturers must guarantee the minimum peak engine power for a range of environmental conditions, altitudes and engine condition which may be experienced to their customers. The process of operating the engine to peak power for these power assurance tests consumes engine life, and it is desirable to be able to acquire these data in a less costly fashion. A thermodynamic engine model is capable of providing these data. It is also capable of providing an accurate extrapolation of sea level test results to engine performance at altitude. The use of such a model can also be useful as a tool to help predict the effects of certain faults such as compressor fouling and blade tip clearance increases on engine performance. This information will be useful in diagnosing engine faults in the field. The engine model will also be of use to field personnel for training purposes, as it will teach them about some of the fundamentals of gas turbine behavior. Future enhancements of the model could be used by helicopter pilots in flight to predict how much power they have in reserve.

It is of primary concern to helicopter operators to ensure that engines do not fail in flight. Towards this purpose, it has been traditional for older engines such as the PT6 to overhaul and replace components on a regular schedule set by the engine manufacturer based on the hours and the number of cycles of operation. Engine overhaul and component replacement costs are high, and as such it would be desirable to minimize the frequency with which they must be performed without compromising safety. Sometimes an engine fault may exist for a considerable time before a scheduled overhaul, and engine damage may accumulate to the point where major unanticipated costs could be incurred when the overhaul is finally done. More recently, many users have begun to move towards overhaul and replacement of engine components or modules on an “on condition” basis. This

involves performing such work when the component in question has deteriorated to the point where maintenance is necessary. The potential to resolve the above problems through the use of “on condition” maintenance is apparent. To utilize it effectively, it is necessary to be able to judge accurately when corrective action is necessary to minimize the overall engine costs, and what component(s) need to be replaced or repaired.

Through the use of a thermodynamic engine model, it is possible to estimate the effects of a given component fault, such as turbine erosion, on the performance of the engine. When the effects of a wide selection of possible engine faults are compiled, we obtain a “fault library” which can be used by maintenance personnel to determine when repairs are necessary.

In power assurance testing, the use of a thermodynamic model may allow the maximum engine power output to be estimated without having to run the engine to full power. Instead, readings can be taken with the engine running at more moderate power levels, such as the maximum continuous rating. The data recorded would include items such as the HP and LP spool speeds, engine output shaft power, torque and ITT. Using these data, the model could be automatically modified to make the operating point(s) the same as the engine under test for a given gas generator spool speed. The model would then approximate the performance of a particular engine being tested. The maximum power of the engine being tested could then be determined by setting limits on variables, such as the maximum temperature, spool speed, or engine torque in the computer model. The fault modeling capability could also be used to verify operation of such a power assurance prediction tool for real, service exposed engines.

1.1.1 Selection of the PT6 Engine for Performance Modeling

Research involving the issues discussed above could be performed for any type of turboshaft powerplant. However, the choice of focusing on the PT6 Twin Pac power plant has been a deliberate one. Recently, the Canadian Department of National Defence

(DND) has purchased 100 Bell 412 helicopters. Their Canadian military designation is the CH 146 Griffon. For these helicopters, the DND is interested in engine health and life usage monitoring in support of maintenance activities. Also, interest has been expressed in the automation of power assurance testing procedures.

1.2 Project Definition

In light of the needs identified above, a program has been initiated at the National Research Council of Canada (NRC) to address these issues. There are three main objectives of this work. A new aerothermodynamic model of the NRC T400 engine which is capable of accurately modeling the steady state performance of a nominal T400 engine is to be developed. It will be able to account for the effects of both the ambient conditions and engine health on engine performance. This model will then be used to predict the changes in measured parameters such as the output shaft power (SHP) as a result of various faults such as a flow reduction in the compressor. Also, work is to be performed to determine if it is possible to isolate engine damage to the component level such as the compressor section through the use of engine thermodynamics. Finally, a procedure for the determination of the maximum engine power available which does not involve operation of the engine to such power levels will be developed and evaluated.

To achieve the objectives mentioned above, the T400 model must be able to provide the minimum guaranteed performance at any ambient temperature and pressure which might be encountered within the engine service envelope. The model must be scaleable to be able to match the characteristics of any particular engine. For instance, it should be possible to model the performance of a particular PT6T-3 power section. There are variations in the performance of every individual engine within an engine type due primarily to tolerance build up both from component assembly at overhaul and engine usage. The adaptation of the model to represent an individual engine given adequate test

data as opposed to the “nominal” engine performance is an important aspect of the work being done.

Once an individual engine has been modeled, it will become feasible to determine or check power assurance test results as mentioned above using the model with good accuracy. It should also be useful for thermodynamic validity checking of test data. Data which do not agree with thermodynamics are probably in error; most probably from sensor errors. By alerting test personnel during the engine testing of this situation, this application has the potential to eliminate wasted time in repeat testing. The standard test data taken in the field are generally inadequate to fix the thermodynamic state of the engine, but the use of an engine model has the potential to “fill in the gaps” of missing information.

Another use of automatically modeling an individual engine could be towards automatic component fault identification, as the model is essentially adjusting efficiencies and flow areas in components during this process. However, a fairly extensive quantity of accurately measured engine performance parameters would be required if the automated fault detection results were to have any accuracy. This is generally too expensive or complex to be done economically in the field, and so this area is not a priority at this time.

It should be possible to simulate typical engine faults through the use of the model and record the effects of each fault on the overall engine performance parameters which are measured. By repeating this process for a variety of engine faults which may be encountered in operating engines, it will be possible to build up a fault library which will aid ground crews in diagnosing engine faults. Such a fault library could include fault matrices which detail the trends in the engine parameters which are caused by various faults, as well as more detailed information about the effect of various faults on life cycle costs or safety parameters.

In order to succeed in its purpose, the new engine performance tool must make life easier for those who are going to use it. It must save them time as opposed to costing time.

Therefore, a more successful model will be one which is easy to use. It must also be able to run on a standard PC such as a 486 or Pentium based machine. The first task of the development of this tool is to develop and verify the numerical tools required.

In summary, the tool will be developed with the goal of application to fault diagnostics, power assurance and engine acceptance testing, and training for engine technicians in the field.

1.3 The Present Status of Engine Modeling

The performance of any gas turbine engine is determined by the thermodynamic processes of compression, combustion, expansion, mixing, and aerodynamics such as pressure losses. Each of these processes along the gas path through an engine are affected by the condition of the various engine components, and as such any change in the status of a component will affect the thermodynamic properties of the moving fluid, and hence the performance of the engine.

General gas turbine modeling capability has developed over the years. Earlier work in the field involved the technique of gas path analysis in which the aerothermodynamic processes above are applied along the gas path of an engine to fix the operating state of each of the engine components. The technique of gas path analysis was introduced as an engine fault detection method by Urban (1972). Staples and Saravanamuttoo (1974) made use of this principle to diagnose faults in helicopter turboshaft engines of a similar configuration as the PT6. Essentially, the gas path analysis technique allows the user to calculate critical unmeasured quantities such as the intake air flow and the turbine inlet temperature (TIT) from other measured data, and estimate the thermodynamic properties of the air along the engine gas path. Using this method, faults could be isolated to the component level. This technique operates using engine test data, and detects faults by determining changes in measured and calculated parameters away from baseline values for

the engine. This method does not independently simulate the performance of a particular engine. Some implementations of gas path analysis may overly simplify non-linear relationships to ease usage.

Gas path analysis was extended by Agrawal et al. (1978) to deal with the diagnosis of instrumentation errors as well as engine faults. The method presented is capable of distinguishing if both the instruments and the engine are unchanged, if one or more instruments are defective but the engine is unchanged, if the gas turbine has changed or if there are both problems with the instrument(s) and the turbine. For the first three cases, the method is able to locate the fault to particular instruments or engine component.

Saravanamuttoo and MacIsaac (1983) describe the development and use of a complete stand alone generic thermodynamic engine model which incorporates the use of detailed component characteristics. The model was one of the earlier ones used to investigate the effects of various component faults on the overall performance of various gas turbine configurations. It was also one of the earliest to recommend the use of generic component maps in the absence of such data from the engine manufacturer. The results were presented in terms of fault matrices and in percent change in various performance variables with a typical defect applied to an engine component in the model. The basic principles of thermodynamic gas turbine engine modeling are now well established, and more detailed “how to” information may be found in references such as Cohen et al. (1992) or in pages 156 to 169.

Stamatis et al. (1990a) have developed a thermodynamic engine model which is capable of modeling the behavior of an individual engine under test. The procedure which performs the adaptation to match the predicted thermodynamic performance to the test data consists of a multivariate minimization routine which applies scaling factors to various component characteristics. This technique is applied to a Ruston Tornado gas turbine. In another paper, Stamatis et al. (1990b) use this same algorithm for the purpose of fault identification in a Ruston Tornado industrial engine. In Lambiris et al. (1994), the

adaptation algorithm is external to the engine model itself, and is thus portable between applications involving different types of engines. The technique is put forward in these papers mainly as a means of engine health monitoring, though it would seem to lend itself well to the power assurance work which is proposed here.

Various studies have been performed in an attempt to understand the effects of typical engine faults on the measured performance parameters as a part of engine health monitoring efforts. Macleod (1991) has performed studies of various engine faults including turbine nozzle erosion and rotor blade untwist, worn compressor seals and rotor tip clearances. The work includes both simulation results from an Allison T56 engine model and a validation of these results with actual engine testing with these faults implanted in an engine. The paper provides information about the typical changes in the component characteristics which would occur for each fault, along with the associated changes in the engine performance. A similar paper by Dupuis et al. (1986) covers a similar study using a model of the J57 twin spool turbojet. This paper covers a greater variety of faults including turbine nozzle erosion and bowing, component fouling, blade damage and air seal leakages. A table provides typical component characteristic modification factors for these effects. An examination of multiple faults is also carried out. The results are purely from the engine model, with no engine test data employed. Many other studies have been performed using more complex techniques such as stage stacking, but data requirements are high.

As a small gas turbine, one would suspect that the PT6 might be more susceptible to fouling than other larger engines. Lakshminarasimha and Saravanamuttoo (1985) examined the factors which could lead to the fouling of compressors in gas pipeline applications. They also established that the most important result of fouling is the reduction in air mass flow through the engine, with a smaller reduction in compressor efficiency. Scaling factors for the component mass flows and efficiencies for typical fouling situations were suggested, and the effects on the performance of the engine were examined. A notable aspect of the work is the inclusion of experimental test data on the

performance of a Pratt & Whitney Canada ST6 engine before and after compressor washing. The ST6 is essentially a PT6 adopted for industrial use. These are the only test data in the area of compressor fouling known to the author. It was found that the compressor efficiency and flow were reduced by approximately 1% and 7% respectively at high engine power settings.

In addition, Seddigh and Saravanamuttoo (1991) have presented work which will aid in the prediction of the susceptibility of axial compressors to fouling. It was found that the ratio of the specific power output of an engine to the enthalpy rise of a compressor stage gave the best correlation with the change in the compressor delivery pressure when 40% of the compressor stages were fouled. A controversial result of this paper was that many of the larger engines examined appeared to be more susceptible to fouling than smaller ones. However, no evidence has been offered to show that these results predicted by logical procedures are incorrect.

Including the present model, two other thermodynamic engine models of the PT6 engine have been found. The first is program P1520 which has been developed by Pratt & Whitney Canada for the purpose of predicting the minimum guaranteed performance of an “as new” engine (1996). It incorporates three component maps, one each for the compressor, gas generator turbine and power turbine. For each engine operating condition the model output incorporates a table of pressures, temperatures and flow rates for each station along the engine. A second table details the overall engine parameters such as fuel flow and SHP. In addition, the compressor corrected flow, PR and efficiency, the combustion chamber efficiency, and various mechanical efficiencies may be varied by the user. The model is capable of accurately modeling the engine’s performance over the entire flight envelope of altitudes, temperatures, pressures and air speeds. As such, it finds use in areas such as determining the minimum guaranteed performance of a new engine. However, it does not have the capability of modeling individual engines in the field. Also, as the compressor is dealt with as one section, damage cannot be isolated to the axial or

centrifugal compressor sections. Finally, this model is proprietary to P&WC, and is not available to the end user.

The P&WC program P1550 is provided to the user, but it provides only nominal engine rating information to the user. It cannot address the issue of engine condition at all. Further work is required to provide a thermodynamic PT6 performance model to the end users in the field. Existing PT6 modeling capabilities of damaged or decayed engines also need to be further developed to allow work involving engine fault detection and power assurance testing to proceed. As a final note, Pratt & Whitney Canada has made the compressor and turbine maps for this model available to the author for use in the creation of this latest model.

Another model was developed by Colantuoni et al. (1996) in an attempt to deal with a very high rejection rate being experienced with overhauled PT6-T6 power sections. The acceptance test involves running the engine at 970 SHP* while maintaining the gas generator spool speed and the exhaust gas temperatures within prescribed limits. It is stated that the major problem is a mismatch between the gas generator and power turbine nozzle guide vane throat areas. The engine model was created with the use of test data already obtained for engines which had passed the acceptance test, and represented the average engine which would pass. It incorporated their best estimation of the component maps and allowed the effects of compressor efficiency and flow, along with variations in the air system on the engine performance to be examined. As with the model above, it could not predict the performance of an individual engine.

Through the use of established thermodynamic gas turbine engine modeling techniques along with the component characteristics provided by Pratt & Whitney Canada, a model of the PT6T-3 power section as used in the T400-CP-400 helicopter power plant can be developed. It should be able to generate the same performance characteristics for the

* Imperial units are used throughout this work as all data which have been provided by Pratt & Whitney Canada and normally used by T400 operators are in this unit system.

engine as the P1520 model over a range of ambient conditions relevant to helicopter operations. It needs to be more capable in the area of engine health monitoring and performance analysis. It needs to be able to match the performance of individual engines in the field, and predict the effects of a wider array of engine faults on the PT6 engine performance than can presently be achieved. It will also introduce the ability to simulate power assurance and engine acceptance testing for engines in various conditions and provide the possibility of predicting accurately the results of such testing without consuming engine life by running it to maximum power. Finally, the model must be simple to use by maintenance personnel in the field without imposing a major new work load on them. As well as the above uses, the model can provide a training tool for the users of the engine to help them understand gas turbine operation.

1.4 The PT6/T400 Twin Pac

The PT6/T400 is a helicopter engine which consists of two PT6 turboshaft engines mounted side by side which drive a common gearbox with a single output shaft. Each of these PT6 power sections in the unit are identical having a single spool gas generator and a free power turbine. Other than a blow off valve to prevent compressor surge at low engine power, the T400 employs no variable geometry. The Twin Pac is an old design, having been first run in 1968 (Beauregard, 1971). The power sections in the engine have been derived from the PT6A-27 turboprop engine. The T400 was the first Twin Pac engine to incorporate cooled gas generator nozzle vanes, which allow for higher cycle temperatures. This in turn allowed for a higher engine efficiency, as well as an increased power output.

The T400 has a maximum continuous SHP of 1600, with a maximum cruise SHP of 1250. The take off rating on the engine is 1800 SHP. The engine has a dry weight including standard equipment of 648 lb (294 kg) (Jane's All the World's Aircraft, 1996/97).

Figure 49 in the Appendices shows a picture of the T400 and the installation of it in the Bell 212 helicopter. An inertial separation system is used in which the exhaust gases act as a jet pump to keep air moving through the system. This could lower the engine output by 5 to 20 SHP for each power section (Davis Engineering, 1997). In addition to this, approximately 5 SHP is removed from the power turbine of each power section to power oil cooler units. An electric starter unit is mounted on the front of each power section in front of the air intake. The same unit serves as an alternator during engine operation. Also, up to 5.25% of the engine intake air may be bled off the compressor delivery for the purpose of cabin heating.

1.4.1 Compressor

There is a single compressor on the PT6. On a PT6T-3 power section, there is a three stage axial section followed by a single centrifugal compressor (CH135 Student Study Manual, 1994). For the purposes of our computer model, the compressor has been separated into these two sections, each of which is modeled separately. The axial section has been labeled as the low pressure compressor (LPC), while the centrifugal stage has been labeled as the high pressure compressor (HPC). This combination has a pressure ratio of roughly 7 at maximum engine power. Mechanical gas generator spool speeds may range from a minimum of around 23,000 rpm to a maximum of 38,100 rpm. The engine has a radial annular intake through a screen.

Air bleeds are only extracted at two places along the compressor. The first bleed is at the junction of the LPC and HPC, the location of the handling bleed. This bleed consists of a series of holes drilled into the outer casing of the compressor which empty into a toroidal chamber which surrounds the engine. A valve connecting to this chamber is then actuated based upon the difference between the compressor and axial section delivery pressures. The bleed air may either be removed from the cycle, or more usually is re-injected into the compressor intake. These mass flows are as shown in Figure 1.

The PT6 compressor incorporates a “pipe diffuser” at the centrifugal rotor exit. In this system, the compressor air is diffused in a number of individual pipes of circular to oval cross section instead of the more traditional annular diffusion channels. Once the compressor air reaches the diffuser exit, the various bleeds are removed and the remainder of the air is fed into the combustion chamber.

The air bleeds at this point include a gas generator nozzle cooling bleed in which air enters the blades axially from the outside radius, circulates through internal passages in the blade, and is ejected from the trailing edge. A further two cooling flows are extracted for PT and HPT disk cooling. Finally, up to 5.25% of the compressor inlet air flow can be bled off the compressor exit for use as a customer bleed on the helicopter. No turbine rotor cooling is provided.

1.4.2 Combustion Chamber

The PT6 engine incorporates an annular reverse flow combustion chamber. Fuel is fed in through 14 simplex injectors with initial ignition being achieved using two spark plugs. The fuel is injected in a circumferential direction around the combustion chamber lining.

1.4.3 Turbines

The T400 HPT is a simple single stage turbine with nozzle vane cooling only, which powers the compressor. The PT is a single stage uncooled unit which powers an independent drive shaft running continuously at 33,000 RPM in order to maintain a constant helicopter rotor speed. The combining gearbox for the two power sections has a reduction ratio of 5:1, giving the engine output speed of 6,600 RPM.

Chapter 2

The NRC T400 Model

2.1 The Engine model Development

It was decided to use the commercially available software package GASTURB 6.0 to create the engine model of the T400. GASTURB is capable of modeling several engine types and has extensive capabilities for dealing with component faults and output. It was desired to be able to isolate faults in each component for the power assurance and engine health monitoring (EHM) studies to be done. To achieve this, the compressor needed to be separated into its axial and centrifugal components, with each being modeled separately. Also, the engine as used in a helicopter injects its handling bleed air back into the compressor intake.

The individual components to be modeled are as follows:

- Engine Intake
- Axial Compressor Section
- Handling Bleed Valve
- Centrifugal Compressor Section
- Combustion Chamber
- High Pressure Turbine
- Power Turbine
- Exhaust Nozzle

A schematic diagram showing the arrangement of the above components in a T400 power section is shown in Figure 1. The air flows shown in Figure 1 were modeled thermodynamically in the engine performance model.

Figure 1 - Schematic Diagram of T400 Engine

Many modifications of the original GASTURB code have been made. These changes both modify the manner in which the model behaves, and adds further capabilities. In the following section, we shall examine the former of these two aspects. In Chapter 5, a series of new capabilities with respect to power assurance testing will be presented. The sections of GASTURB code which have been modified to form the T400 model will be referred to as the NRC T400 model for the remainder of the discussion. The name GASTURB will refer to the entire software package as purchased.

2.2 The Component Matching Procedure

A typical off-design computer thermodynamic engine model incorporates the component performance characteristics of various components of the engine. In GASTURB, these components have been modeled separately as mentioned above. The model will accept as inputs the ambient conditions of temperature and pressure at which the engine is to operate and a variable which determines the engine power. In GASTURB, this variable can be either the mechanical HP spool speed or the TIT.

Each component in the model describes mathematically what the output conditions will be for a given set of inputs. For example, the compressor section reads and uses a compressor map from which may be calculated the exit temperature, pressure and mass flow for a given spool speed, pressure ratio, and entrance temperature and pressure. The outputs from each component in turn become the inputs for the next.

The gas properties such as enthalpy or entropy of the air moving through the engine are calculated as a function of both the temperature and FAR for each station indicated in Figure 1. The process used is similar to that described in Chappell and Cockshutt (1974)

To obtain a valid engine operating point, it is necessary to match the operation of each of the above components. This means that each of the output variables from the previous component must equal the input variables of the next. In performing this process, there is insufficient information to immediately fix the state. For example, in the compressor above, the PR also varies with the input mass flow, which is not yet determined when the component matching process is beginning. Therefore, one of these variables must be guessed initially to allow the calculations to proceed. In the T400 model, a total of four such variables must be guessed to allow an initial iteration to proceed. These include β_{LPC} , β_{HPC} , TIT or N_{HP} , and β_{PT} . The Beta values here refer to a set of lines which have been fitted to the compressor and turbine characteristic maps to allow the maps to be easily read by GASTURB. It most closely corresponds to the component PR and is used to ease the problem of interpolating in the component maps. A further discussion may be found in section 2.4.

When these four variables have been guessed for the first time, it is most probable that the outputs of some of the components will not match the inputs of succeeding components. The mismatches comprise the errors in the matching process. In the T400 model, these errors are taken as the corrected mass flow in the two compressor sections, the corrected mass flow between the combustion chamber and the HPT, the corrected mass flow between the HPT and the PT, and the pressure available at the exhaust nozzle as

compared to that needed to discharge the calculated mass flow. Though there are other errors available to be calculated, it is only necessary to eliminate one error between each of the components. This then defines a four dimensional minimization problem. It is unusual that the conservation of work between the compressor and HPT is not directly used. However, this and all other errors will also drop to zero when the four errors previously discussed are minimized. The component matching process consists of the iterations which serve to reduce these four errors to zero so that the components are matched to each other. For any N_{hp} and ambient temperature and pressure, there is only one condition for which the components will be matched. Figure 50 on page 160 in the Appendices illustrates how this process is executed in the NRC T400 model

In Figures 51 to 59 in the Appendices, the details of the calculations for each of the boxes illustrated in Figure 50 are given. Also, a brief illustration of the other features of GASTURB is provided. These figures incorporate the changes discussed below.

2.3 Modifications of the GASTURB Code

As purchased, GASTURB cannot model the two compressor sections as required. In the original form of GASTURB, the HPC and HPT are mounted together on a single shaft, with the HPC receiving power from the HPT. The LPC is powered directly by the PT on a separate shaft. The PT also powers through a reduction gearbox the engine power takeoff. Also, the handling bleed cannot be mixed with the compressor intake flow with the original model. As explained in more detail later, the handling bleed flow is injected back into the compressor intake flow in a stock Bell 212 T400 installation. Fortunately, the source code for the program can be modified using the Boosted Turboprop engine type to make the GASTURB model more closely suit our needs.

In our case the LPC corresponds to the axial compressor section of the PT6. We need to move the axial compressor section from the LP spool onto the HP spool with the centrifugal HPC section. There are three component matching parameters which need to

be examined for this. The conservation of mass flow through the engine is already taken care of, and the mass flows will be the same in the modified engine model as in the original, and so it does not have to be modified. The other two parameters are the conservation of work within the engine and the fact that all the gas path components mounted on a given spool must rotate at the same mechanical speed.

Two equations involving the conservation of work must be modified, one for each spool. For the HP spool, the work equation was changed to include both the axial and centrifugal compressors. The numerical subscripts refer to the stations shown in Figure 1. For example, $\Delta H_{25,3}$ refers to the change in enthalpy which occurs between stations 25 and 3.

$$\Delta H_{41,44} = \frac{(W_3 \times \Delta H_{25,3} + W_2 \times \Delta H_{2,24} + PW_{po,HP})}{W_{41} \times \eta_{m,HP}}$$

Here, the following work term for the axial compressor section has been added:

$$PW_{LPC} = W_2 \times \Delta H_{2,24}$$

For the LP spool, the work term above is removed. In addition, an additional power takeoff term which will be used to model an accessory drive from the power turbine has been added:

$$PW_{SO} = \eta_{m,LP} \times W_{45} \times \Delta H_{45,49} - PW_{po,LP}$$

Finally, the mechanical speed of the axial compressor section had to be adjusted. This was achieved by changing the equation which calculates the corrected speed used to fix the operating point of this compressor in its component characteristic. The corrected HP spool speed is used now, instead of the corrected LP spool speed.

The modification of the source code to deal with the mixing of the bleed flow with the compressor intake flow requires that the code for the axial compressor section and bleed valve must be iterated within the overall component matching procedure. This is required

because the axial compressor section code must be run first to determine the bleed valve enthalpy, H_{25} . This is assumed to be an isenthalpic throttling process for the purposes of the calculation. From this, T_{25} is found from the thermodynamic gas properties of air, and hence the corrected speed of the centrifugal compressor is found. Now, the bleed valve section of code determines the fraction of the intake mass flow which is bled off as a handling bleed. This bleed is calculated as a function of the corrected gas generator spool speed at the centrifugal compressor entrance. From the intake calculations, the total enthalpy of the incoming air is known, and we now have sufficient information to perform a mixing calculation between the bleed flow and the incoming flow from the intake to determine a new H_2 at the entrance to the compressor. We now iterate this section of code until the error between the old and new values of T_2 drops to less than 0.01 K (0.018 °R). A new input has been added to the code which allows the user to select whether to operate the model in the original mode with the handling bleed being dumped to an external environment, or the new mixed flow mode above which represents the stock engine as installed in a helicopter.

As one of the major requirements of the study is to model the effects of various component faults on the overall engine performance, it is desired to be able to perform fault simulations through the modification of component flow and efficiency functions. GASTURB as provided already allows the compressor and turbine efficiencies to be scaled, but cannot scale the compressor flow functions independently. This capability was added by simply multiplying the corrected flows as read from the compressor maps by a given scaling factor before using them in further calculations. The component matching procedure as described above will then determine the new operating point of the engine.

The original GASTURB 6.0 source code deals with the combustion chamber efficiency by defining it as a constant value. In our case, it is necessary to make provision for some variation in combustion chamber efficiency in order to accurately calculate the correct fuel flow for all engine operating conditions. Originally, a curve fit was applied to the

efficiency of the combustion chamber as a function of an air loading parameter, Ω , as described in Eatock and Sampath (1993). This parameter is defined as follows:

$$\Omega = \frac{W_{31}}{P_3^{1.8} \exp(T_3 / 540) \cdot \text{Vol}}$$

The mass flow is expressed in pounds/second, the pressure in psi, and the temperature in degrees Rankine. The combustor primary combustion zone volume (Vol) has been considered constant. It was found that this procedure did not collapse the data onto a single curve over the flight envelope of the engine. After some experimentation, it was found that the gas generator spool speed corrected using the compressor delivery temperature was the best parameter for this purpose. This use of this parameter allowed for a nearly perfect collapse of the combustion chamber efficiency curves for the P&WC P1520 data for altitudes from MSL to 15,000 ft in the international standard atmosphere. The results of this analysis may be found in Figure 2.

Figure 2 - Percent Difference Between P&WC P1520 and NRC T400 Combustor Efficiencies

It must be noted that it is strongly suspected that various empirical factors are included the combustion chamber efficiency curve as found in P1520. This would explain a design point efficiency used in the program being somewhat lower than that shown Eatock and Sampath (1993), and an unusual shape of the efficiency curve with respect to the combustion chamber loading factor. As it would be difficult to track down each of these factors, it has been decided to use the combustion efficiency curve from the P&WC engine performance program P1520 without modification.

The compressor delivery pressure predicted by the NRC T400 model is a total value. However, the plenum pressure measured on the T400 engine under test at the NRC is essentially a static pressure at the pipe diffuser exit. Therefore, some means of finding the static pressure from the total pressure of the NRC T400 model would be useful for comparison purposes. To do this, the principles of gas dynamics are used. We first guess a Mach number at the compressor delivery and set initial values of the static temperature and pressure equal to the total values. Using the ideal gas equation, we calculate an initial guessed static compressor delivery pressure using these values. Now, an iterative process is begun in which the three calculations to follow are performed.

$$M = \frac{W_{25}}{\rho_s \cdot Area \cdot \sqrt{\gamma \cdot R \cdot T_s}} \quad \rho_s = \frac{\rho_0}{\left\{1 + \left(\frac{\gamma - 1}{2}\right) M^2\right\}^{\frac{\gamma}{\gamma - 1}}} \quad T_s = \frac{T_0}{\left\{1 + \left(\frac{\gamma - 1}{2}\right) M^2\right\}}$$

This calculation will converge to the true Mach number, static pressure and temperature provided the flow area has been guessed correctly. Unfortunately, we do not have available the actual flow area at the exit of the pipe diffusers within the compressor. Even if we know the total cross sectional area at the end of these pipes, the flow area will be somewhat smaller due to boundary layer development and flow separation. As we shall see in Chapter 3, an area of 12.4 in² seems to provide reasonable results, and so this number has been used.

Finally, the bleed valve manipulation input was moved to the engine data input file. The original model required the user to input the bleed valve settings each time an engine running line was computed. Now, the values are stored on file and do not have to be retyped. Also, the GASTURB interface has been modified so that the original “Boosted Turboprop” menu selections of the modified thermodynamic model are now named as “PT6/T400 Helicopter Engine”.

The annular intake on the T400 engine provides a large flow area for incoming air. As a result, velocities are low, and the pressure loss in the intake duct is on the order of 2 inches of water. The exhaust nozzle has a somewhat larger pressure loss of around 14 inches of water at maximum engine power. This figure has been confirmed both by measurements at the NRC and from the P&WC data. This loss has been implemented in the NRC T400 model by applying a constant pressure ratio across the exhaust nozzle. Due to the low magnitude of the inlet pressure losses, they have been ignored.

2.4 Compressor and Turbine Component Maps

To create a thermodynamic model of any gas turbine, a set of compressor and turbine characteristics are normally required. These generally take the form shown in Figures 52, 54 and 57 in the Appendices. For compressor characteristics, the horizontal axis is the corrected intake mass flow, and the vertical axis is the PR. The term “corrected” here means that the engine performance has been corrected to what it would be at MSL, ISA conditions. The process involved is as described in section 3.5 in chapter 3. For turbines these axes are generally reversed. Within this corrected flow - PR field there are a series of constant corrected spool speed lines and an efficiency contour plot which defines the isentropic efficiency of the component at any operating point. Additionally, in the GASTURB implementation there are a series of “Beta” (β) lines fitted to the compressor map data as shown which are more amenable to interpolation in computer code than the PR. Such Beta lines do not have any physical significance. They are used to ease the interpolation of the operating point in a component map between corrected speed lines.

This is useful because in many regions of a typical map, the PR is nearly constant. In other sections, the corrected flow may be nearly constant. A large error may occur when using either of these parameters for interpolation purposes in these sections of the map. By interpolating new points which are on both the Beta lines and the speed lines and using this as our input map for the model, we can now use the Beta value of each point for interpolation (Kurzke, 1992). As the Beta values will vary in an even linear fashion throughout the map, the above problem is solved. This linear variation exists because the Beta lines were fitted in such a way as to provide it. Using such a map, one can determine the component's operating state once any two of the above variables have been fixed.

Normally, component maps are proprietary information of the engine manufacturers and as such are not available for engine modeling purposes. Fortunately, an agreement between Pratt & Whitney Canada, the Department of National Defence and the National Research Council has made these maps available in a controlled manner for use in the T400 engine model.

These data provided are in a tabular form of corrected speed, flow, PR and isentropic efficiency. In order to use these data in GASTURB, it was necessary to fit the Beta lines mentioned above and present the results in a format which the software will accept. One option to perform this task was to purchase the software packages SMOOTHC and SMOOTHT for compressors and turbines respectively from the same source as GASTURB. However, it was found that it was adequate for the purposes of this model to write a series of 4 programs in ANSI C to perform this function.

2.4.1 Basic GASTURB Component Map Generation

Determining the compressor maps for the LPC and the HPC at MSL, ISA was somewhat challenging. P&WC provided the data as a single component map for the entire compressor, as well as instructions for splitting it into the two sections as required for the model. The process of splitting the map into its axial and centrifugal parts has been done

on a Microsoft Excel 6.0 spreadsheet. To begin, the temperature ratio across the entire compressor was determined using the following compression equation:

$$\frac{T_3}{T_2} = 1 + \frac{1}{\eta_{2,3,isen}} \left[\left(\frac{P_3}{P_2} \right)^{(\gamma-1)/\gamma} - 1 \right]$$

Constant specific heats are assumed with $\gamma = 1.4$, and the remaining data are read from a point on the compressor map. Now, the polytropic efficiency for the entire compressor is calculated as follows:

$$\eta_{1,3,poly} = \frac{\gamma - 1}{\gamma} \frac{\ln(P_3/P_2)}{\ln(T_3/T_2)}$$

Next, we assume (with P&WC guidance) that 1/3 of the temperature rise occurs in the axial section of the compressor. From this, the value of $T_{2.5}/T_2$ may be determined.

Assuming that the polytropic efficiency of the axial section is the same as that for the entire compressor, the pressure ratio of the axial section may be found:

$$\frac{P_{2.5}}{P_2} = \left(\frac{T_{2.5}}{T_2} \right)^{\eta_{poly} \frac{\gamma}{\gamma-1}}$$

Knowing the temperature and pressure ratio for the axial section, its isentropic efficiency may be found:

$$\eta_{1,2.5,isen} = \frac{\left[\left(\frac{P_{2.5}}{P_2} \right)^{\gamma-1/\gamma} - 1 \right]}{T_{2.5}/T_2 - 1}$$

From this procedure, we also know the pressure and temperature ratios across the centrifugal compressor, so the above equation may also be used to determine the isentropic efficiencies for the centrifugal section.

In performing these calculations, a few assumptions had to be made. The assumption of constant specific heats is a good one in this case because the compressor itself is of a

relatively low PR of approximately 7. For lower PRs, lower changes in temperature, and hence properties occur in the air as it passes through the compressor. The second assumption that 1/3 of the temperature rise across the compressor occurs in the axial section has been made because no better information is available for the T400. To keep this value constant requires that the efficiencies and PRs in the axial section vary in the same manner as that for the entire compressor. The assumption that the polytropic efficiencies of the axial section and the entire compressor are the same is also made. As we will later see, these assumptions are quite reasonable and the results for the engine model using the split compressor map will agree closely with Pratt & Whitney Canada's P1520 model which uses a single compressor map.

As the entrance temperature and pressure to the overall compressor do not change due to compressor operation, the corrected mechanical speed at the entrance is constant. This means that when the map has been split into the two sections above, the axial section can be described in the form of a series of constant corrected mechanical speeds and as a complete compressor map on its own.

2.4.2 The Axial Compressor Section

For the axial compressor, the remaining step is to fit the Beta lines to it and write the data in the file format that GASTURB requires. The program COMPMAP.C on pages 209 to 230 accomplishes this. It accepts as input the corrected axial compressor speed lines calculated as above, and the design point corrected mass flow and PR. Also, the user can select the number of Beta lines to fit. The program begins by determining the equations of a set of Beta lines in the plane of PR -vs- corrected mass flow which encompass all of the input speed lines. Referring to Figure 3, the Beta lines are fitted as follows. We start with the points of each constant speed line which have both the minimum corrected flow and the maximum PR. The equation of the line connecting each of these points and point 1 in Figure 3 is determined. The line with the greatest slope is kept as our uppermost Beta line and is assigned $\beta=1$. This process is then repeated for points of each constant speed line

with the maximum corrected flow and the minimum PR. The line with the lowest slope becomes the $\beta=0$ line. This defines the four outermost map points. These two Beta lines are then solved to determine their meeting point labeled as the Beta origin in Figure 3. From this point, we then interpolate a family of lines through this point with equally spaced slopes and Beta values between them.

Figure 3 - β Line Fitting to Compressor Maps

Now, the values of corrected mass flow and mechanical speed, PR and efficiency must be determined at each point where the Beta lines and the speed lines intersect. Each of these points will now also have a Beta value associated with it in addition to the four quantities just mentioned. To do this, a set of linear equations are determined for the lines which connect each pair of sequential points in the speed line. For each of these segments, a solution is found for its intersection with each of the speed line segments for each speed line in turn. For each Beta line, there will be an intersection with each speed line segment in any given constant speed line. Only one of these will be a solution which lies on the speed line. To determine which solution is the correct one requires an elimination procedure. There are three possibilities for a solution. The first is that the intersection is at a PR below that of the lowest PR point in the speed line and the speed line segment which the Beta line intersects runs through the lowest PR line in the speed line. The second is that the corrected flow of our intersection point is between that of two points on

the speed line segment. The third is when the corrected flow is less than that of the minimum corrected flow input data point on the speed line and the intersection is with the minimum corrected flow speed line segment. This corresponds to a point above the surge line of the compressor. For the first and last cases, we must perform a linear extrapolation to find the new speed line point. For the second case, we interpolate between the input speed line points.

All that remains is to write the new data set of points to a suitable output file which GASTURB will read and use. A brief explanation of the format of GASTURB component characteristic files may be found on pages 245 to 247, along with sample input files for COMPMAP.C and INTERP.C.

2.4.3 The Centrifugal Compressor Section

The centrifugal compressor is somewhat more complex. As we proceed along a constant corrected speed line in the axial compressor, the exit total temperature T_{25} will vary. This means that the corrected speed of the centrifugal section will also vary. The result of this process is then a field of points as viewed in a PR -vs- corrected flow field. Each point has its own value of corrected speed, corrected mass flow, PR and isentropic efficiency. To obtain the centrifugal compressor map, it is necessary to interpolate from these data a set of constant corrected speed lines.

The first step in this procedure is to plot the centrifugal compressor efficiency and corrected mass flow with respect to the PR to ensure that the data points are arranged in smooth lines which correspond to the constant corrected speed lines of the axial section. Once the data is verified to be of a smooth nature, the ANSI C program INTERP.C is used to interpolate the data. It accepts as its major input the raw data points arranged in groups which correspond to the plotted lines above. Within these groups, the corrected centrifugal compressor speed is in an ascending order. The other numerical input is the compressor's design point air flow, PR and corrected speed.

INTERP.C uses a linear interpolation/extrapolation scheme which is essentially an expanded version of that used in COMPMAP.C which also interpolates the corrected speed values for each intersection point between a Beta and constant speed line. This was selected because once a set of points has been fitted onto the intersection points of the speed and Beta lines the interpolation process becomes rather simple. The result is an output data set similar to that in COMPMAP.C. For each Beta line, we now have a string of points in the corrected mass flow - PR plane. A simple linear interpolation between each of these points will produce a set of points, each with a known constant speed value. By repeating this process for each Beta line, we will have a series of new speed lines, each with a constant known value of corrected speed. It is these lines which are written to disk.

The file CENTMAP.C merely takes the output of INTERP.C and writes it to file in the GASTURB data file format. As the Beta lines have already been fitted, there is no need to do any more.

2.4.4 The Gas Generator (HP) Turbine

GASTURB does not make use of a turbine map for the gas generator turbine for multi-spool engines. As shown in Cohen et al. (1992), the gas generator turbine operating point is essentially fixed for the entire running range of the engine. This means that the corrected mass flow and efficiency are fixed at the design value. This situation arises due to the presence of the power turbine behind it. The power turbine always runs in a choked state except for a period during engine startup at low spool speeds. The choked power turbine controls the corrected mass flow available to pass through the gas generator turbine which itself runs choked for most of its operating range. This situation was verified with the P1520 data.

2.4.5 The Power Turbine

The power turbine component map must also have a set of Beta lines fitted to it. This is done in the program TURBMAP.C as on pages 231 to 244. The process is quite simple in that the Beta lines are fitted to each speed line by merely dividing it into equal PR increments, and placing the intersections at these evenly spaced points. The data are then written into the GASTURB turbine map format which is described on pages 245 to 247.

2.5 Reynolds Number Effects

The final step in creating proper component maps is to deal with the possibility of Reynolds number effects upon their performance. Low Reynolds number effects become more pronounced with smaller turbines and compressors, and the PT6 is certainly in this category. On the other hand, Jane's All the Worlds Aircraft (1996) states that the service ceiling of the Bell 212 Helicopter with the T400 Pratt & Whitney Canada Twin Pac installed is only 13,000 ft. This low altitude will minimize the influence of the Reynolds number. Throughout much of the operating range, Reynolds number effects are small, and may be ignored. However, below some critical Reynolds number both the efficiency and flow functions of the compressor and turbines will be reduced at a greater rate. Schäffler (1979) states that there are three main regions of operation with respect to the Reynolds number. The first is when the flow over the blading is turbulent and attached and the surface is hydraulically rough. In this region Reynolds number effects are small and may be ignored. At lower Reynolds numbers, the blade surface becomes hydraulically smooth and losses increase. In the third region laminar separation occurs on the blades and high losses will occur. This is summarized in Figure 4.

Figure 4 - Turbomachinery Efficiency Variation Over a Full Range of Reynolds Number

Typically, Reynolds number effects will cause a change in mass flow that has been estimated at half that of the efficiency (Kurzke, 1974). For example, if the efficiency scaling factor was 0.985, the mass flow scaling would be 0.9925. It has been decided to investigate the Reynolds number influence on component efficiencies, and decide if the change in mass flow will be significant. Changes of less than half of a percent could be neglected for the present studies.

Sufficient engine performance data for operation of the engine at altitude is required to determine the efficiency and air mass flow rates in the compressor and turbines. At the time this study was performed Pratt & Whitney Canada had provided data from their P1520 performance program (1996).

2.5.1 Compressor Reynolds Number Effects

Complete P1520 running lines were available for a standard engine in the International Standard Atmosphere (ISA). These included operation at altitudes of sea level, 5000 ft, 10000 ft and 15000 ft. The variation in the ambient temperature and pressure through these altitudes caused a variation in the inlet Reynolds number experienced by the compressor and turbines.

The data provided include the isentropic efficiency of the whole compressor and the two turbines. Other variables used for this study include T_2 , P_2 , T_{25} , P_{25} , T_3 , P_3 , W_2 , W_{hb}/W_2 ,

ITT, P_{45} , EGT, and P_5 . In order to isolate Reynolds number effects from the many other processes occurring in a compressor or turbine, Wassel (1967) recommends that a constant value of $C_p \Delta T / T_{in}$ be used as this will approximately hold constant the mean velocity triangles on the compressor blades. This technique was suggested for conditions at or near the design point of the compressor, but as our area of interest is in a fairly restricted region with $N/\sqrt{\Theta_2}$ above 0.9, the use of this procedure was deemed to be acceptable. A repetition of the process to follow was performed on the HPT using the non dimensional work coefficient, and the results obtained were similar.

As in Figures 51 to 59 in the Appendices, for each compressor intake temperature a corresponding enthalpy was calculated to find $C_p \Delta T = \Delta h$. This process is as described in Chappell and Cockshutt (1974). A Reynolds number index similar to that defined by Kurzke (1996) was also calculated:

$$RNI = \frac{P / P_D}{T / T_D} \frac{\mu_D}{\mu_{T,FAR}} \frac{N}{N_D}$$

This parameter is the ratio of the actual and design point Reynolds numbers and is used in place of the Reynolds number. The component maps are assumed to describe the component performance at design point conditions. The actual operating state defines the other operating point. The properties are defined at the entry to the compressor. Engine dimensions may be neglected because they are all constants. In addition, an efficiency scaling factor was defined as follows:

$$f = \frac{\eta_{altitude, work}}{\eta_{D, work}}$$

Each of these RNI and efficiency scaling factors was calculated for a constant value of compressor work coefficient. This process was repeated for a series of different work coefficients. It was found, by plotting the efficiency scaling as a function of the Reynolds number index for various values of the compressor work coefficient, that the separate curves collapsed remarkably well. The results for the axial and centrifugal compressor sections are as shown in Figure 5. A curve fit to these data revealed the Reynolds number efficiency corrections which were applied to the Pratt & Whitney model. Holding $\Delta h / T_{in}$

constant was found to also hold corrected compressor speed nearly constant as well. Thus, similarity of the flows has been achieved.

For the centrifugal section, the Reynolds number index was defined in the same manner as for the axial section, using axial compressor entrance conditions. This somewhat inexact usage was due to the fact that the original Pratt & Whitney Canada compressor characteristics were defined for a single compressor including both compressor sections. As such, the Reynolds number effects in the P1520 model were applied to the entire compressor based on its entrance conditions. The data points in Figure 5 represent lines of constant Reynolds number calculated at three different altitudes.

On the examination of the Reynolds number effect plots produced, it becomes apparent that at the service ceiling of the Bell 212 helicopter the compressor efficiencies are reduced by less than 1.5 percentage points. Therefore, we can conclude that the mass flow corrections would be around 0.75 percentage points based on the literature. Through comparisons of the NRC T400 model using these corrections to altitude variations with the P1520 results, it was found that accurate results were obtained.

A significant problem was encountered during the compressor Reynolds number effects study. It was found that the compressor efficiency dropped as expected for both the engine high and low end power ranges. In the mid power range, it was found that the efficiency varied somewhat erratically. In places the compressor efficiency actually increases with increasing altitude and Reynolds number. Fortunately, the normal operating range of the engine with corrected N_{HP} values greater than 90% is well behaved in nature, as is the low power end of the curves. This variation in the mid power range could not be explained. It is below the normal operating range of the engine and due to the relatively small total efficiency variations involved, it was decided to perform the Reynolds number effects study utilizing the upper power range of the engine.

Figure 5 - Reynolds Number Effects on Compressor Efficiency

2.5.2 Turbine Reynolds Number Effects

For the turbines, the Reynolds number effects on the efficiency have been calculated in the same way as for the compressors, with a few exceptions for the HPT which will be

discussed shortly. These results are as in Figure 6. Corrections for turbine mass flow have been treated in the same manner as for the compressor sections.

The HPT is unique because the entrance temperature and pressure to it are strongly dependent upon the gas generator mechanical spool speed. This is different from the compressor and power turbine, each of which may have its mechanical speed varied without affecting its entry conditions significantly. One of the results of this is that at high power settings the plot of HPT efficiency with respect to $\Delta H/T_{in}$ “loops back” on itself. This was dealt with by interpolating using constant $N/\sqrt{\Theta_{41}}$. Values of $\Delta H/T_{in}$ were also interpolated out for each value of $N/\sqrt{\Theta_{41}}$, and it was found that $\Delta H/T_{in}$ varied by a maximum of 3% from a mean value. Also, the definition of the RNI had to be changed by inverting the N/N_D term. This was necessary to correct for the dependency of the inlet temperature and pressure on the mechanical spool speed. The net result was the best obtained collapse of the various $\Delta H/T_{in}$ lines and hence the most accurate Reynolds number correction found.

Figure 6 - Reynolds Number Effects on Turbine Efficiency

Chapter 3

Verification of the Computer Model

Following completion of the basic model and data, the next step was to verify that the results were physically plausible, and agree with what would be encountered in the operation of a typical engine. This work proceeded in three stages. The first was the verification of the computer model running line with respect to P&WC P1520 model data. The second involves the comparison of the NRC T400 model results with NRC test data corrected for temperature. As mentioned in Chapter 2, the NRC T400 model refers to the calculations within GASTURB which perform the T400 thermodynamic performance modeling. The third was the determination of the temperature lapse exponent applied to Θ using Program 1520 and the verification of it with the NRC T400 model and NRC test data. Important engine parameters are compared at various power settings and altitudes to ensure that good agreement has been obtained. As a final note, all data plots presented will be normalized by reference values of the various parameters. This was required by P&WC.

3.1 Overall T400 Engine Performance

To place the results presented below in perspective, it is useful to take a brief look at the overall power section performance as predicted by the NRC T400 model. The gas generator idle speed is approximately 60% of the design point value, while the normal operating speed of the engine ranges from 90% to 100% of the design speed. As such, it is highly important for this upper speed range to obtain accurate performance predictions. The speed range from 60% to 90% is of significance mainly for transient operation such as an engine acceleration or deceleration as opposed to steady state operation. Transients were not part of the present studies.

In Figure 7 below, the SHP, ITT and W_f predicted by the NRC T400 model are plotted with respect to the normalized corrected N_{hp} . The term “Relative Corrected N_{hp} ” means that N_{hp} has been corrected with respect to the engine intake temperature and normalized by the design speed. The performance shown in Figure 7 is typical of a turboshaft engine. Of note is the large variation of output power with respect to the gas generator spool speed. The fuel flow also varies greatly with the spool speed, but not to the same extent as for the SHP. As a result, useful output power and an acceptable SFC are only achieved at gas generator spool speeds close to the design values. It is for this reason that the normal operating gas generator speed is above 90% of the design point value. Gas generator speeds of less than 80% would never be set for steady state operation.

As a final note, the ITT plotted in Figure 7 is much less dependent on the gas generator spool speed than the SHP or W_f . This is because temperature is a gas property which is independent of the air mass flow through the engine. The SHP and W_f are very much dependent on the engine air mass flow, which in turn directly depends on the gas generator spool speed.

Figure 7 - SHP, W_f and ITT -vs- Corrected N_{hp} Predicted by NRC T400 Model at MSL, ISA

3.2 NRC T400 Model Verification at MSL, ISA

The most important step in determining the validity of the new NRC T400 model is to compare the output with that of the Pratt & Whitney Canada thermodynamic model P1520. Some details about the two sources of information are required here. The performance program P1520 is the P&WC thermodynamic model of the PT6T-3 gas generator. This is the model which is used for determining the overall performance of the engine and for determining the minimum acceptable performance of new engines which have not incurred degradation in service. According to P&WC, it has been compared to test results obtained by new PT6T-3 engines, and as such presents an accurate description of engine performance. The component maps and the design point used in the NRC T400 model are the same as in this program.

The test data used for comparison are from a T400 Twin Pac owned by the Canadian Department of National Defence. There are test data for each of the two power sections in the engine. Generally, engines sent to the NRC for testing are those which are on their last hours before their time before scheduled overhaul. The number of hours required for testing is generally small in comparison to the number of hours the engines are used in the field. Testing is performed near the engine TBO because the engines need to be removed from the helicopters at this time anyway. This eliminates the need to remove a power section, test it, and then reinstall it. The main consequence of this is that most of the power sections received at the NRC have received in service degradation, and generally reflect the lower end of engine performance which would normally be seen in service. These PT6T-3 power sections are no exception.

3.2.1 Comparison to Pratt & Whitney P1520 Data

Here, the NRC T400 model is verified in a comparison with the P1520 deck. The two models should provide a very close match for all of the parameters if the NRC T400

model is functioning correctly. To begin, the running lines on each of the gas turbine components and the overall engine performance parameters are compared between P1520 and the NRC T400 model. A further comparison is then made between the NRC T400 performance predictions and NRC engine test data.

3.2.1.1 Component Running Lines

The normalized axial and centrifugal compressor section and power turbine component running lines are as shown in Figures 8 to 10. As the component maps are themselves proprietary property of P&WC only the percent difference between the NRC T400 and P1520 predicted running lines are shown. The compressor maps use the corrected air mass flow on the horizontal axis and the pressure ratio or the isentropic efficiency on the vertical axis. As explained in Figures 51 to 59 in the Appendices, the turbine maps and running lines are displayed in a similar manner, except that it is the pressure ratio which is on the horizontal axis. As shown earlier, the gas generator turbine operating point is essentially fixed, and hence no running line is shown for that component.

As expected, the agreement between the P1520 and NRC T400 model component running lines is very good. Figure 8 depicts the difference between the axial compressor section running lines for a nominal engine as predicted by P1520 and NRC T400. The difference between the two running lines between 0.6 and 0.80 of the design point corrected flow is at least partially the result of the handling bleed valve actuation. This valve must be incorporated to prevent the axial compressor section from surging during startup and acceleration. The opening of the handling bleed valve lowers the air flow through the rest of the engine behind it, and the component matching at this new condition will lower the back pressure upon the axial compressor, keeping its operation below the surge line. In the PT6, the bleed valve begins to open at a corrected gas generator spool speed of around 90% of the design point value. Also, as mentioned in Chapter 2 the Reynolds number corrections on the component efficiency and flow as implemented in the NRC T400 model are least accurate in this intermediate power range. Also, there could be an

interpolation error at a normalized intake flow of 0.65. This is supported by a sudden change in the component efficiency indicated by the axial compressor map in the vicinity of this operating point.

Figure 8 - % Difference Between NRC T400 and P1520 Predicted Axial Compressor Running Lines under MSL, ISA Conditions

As can be seen in Figure 8, the axial compressor efficiency running lines also show excellent agreement within the normal operating range where the handling bleed is shut. The cause of the sudden “dip” in efficiency at a normalized flow of 0.65 is almost certainly related to a similar “kink” in the corrected flow curve. It shows up to a much lesser degree in the centrifugal section map, but is absent from either of the turbine maps. This “dip” does not noticeably affect the overall engine performance parameters.

Figure 9 - % Difference Between NRC T400 and P1520 Predicted Centrifugal Compressor Running Lines under MSL, ISA Conditions

The centrifugal compressor running lines shown in Figure 9 show a similar agreement as for the axial section. One must remember that the centrifugal compressor section map is an effective map obtained by splitting the complete compressor map used by Pratt & Whitney Canada as discussed in Chapter 2. Actuation of the handling bleed valve has little effect the running line position or shape here. The efficiency map also shows excellent agreement.

The power turbine running lines in Figure 10 show excellent agreement between the P1520 and NRC T400 models. It is of interest to note that the power turbine is operating in a choked condition with the corrected inlet flow constant for much of its operating range. Its isentropic efficiency is also essentially constant. Therefore, it is possible to model its performance with only a single turbine speed line without suffering a significant penalty in the accuracy of the model. We implement the entire map in NRC T400 as we already have a multiple speed line PT map and a software package capable of using it.

Figure 10 - % Difference Between NRC T400 and P1520 Predicted PT Running Lines Under MSL, ISA Conditions

3.2.1.2 Engine Performance Parameters

Now, the more usual test parameters which are measured in the field are compared between the P1520 and NRC T400 thermodynamic models. In Figure 11, the thermodynamic ITT and EGT have been plotted with respect to N_{HP} . Here, the ΔT is shown instead of the percentage temperature change. We are generally interested in temperature margins such as the margin between the present operating ITT and the maximum allowable value as opposed to a percent temperature change. Within the normal operating range above $N_{hp} = 0.9$, the agreement is nearly perfect between the new model and P1520. Within the mid range between idle and operating conditions, the temperature difference rises to a maximum of around 30°R . This is most probably due to a combination of interpolation errors in the compressor map and the Reynolds number correction factors for the efficiencies and flows as described in Chapter 2. The errors are small and outside the working region of the engine. Therefore, they are not a significant concern.

Figure 11 - Temperature Difference Between NRC T400 and P1520 -vs- Corrected N_{hp} Under MSL, ISA Conditions

Figure 12 - % Difference Between NRC T400 and P1520 Predicted Performance -vs- Corrected N_{hp} Under MSL, ISA Conditions

In Figure 12, the SHP, W_2 , and W_f have been plotted with respect to N_{hp} . All of the plots of the new and P1520 model parameters show only small deviations between each other when plotted with respect to N_{hp} . Furthermore, these deviations occur for the most part below a corrected N_{hp} of 0.9 and hence are not within the normal operating range of the engine.

The same applies to the plots drawn with respect to the ITT. In Figure 13 we see that once again these deviations are small in magnitude and below the normal working range of the engine. Therefore, they are not very important.

Figure 13 - % Difference Between NRC T400 and P1520 Predicted Performance -vs- Normalized Corrected ITT Under MSL, ISA Conditions

3.2.2 Comparison to NRC Test Data

Recently, the National Research Council in Ottawa, Ontario has been performing engine testing on the T400 as part of the development of a new exhaust duct which cools the engine exhaust for the purpose of infrared suppression. The resulting test data shown in Figures 14 to 18 are from NRC test Runs 15, 16 and 17 in which the engines were tested with their stock exhaust ducts and bellmouths installed to measure the intake air mass flow. These data reveal much about the variability in the performance of one engine as compared to another, as the variation between the two data sets is similar to the variations between each of them and the NRC T400 model prediction of the nominal engine performance.

The first power section (PS1) has serial number 78095. It has spent much of its time since overhaul (TSO) in the hostile environment of the Sinai Peninsula. Heavy sand ingestion will act to reduce the performance of the engine. The second power section (PS2) has serial number 78117. While also nearly at its TBO, its service life has been spent in a less hostile environment, and therefore is not degraded to the extent which may be observed in PS1.

The P1520 results and the engines under test function slightly differently. The test results were for stock engines with the handling bleed flow being ingested back into the engine as in the Bell 212 helicopter installation. The P1520 results are for an engine with the handling bleed air diverted overboard. This was done so that the secondary effects of the bleed recirculation would not influence the test results.

In a stock Bell 212 engine this bleed flow injection occurs at a single point on the annular intake circumference, posing some difficulty as to how it should be best modeled. In the NRC test cell, the intake temperature is measured through the use of three thermocouple probes on the intake screen spaced evenly around the engine circumference.

Unfortunately, the mixing of the bleed air at the intake is a highly complex affair which cannot be adequately measured with only three thermocouples. To further complicate the issue, the intake ducts for the two engines are mirror images of each other, with both power section gas generator spools spinning in the same direction. As a result, the flow at the intake of each power section is different. As more detailed measurements are not available, the average temperature for these three probes has been used as the intake temperature with the limitation that there is considerable uncertainty in this average temperature.

In Figure 14, the NRC T400 model and test ITT are compared with respect to N_{hp} . Exhaust gas temperature was only available for PS1, as it was fitted with a total temperature probe in the exhaust duct. Instruments to record EGT and W_2 are not standard on the PT6, and these parameters cannot be measured in the field.

Figure 14 - NRC T400 and Tested Corrected ITT -vs- Corrected N_{hp}

Figure 15 - NRC T400 and Tested Corrected W_f -vs- Corrected N_{hp}

In Figure 15, the corrected fuel flow is plotted with respect to the corrected gas generator spool speed. From Figures 14 and 15, we can see that when plotted with respect to N_{hp} , the ITT and W_f for PS2 are generally lower than or equal to the model output. The ITT for power section 78095 is lower than that for power section 78117. In addition, power

section 78117 has been used for several months in the Sinai Peninsula where it was subject to considerable dust ingestion. This would suggest that the latter power section has received more hot section damage than the former even when taking the potential temperature measurement errors at the compressor face.

Figure 16 - NRC T400 and Tested Corrected W_2 -vs- Corrected N_{hp}

As shown in Figure 16, the intake air flow W_2 is basically identical between the two power sections at high power. With lower gas generator spool speeds PS2 draws less air. Due to the gas generator speed at which this divergence between the two curves occurs, it is probable that the situation is traceable to a slightly different actuation of the handling bleed valves from engine to engine. Test data from both engines indicate a considerably lower air flow than predicted by the model. The SHP is plotted with respect to the corrected N_{hp} in Figures 44 and 45 in Chapter 5.

When compared on the basis of ITT in Figure 17, the SHP and W_f for power section 78095 yield values similar to those predicted by the nominal NRC T400 model. Power section 78117 shows significantly decreased values of SHP and W_f for a given ITT as compared to the both the nominal NRC T400 model and power section 78095. Power section 78117 would appear to be the more damaged of the two.

Figure 17 - Corrected SHP and W_f -vs- Corrected ITT

Figure 18 reveals that the test engines produced a lower PR than what both thermodynamic models predict. However, the compressor delivery pressure measured on the engine is essentially a static value, while the model values are total pressures. Due to the small spread in the overall PR between the two engines, it is speculated that the PR is somewhat less sensitive to the engine condition than the corrected mass flow. Therefore,

a correction for the GASTURB compressor delivery pressure has been attempted to predict the static pressure value. It has been matched to the PS2 curve with excellent agreement. The methodology for this correction is as discussed in Chapter 2.

Figure 18 - PR -vs- Corrected N_{hp}

We can see that many of the trends between the test data and the NRC T400 predictions are the same, and indeed many of the values are the same. However, we have only isolated the variables of throttle settings and ambient conditions. It is unfortunate that test data for an “as new” engine are not available so that the remaining variable of engine condition could not be isolated. Later in this work, this problem will be addressed by attempting to add into the NRC T400 model the ability to automatically scale component efficiencies and flow coefficients in order to match the model to the engine data. In light of the existing variability observed from engine to engine, the GASTURB model predictions of engine performance are certainly within a reasonable range.

3.3 NRC T400 Model Verification at Altitude

As another check in the accuracy of the model predictions, it is necessary to perform comparisons between the P1520 and NRC T400 model at altitude. As the new model has

been verified at MSL, ISA conditions, it was decided to examine the engine performance at 10,000 ft, ISA. This correlates to an ambient temperature of 483°R and 10.1 psia. If the NRC T400 and P1520 model output compare well at the extremes of the flight envelope of the Bell 212 helicopter as well as at MSL, ISA conditions, it is reasonable to assume that good agreement will occur between the two at less extreme conditions. An altitude of 10,000 ft was chosen because this is approximately the maximum altitude which the Bell 212 will reach in normal operating practice. As we are primarily interested in verifying the previous sea level checks for operation at altitude, it will not be necessary to repeat all of the plots created above. Instead, we will focus on variables which may be measured in the air or which help to confirm the validity of the Reynolds number corrections found in Chapter 2. This limits us to an investigation of the SHP, W_f , W_2 , and ITT. As a final note, these variables were not corrected for temperature or pressure, because as we are interested in the engine performance at altitude, there would be no sense in correcting the numbers to sea level conditions.

Figure 19 - % Difference Between NRC T400 and P1520 Predicted Performance -vs- Normalized N_{hp} at 10,000 ft ISA

Figure 20 - ITT Temperature Difference Between NRC T400 and P1520 at 10,000 ft ISA

Once again, all of the variables above show excellent agreement between the two thermodynamic engine models. When plotted with respect to the mechanical N_{HP} in Figure 20, the ITT is nearly identical between the two models throughout the normal running speed range of the engine.

The fuel flow and SHP also give a good correlation between the two models when plotted with respect to the mechanical N_{hp} . The NRC T400 model seems to over predict the SHP and PR by around 2% within the upper power range of the engine, while giving a nearly perfect match elsewhere. Although this error occurs within the working power range of the engine, due to its small magnitude and the fact that we are at the upper altitude edge of the normal performance envelope of the Turbo Twin-Pac there is no reason for concern. It is to be expected that some limited degree of prediction error will occur at this condition. Also, the trend between the two models at the high power range is very close.

The Reynolds number index correction applied to the component efficiencies and mass flow functions seem to be validated by the mass flow plot in Figure 19. As can be seen, the agreement is excellent throughout the entire engine running line.

3.4 Hot Day Performance

Finally, we shall examine briefly the case of hot day at sea level performance. This corresponds here to 40°F above ISA, MSL (37°C) at an ambient pressure of 14.696 psi. As for the high altitude case, we will not correct for temperature as both the P1520 and NRC T400 models should predict the same performance for these ambient conditions. The fuel flow, ITT, SHP and intake air mass flow will be examined with respect to N_{hp} .

Figure 21 - % Difference Between NRC T400 and P1520 Predicted Performance -vs- Normalized N_{hp} at MSL, ISA +40°F

As can be seen in Figures 21 and 22, excellent agreement is obtained for all of the measured parameters in the normal operating range of the engine on a hot day condition. In Figure 21, a very noticeable apparent variation occurs in both the SHP and W_f between the two thermodynamic T400 models. However, these variations are expressed in terms of percentages, and at the location of the “spike” in the graph we are operating at low engine power. The actual difference in the SHP prediction between the two models at this

point is no greater than 18 SHP. In Figure 22, we see a considerable over-prediction of the ITT by the NRC T400 model as compared to the P1520 model at this same operating state. Possible sources for these variations include Reynolds number effect correction errors as well as interpolation in the compressor maps as explained above. Again, due to the limited magnitude of these variations with respect to the total temperature and the fact that they occur below the normal operating range of the engine, they are not of significant concern.

Figure 22 - ITT Temperature Difference Between NRC T400 and P1520 at MSL, ISA +40°F

3.5 Determination of the Temperature Lapse Rate

In the process of engine testing, it is common practice to correct the data which are recorded with respect to the ambient temperature and pressure so that the engine performance may be reported at standard conditions for various tests. Some of the more significant variables to be corrected are as follows:

Table 1 - Ambient Temperature Corrections

Variable	Ambient Temperature Correction	Classical Exponent x
T	$\frac{T}{\Theta^x}$	1
SHP	$\frac{SHP}{\delta \Theta^x}$	0.5
W_f	$\frac{W_f}{\delta \Theta^x}$	0.5
$W_{a,g}$	$\frac{W_{a,g} \Theta^x}{\delta}$	0.5

The first column are the actual variables, while the third column represents the corrected groups derived from similitude. Here, T_{ref} and P_{ref} are 518.67°R and 14.67 psi respectively. For all of these cases, the exponent applied to Θ has been derived from dimensional analysis and simplified one dimensional aerothermodynamics (Zucrow, 1958). Air and combustion products have been assumed to behave as ideal gases with constant specific heats. Air and fuel properties are assumed to be fixed as stated by Jarvo and Muir (1989). In reality, at temperature extremes, the actual exponents vary from the theoretical values. These variations seem to be engine specific. However, empirical results have typically been found to match cycle test and model data.

3.5.1 Estimation of Empirical Exponents

To determine the actual values of these exponents, we start with the Pratt & Whitney Canada P1520 program which is the best available estimate of the PT6T-3 engine performance. When a family of running lines are available on an engine with varying ambient temperatures, the correct temperature exponents will be the ones which would allow all of the them to collapse onto the running line obtained at MSL, ISA. This is the

principle which has been used to find a set of empirical exponents. The following data at MSL were obtained from the P1520 program for the test:

Table 2 - P1520 Data Used in Temperature Exponent Fits

Ambient T for each running line ($^{\circ}\text{R}$ deviation from ISA, MSL)	Mechanical N_{HP} Settings for Each Running Line (SHP)
-40	0.608
0	0.688
-40	0.741
	0.794
	0.847
	0.899
	0.951
	1.000

The engine variables of SHP, W_f , PR, T_{25} , CDT, ITT, and EGT were obtained for each running line. A temperature exponent was found for each of them. The temperature at ISA, MSL conditions is 518.67°R . The calculations to determine the exponents for the above variables were done for the power ranges as specified in Table 3.

Table 3 - Arrangement of Data for Each Exponent Fit

Description	Mechanical N_{HP} Speed Range
Low power range	≤ 0.794
High power range	> 0.794
Full power range	All of the above speed settings

Table 3 specifies a total of three fits for the exponent of each variable to isolate the

variation with the engine power settings. Mechanical speed has been used here simply because the values given in Table 2 are the same for each ambient temperature indicated.

For each of the low, high and full power ranges, the variables of interest are tabulated in their corrected form using an arbitrary value of the exponent. The range of ambient temperatures indicated was used for each power setting.

The solution process was performed using a Microsoft Excel 6.0 Spreadsheet and Tecplot™+3DV ver 6.0. The first step in the solution was to apply a polynomial best fit curve to the ISA, MSL P1520 data for the various variables above using Tecplot. These were cubic polynomials except for the EGT and ITT, which required cubic splines to be fitted because of the shape of these curves. Then, the standard error between the remainder of the data and the ISA, MSL line was minimized by manipulating the various temperature exponents. This standard error is defined as follows:

$$S_{y/x} = \left(\frac{1}{(n-2)} \sum_{i=1}^n [y_i - y(x_i)]^2 \right)^{1/2}$$

Here, y_i is the actual P1550 variable value, $y(x_i)$ is the value of the line fitted at the same corrected gas generator speed x_i , and n is the number of points in the P1520 data set used. The Excel Solver is used to reduce this standard error to a minimum value by varying the temperature exponent x for the tested variable.

The above process was repeated three times for each variable: the first was for the entire engine power range, the second for the low power, and the last for the high power. To provide an independent parameter, it was necessary to assume that the exponent for the corrected speed was the classical value of 0.5 for these studies.

The results of this study are as presented in Table 4. The temperature correction exponents for the PR were also evaluated, but have been found to be insignificant.

Table 4 - Calculated Exponent Results for P1520 Data

Corrected Variable	Relative Corrected HP Speed Range		
	< 0.795	> 0.795	All
SHP	0.453	0.586	0.579
Wf	0.544	0.661	0.638
T2.5	0.993	0.975	0.989
T3	0.982	0.947	0.975
ITT	0.999	0.982	0.988
EGT	1.000	1.007	1.004

As can be seen, the calculated exponents show fairly minor variations across the power range, but this variation is always monotonic. Some of the exponents assume lower values with increasing speed, while some increase.

The standard errors defined above for the solutions in Table 4 are shown in Table 5.

Table 5 - Precision Errors with Respect to Curve Fit on P1520 Data

Corrected Variable	Relative Corrected HP Speed Range					
	0.608-0.794		0.794-1		All	
	Std. Error*	Average % Error**	Std. Error*	Average % Error**	Std. Error*	Average % Error**
SHP	5.62	5.62%	6.74	1.18%	5.93	1.82%
W _f (lbm/s)	5.80	3.26%	2.63	0.66%	4.46	1.57%
T _{2.5} (°R)	1.85	0.31%	0.94	0.14%	1.31	0.21%
T ₃ (°R)	5.54	0.72%	2.72	0.29%	3.93	0.46%
ITT (°R)	6.00	0.43%	4.08	0.23%	4.38	0.28%
EGT (°R)	2.61	0.35%	2.15	0.26%	2.09	0.27%
PR	0.06	1.86%	0.05	0.91%	0.04	0.94%

* The units indicated apply to the standard error results.

** These errors are equal to the ratio of the standard error to the average value of the variable in question over a particular mechanical speed range. They are intended only as an estimate of a typical error which might be incurred using the calculated exponent.

These results show that simple theta corrections may provide a fairly accurate data correction method for widely varying power and temperatures.

3.5.2 Check and Comparison with NRC T400 Output

In an attempt to confirm the above results with the model, two main approaches were taken. In the first, the above process was repeated for the NRC T400 data for finding a second set of exponents. In the second, the exponents as found above were applied to the NRC T400 data. In addition, the collapse of the corrected SHP -vs- corrected N_{hp} was plotted using the temperature lapse rate exponents found using the P1520 data. One set used the classical exponent, one the exponent found for the full power range, and the other used the three exponents found for the low, mid and high power ranges.

3.5.2.1 Exponents Derived from NRC T400 Output

As the NRC T400 model has been developed in house, it was possible to utilize a wider range of ambient temperatures for a temperature exponent study. Therefore, the same ambient temperatures were used as for the P1520 study, with the addition of $\pm 20^{\circ}\text{R}$ and $\pm 60^{\circ}\text{R}$ from ISA, MSL. Also, mechanical N_{hp} values from 0.55 to 1.0 were used in increments of 0.05 and a quartic polynomial fit was used instead of a cubic one for most variables.

A comparison between the NRC T400 and P1520 results as in Table 6 should reveal whether or not the observed trends above are real or are an artifact of the various thermodynamic models used.

Table 6 - NRC T400 and P1520 Temperature Exponents Compared

Corrected Variable	Full Power Range		
	NRC T400 x	P1520 x	Difference
SHP	0.605	0.579	0.026
Wf	0.703	0.638	0.064
T2.5	1.000	0.989	0.011
T3	0.993	0.975	0.017
ITT	1.046	0.988	0.058
EGT	1.058	1.004	0.054

The agreement for the temperature variables is excellent. The NRC T400 data indicates that the ITT exponent should be greater than the classical value of 1, while the P1520 results predict a value less than 1. The magnitude of the error is still small.

By contrast, the SHP and W_f exponents show a poorer agreement. For the SHP, a roughly 5% difference exists between the NRC T400 and P1520 values, while the W_f values are off by around 10%. It is speculated that the estimated variation in the combustor efficiency over the power range tested in the NRC T400 model is responsible for the majority of this error. Earlier NRC T400 runs with a constant combustor efficiency produced a value of the fuel flow temperature exponent somewhat closer to that of the P1520 trial. However, the fuel flow with the constant combustor efficiency was around 10% too low in the NRC T400 model as compared to Pratt & Whitney Canada data, and hence the P&WC combustion chamber efficiencies were used to correct that problem.

3.5.2.2 Application of P1520 Exponents to NRC T400 Data

Similar trials were performed to collapse the NRC T400 data using the exponents obtained earlier from the P1520 data only. It was anticipated that the curves would collapse the best when the exponents for the low, mid and high power ranges were applied separately. The full range exponents should be less effective at collapsing the curves down, while the

classical exponents should be the least effective. This study showed mixed results. The errors in the corrected variables below as defined above are presented for the scenarios mentioned in Table 7.

Table 7 - Standard Errors of P1520 Exponents in Collapsing NRC T400 Data

Corrected Variable	Segmented Fit	Single Fit	Classic
SHP	3.849	3.840	4.687
W_f (lbm/s)	2.669	2.544	4.716
$T_{2.5}$ ($^{\circ}$ R)	1.253	1.079	0.948
T_3 ($^{\circ}$ R)	2.304	1.788	1.493
ITT ($^{\circ}$ R)	9.835	10.091	9.238
EGT ($^{\circ}$ R)	8.705	8.619	8.923
PR	0.021	0.014	0.013

As can be seen, only the SHP, W_f , and EGT follow the expected pattern of results, and even then only partially. There seems to be no benefit in attempting to utilize different exponents for varying engine power output. However, one should not read too much into this. By examining the data, it becomes apparent that the sensitivity of the errors to changes in the exponent used is itself very small. The expected trend will only hold true if the exponent as found from the NRC T400 results and the P1520 data are all larger or smaller than the classical value. Furthermore, the exponents must proceed in the order from the closest to the furthest from the classical value of the full power range fit, the high, mid and low power range combination, and then the NRC T400 fit. Where the trend in the errors above proceeds in the opposite direction, it means that the NRC T400 and P1520 exponents are on the opposite side of the classical value, such as occurs with the T_3 value. Cases where the NRC T400 and P1520 exponents are all larger or smaller than the classical value, but in which the NRC T400 value is not the most distant value, will show mixed results.

An example of how these temperature exponents correlate to engine performance prediction is shown in Figure 23 for the SHP. Exponents found using P1520 data are used.

Figure 23 - % Variation from MSL, ISA SHP Curve for Temperature Corrected Data

In Figure 23 we see that for a hot day the segmented fit and single fit temperature exponents determined using the P1520 data have a similar effectiveness in collapsing the SHP -vs- corrected N_{hp} curve down to the Nominal MSL, ISA curve. The classical exponent of 0.5 is somewhat less precise. For cold day operation above 85% of the design N_{hp} , all of the exponents examined have similar success in collapsing the data. As seen in Figure 7, many engine parameters vary greatly with the N_{hp} . In Figure 23 we see that for hot day operation the predicted SHP is up to 5% in error. However, under such conditions the engine SHP has been considerably reduced, and this 5% error corresponds to around 2 SHP.

3.5.3 Comparison with NRC Exponents, and Conclusions

The final step in the ambient temperature exponent testing is to verify that the values as determined above agree with those obtained from real engines. A T400-CP-400 Twin Pac engine has been under test at building M-7 on the Montreal road campus of the NRC for some months now, and considerable test data have been obtained from it. It has been anticipated that the ambient temperature range and number of data points available from the engine testing would be limited as compared to what the performance models above are capable of predicting. Therefore, a simplified procedure has been used. Data from Runs 20, 21, 22 and 60 in the T400 test series at the NRC have been analyzed. These runs were conducted on different days, but on the power sections in their stock configuration as would be seen on a Bell 212 helicopter, with the exception of the oil cooler fans which were not installed on the NRC test stand. For each run, the relevant measured performance parameters were corrected using a given value for the temperature correction exponent. Values for each of the engine parameters considered were interpolated out for each of four given corrected gas generator spool speeds. For each of these speeds, over all of the test runs performed, a rough “average” error was calculated as follows:

$$\% \text{ Error} = \frac{(\text{Max Value} - \text{Min Value})_{\text{At Given Speed}}}{\text{Average of Two Values Above}}$$

The percent error calculated for each of the four spool speeds considered were then averaged to obtain an overall average percent error. This process was repeated twice for each power section tested. A percent error was calculated as above using the exponents determined using the P1520 data. Then, the Microsoft Excel 5.0 Solver was used to minimize this percent error for each measured engine parameter in turn to generate a new set of exponents for comparison purposes.

Table 8 - Temperature Exponents Applied to Power Section 78095

Corrected Variable	Tested x	Error*	NRC T400 x	Error*
SHP	1.119	2.2%	0.579	3.5%
W _f	0.910	1.0%	0.638	1.4%
ITT	0.939	0.1%	0.988	0.3%
EGT	0.959	0.2%	1.004	0.3%

* Corrected speeds of 0.8, 0.9, 9.95 and 0.98 used for Error Determination

Table 9 - Temperature Exponents Applied to Power Section 78117

Corrected Variable	Tested x	Error*	NRC T400 x	Error*
SHP	0.944	6.0%	0.579	6.9%
W _f	0.698	3.6%	0.638	3.7%
ITT	0.889	3.5%	0.988	3.7%

* Corrected speeds of 0.8, 0.85, 0.9 and 0.96 used for Error Determination

By examining Tables 8 and 9, two things become readily apparent. The temperature exponents found for the fuel flow and the SHP using the test data tend to be larger than what one should expect. Also, the range of exponents shown in these tables does not seem to have a large impact on the error. In other words, the error as calculated is not highly sensitive to the temperature exponents used.

We must qualify the accuracy of the exponents found from the test data alone. As in the stock T400 engine, the handling bleed air is injected back into the compressor. A measured intake temperature variation of around 60°F is encountered over the power range tested due mainly to this effect. By contrast, the total ambient temperature variation over all of the engine runs is only around 45°F. An examination has been performed on the temperatures indicated by each of the three thermocouples on the compressor intake scroll for power section 78095. Two of them read similar temperatures, while the third

reads as much as 15°F to 20°F lower. This indicates that the flow field at the compressor intake is inadequately resolved by the three thermocouples. Unfortunately, it has not been possible to further investigate this issue, but it seems likely that the temperature read is higher than the actual value.

As a result of these errors, the low ambient temperature range under which the engine has been operated, and the relatively low sensitivity of the corrected engine parameters to the temperature exponent, it becomes difficult to accurately determine the temperature exponent. From the information in Tables 8 and 9 we may conclude that the temperature exponents as determined using the P1520 and NRC T400 models are consistent with the test results. However, we have not been able to verify the actual values of these exponents with the test data. The temperature exponents found from these two thermodynamic models are consistent with each other, and seem to be reasonable values for these quantities.

3.6 Conclusions

As a result of these comparisons between the NRC T400 and P1520 thermodynamic models for the T400 engine, it has been shown that each of the above models provides essentially the same performance predictions over the entire normal engine performance envelope of ambient temperature, pressure, and power setting. Now it is time to address the issue of modeling component faults and dealing with engine condition.

Chapter 4

Fault Detection and Isolation

On an aerothermodynamic level, faults in compressors or turbines generally appear as variations in isentropic efficiency or corrected flow in the affected component. Each of these component performance variations act to cause variations in the observed engine parameters such as SHP or ITT. The sets of variations in engine parameters are referred to here as fault signatures. One of the basic uses of an off-design thermodynamic engine model is for the determination of fault signatures. Different engine faults will manifest themselves with different fault signatures. Therefore, the changes in engine performance over time provide a valuable insight into the condition of the engine. This principle will be investigated to determine if, through thermodynamic means, various typical engine faults may be isolated to a component level..

4.1 Fault Signatures

Typical T400 component faults in rough order from the most to the least common include handling bleed valve leakages, air-fuel control unit (AFCU) problems, compressor flow reductions, HPT efficiency reductions, compressor efficiency reductions, PT efficiency reductions, and HPT and PT flow function increases. The Canadian Department of National Defence (1997) indicates that the handling bleed valve may either develop a continuous leakage through a damaged seal, or the scheduling of the valve with respect to the corrected N_{hp} may drift from the optimal settings. The former fault may develop through the erosion of the valve seal. The latter problem is usually due to the partial blockage of the venturi tube which delivers the control pressure for the bleed valve. It is the difference between this control pressure and the pressure on the inside of the bleed valve which controls the valve actuation schedule. The AFCU is part of the control system and as such would require a transient T400 model for fault diagnosis. It is only

during transient operation that the control system characteristics actively reveal themselves. We have not actively considered such problems with this unit. Pratt & Whitney Canada (1996) indicate that turbine flow variations are typically not significant once the engine has entered into service.

Compressor fouling is an issue for small gas turbines. Saravanamuttoo and Lakshminarasimha (1985) have shown for the industrial version of the PT6 engine that the principal effect of compressor fouling was a reduction in compressor flow as opposed to efficiency. For a typical T400 compressor, the mechanisms affecting the corrected flow and efficiency may include fouling as debris attach themselves to the compressor blades, or blade surface roughness and leading edge geometry changes caused by sand or dirt (Turyk, 1989). Tip clearance increases may result due to blade tip rubbing and the effect of ingested sand or dirt being centrifuged to the blade tips. In turbines, hot exhaust gases tend to bow or erode the nozzle and rotor rows, resulting in an increase in the corrected flow function and a decrease in efficiency. It is, however, possible for deposition to occur which may reduce turbine flow. The other mechanisms mentioned for the compressor apply for the turbines as well.

As a further complication, the operating state of each component depends upon that of the other components. For example, the operating efficiency of a compressor may increase due to a reduction in the turbine nozzle area. Such a fault would increase the back pressure on the compressor, pushing its operating point closer to surge where its efficiency is greater. Each of these faults has a fault signature associated with it. Overall engine efficiency will almost always drop when engine faults are present.

The aerothermodynamic component faults identified above have been examined in an attempt to correlate with them the effects they have on engine performance. We shall begin by examining the various fault signatures associated with them. For the purposes of the results to follow, all of the faults applied represent a 1% degradation in the component performance so that it is possible to readily compare the fault signatures obtained. Also,

the parameters chosen have been limited to those which may be measured on the engine either “on the wing” or in a test cell. The parameters available in the test cell include the SHP, N_{hp} , ITT, EGT, W_2 , CDT, fuel flow and overall compressor PR. The faults examined include degradations in the efficiency and flow of the compressor and turbine characteristics. Also, the effect of a handling bleed valve leakage has been examined, as this is one of the more common problems encountered in service.

For any fault signature, it is necessary to specify the engine operating condition. This includes the ambient conditions of temperature and pressure, and one engine variable to specify the engine power setting. The effects of a given fault are therefore dependent on which engine variable is chosen to be held constant. The fault signature for the engine with a constant N_{hp} will be different than that for the same fault but with the SHP constant. Thus, each fault signature with a different engine variable held constant will convey unique information about the nature of a given fault. Therefore, it has been decided to examine three fault signatures. The constant parameters for these will be the N_{hp} , SHP and ITT. It should be possible to examine the usefulness of each fault signature in turn for the purpose of fault detection and isolation.

The next step will be to examine the effects of multiple faults on engine performance to determine if the effects of these faults are additive. If they are, then it will be possible through the superimposition of individual faults to predict the degraded engine performance with multiple faults. To isolate engine faults effectively using fault signatures, this additive nature of multiple faults is usually implicitly assumed. In addition, the examination of multiple simultaneous faults will provide trouble shooting guidance for where each fault signature is useful and where problems occur. We will begin by examining multiple faults in individual components, and then expand to faults in multiple components.

With the fault signatures developed and explored above, it should then be possible to examine the state of the T400 engine under test here at the NRC to determine the state of

health of the engine. A diagnosis of the engine condition will be attempted. With this goal it is necessary to adequately model the handling bleed as it occurs in a standard helicopter installation.

4.1.1 Handling Bleed Valve Leakage

As mentioned in earlier sections, in a stock T400 engine the handling bleed is injected into the compressor intake flow. The average temperature for three thermocouples has been used as the intake temperature with the limitation that there is considerable uncertainty in this average temperature due to the difficulties in resolving the complex flow at the compressor intake.

An examination of the reliability of the present NRC T400 method of mixing the handling bleed with the intake flow has been carried out. Figure 24 shows the average intake temperature of each of the tested power sections as well as two intake temperature curves generated by the NRC T400 model. The lower of these NRC T400 curves has been generated assuming isenthalpic expansion of T_{25} air to the intake, followed by perfect mixing. This simple model has been scaled to match the test data of engine 78117 by adding 2°R and multiplying the difference between the ambient and mixed air by 1.353. These numbers yield the best agreement with the engine data. These factors provide a good correlation between the NRC T400 line and the test data. The trends of the lines generated by the model and those measured on the engine are the same, which supports the approach used in the model. Each engine installation or condition may have a different characteristic as seen for the two power sections in Figure 24.

Figure 24 - Intake Temperature Rise -vs- Normalized Corrected N_{hp}

For the off-design effects study to follow, it has been decided to use the former of the two NRC T400 model lines as described above. There are two primary reasons for this. As the process of fault diagnosis described below predicts the changes in the measured parameters as opposed to their actual values, either of the above model curves would suffice. It is therefore desirable to avoid introducing the usage of empirical scaling factors and keep to the basic physics of the situation for a generic engine. Furthermore, we already know that the above measured temperatures are not particularly precise, and appear to vary from engine to engine and installation to installation. There may also be handling bleed valve leakage in engine 78095. Attempting to account for this at this stage would needlessly complicate the situation.

4.1.2 Impact of Mixed Handling Bleed on Fault Signature

To be certain that the usage of the basic isenthalpic throttling and perfect mixing curve is valid, it has been decided that a quick check should be performed. A fault signature

generated for each of the two model lines in Figure 24 will reveal the sensitivity of the off-design effects to the treatment applied to the handling bleed valve. With the NRC T400 model, a fault signature may be readily obtained assuming a 1% degradation of the turbomachinery efficiency and corrected flows, or a 1% increase in the handling bleed valve leakage. The fault signatures calculated using a constant $N_{hp}/\sqrt{\Theta_2}$ are shown here. The sensitivity of the fault signatures based on constant ITT or SHP to changes in the handling bleed valve schedules are similar. The fault signatures in Figure 25 have been calculated for a mechanical gas generator spool speed of 80% of the design speed.

From Figure 25, we can see that any differences in the engine fault signatures which occur due to variations in the compressor intake temperature are less than 0.5%. Therefore, our usage of the most simple handling bleed analysis and corrected parameters is acceptable in the determination of a fault signature. The engine operating state is altered by changes in compressor intake temperature. A more detailed discussion of the reasons for these signatures is given later after investigating the effects of ambient conditions.

Figure 25 - Corrected Fault Signatures for Two Compressor Intake Temperature Schedules at $N_{hp} = 0.8$

4.1.3 Ambient Temperature, Altitude and Power Setting Effects on Fault Signatures

The fault signatures to follow have been developed at MSL, ISA conditions and at high power settings. However, many of the fields from which helicopters operate are at considerable altitude, and the ambient temperatures in Canada may drop far below the

freezing point. In order for the fault signatures to follow to be universal in nature, the trends of changes in the measured parameters must remain the same for these varying conditions and power settings. To determine if this is so, a series of three plots have been prepared in the same manner as Figure 25. These are calculated at constant values of $N_{hp}/\sqrt{\Theta_2}$ of 0.95. Figure 26 is a reference case at MSL, ISA conditions. Figure 27 is the fault signature at 10,000 ft altitude, and Figure 28 is for an ambient temperature 72°R below MSL, ISA conditions (-25°C). Also, a comparison with Figure 25 will be useful to determine the effects of engine power setting on the fault signature.

From Figures 26 to 28, it can be seen that the ambient conditions under which a T400 engine is operated have no significant effects on the fault signatures of the engine. A comparison between Figures 25 and 26 indicate that some changes do occur in the fault signature due to changes in gas generator spool speed. The sensitivity of the engine performance to typical engine faults at low power settings is generally greater than, or equal to, that at higher power settings. A comparison of Figures 27 and 28 to Figure 26 show only small changes in PR for HPT and PT flow faults. As well, the majority of the measurable trends are in the same direction. The major exception is the intake corrected mass flow which is generally not measured anyway. As a result, for the isolation of engine damage to a certain component the conditions at which the engine testing is performed is not important as long as the measured variables are corrected to MSL, ISA conditions. However, for engine trending where the magnitudes of the changes are important, it is recommended that the engine testing occur at the power settings near those under study.

Figure 26 - Corrected Fault Signature at Constant Corr N_{hp} of 0.95 at MSL, ISA

Figure 27 - Corrected Fault Signature at Constant N_{hp} of 0.95 at 10,000 ft, ISA

Figure 28 - Corrected Fault Signature at a Constant Corrected N_{hp} of 0.95 at 72°R Below MSL, ISA

4.2 Fault Signature Investigation

4.2.1 Fault Signatures with Constant N_{hp}

The fault signature as calculated using a constant corrected N_{hp} is plotted in Figure 29. As the fault signature does not change significantly in the range of $0.9 < N_{hp}/\sqrt{\Theta_2} < 1$, Figure 29 is an average fault signature over this speed range. The left hand axis depicts the percent change in the measured, corrected engine parameters displayed by the bars, while the right hand axis depicts the net temperature changes as shown by the symbols.

A brief examination of this graph on a component by component basis is most useful. A handling bleed valve leakage acts to increase the intake temperature to the compressor by mixing hot air from the mid section of the compressor with the intake flow. This temperature increase acts to increase the corrected mass flow for a given actual mass flow. The release of air at the bleed valve also acts directly to reduce the air mass flow through the combustion chamber and turbines. The latter effect means that the specific work

Figure 29 - Corrected Off Design Effects Averaged over $0.9 < N_{hp} < 1.0$ for Constant N_{hp}

required from the flow through the HPT is increased in order to continue to power the compressor. This requires an elevated HPT temperature drop, and hence an increase in the TIT. As seen in Figure 29, the ITT is not significantly changed. As a result, the lower gas mass flow through the PT will reduce the SHP of the engine.

Faults in the axial and centrifugal compressor stages have essentially the same effect on the measured performance parameters. A reduction in the compressor corrected flow reduces the amount of work which the HPT must produce. As a result the ITT and fuel flow required are reduced. The total airflow through the engine is also reduced and the combination of these factors reduces the power output of the engine. The reduced overall flows also lead to a reduced engine PR. When the compressor efficiencies are reduced, the effect upon the HPT turbine is the opposite to that for a flow reduction. More fuel must be injected to power the HPT, and as a result the ITT and EGT rise. With this temperature increase, the power output of the engine actually rises. However, the fuel flow into the engine increases even more than the SHP, and the overall cycle efficiency must decrease.

As can be seen in Figure 29, this engine cycle is most sensitive to degradations in the HPT. When the swallowing capacity of this turbine is increased, the required PR across it for a given intake corrected mass flow also decreases. To extract the same amount of work to power the compressor, the TIT must be raised in order to provide an adequate temperature drop across the turbine with the smaller PR. This translates into increased ITT, EGT and fuel flow. The HPT efficiency also has a tremendous impact on the engine performance. When the efficiency is reduced, a greater PR is required to maintain a constant temperature drop and work output. The thermodynamics of gas expansion requires that the TIT must increase to produce this higher PR. The higher TIT leads to higher values of the ITT and EGT which will increase the specific work output. As the air mass flow through the engine is relatively unchanged, the overall engine SHP will also increase. The fuel flow must also increase to provide these higher temperatures.

The power turbine corrected flow is also a significant factor in determining engine performance. An increase in its swallowing capacity will decrease the PR across it for a given corrected input flow. As a result of the component matching process, the PR across the HPT will increase for a given mass flow, which increases the specific work output of the HPT. This means that a lower TIT will now suffice to produce the required HPT temperature drop. The ITT, EGT and fuel flow must decrease as a result. The power turbine efficiency affects only the power output of the engine. This is expected because there is no work sharing between it and the other turbomachinery components of the engine.

As can be seen, a fault signature created as a function of the corrected gas generator spool speed provides significant predictions of changes in measured parameters of the engine. The fact that some of these parameters increase and some decrease with various faults is useful in isolating a fault which may be responsible for measured deviations in the trended parameters.

Sensitivities of the CDT have been plotted in Figure 29 for variations in the compressor efficiencies and the HPT efficiency and flow. As we shall see, faults in these four parameters are the most difficult to distinguish. For testing with a constant corrected spool speed, the CDT shows a similar trend as the PR. Unfortunately, the magnitudes of the changes in the CDT are such that the largest change of around 4°R is within the accuracy of a typical type K thermocouple as indicated by ANSI MC96.1 (1975). In addition, this parameter is not normally measured on the T400 engine, but was considered for a special test cell installation if warranted.

4.2.2 Fault Signatures with Constant SHP

As Saravanamuttoo and MacIsaac (1983) have found, it is often necessary to use fault signatures with more than one independent variable to isolate faults. Some faults may indicate similar effects on measured parameters when only one variable has been held constant. Therefore, we now expand our database by examining a fault signature created with the corrected SHP held constant. This approach is of interest to operators who want to maintain power even as an engine degrades in service.

The same range of corrected gas generator spool speeds have been considered here as for the previous fault signature. Again, it has been found that the changes in the fault signature over the range of corrected gas generator spool speed considered are small, so it has been decided to present an average of these results over a speed range from $0.9 < N_{hp} < 1.0$. These results are as in Figure 30.

Figure 30 - Corrected Off Design Effects Averaged over $0.9 < N_{hp} < 1.0$ for Constant SHP

Once again, it is useful to briefly examine the processes behind the changes which Figure 30 indicates in the measured parameters. With a handling bleed valve leakage, the increase in the intake temperature will cause an increase in the corrected intake flow which will in turn increase the work which the compressor must do. This increases the fuel flow and hot section temperatures required to maintain a constant engine SHP. It must be noted that while the corrected mass flow has increased, the actual mass flow will decrease.

As for the constant speed fault signature, the two compressor sections possess similar fault signatures. They will therefore be discussed together. On the basis of constant corrected SHP, a 1% drop in the compressor flow function does not have a measurable effect upon the engine performance. To maintain a constant power output, the gas generator spool speed and the ITT will both increase slightly. The combination of these changes acts to reduce the changes in the other measured variables. Compressor efficiency has a more significant impact. A reduction in efficiency increases the work load on the HPT, which in turn requires higher hot end temperatures and a higher fuel flow for a given output power. This in turn increases the specific work on the PT slightly. With a

higher specific PT work, a smaller corrected mass flow is required to maintain a constant SHP. A smaller mass flow through the compressor translates into a lower PR.

As for the constant gas generator speed fault signature, the changes are most sensitive to changes in the HPT condition. When the HPT flow function is increased, the PR across the turbine will decrease. Due to the thermodynamics of expansion, the TIT and the ITT must increase in order to maintain a constant work output. This higher ITT will also act to reduce the PR across the PT in a similar manner. The result of this is that the overall engine PR decreases, and the fuel flow increases. Changes in HPT efficiency affect the measured parameters in the same manner as for changes in the compressor efficiency.

As the work output of the PT is proportional to the product of the mass flow through and the temperature drop across it, an increase in the mass flow function will act to reduce the temperature drop across it for a given engine power output. As a result, the ITT will drop. Also, the gas generator spool speed must increase slightly to increase the corrected flow delivered to the PT. This causes the compressor to produce an increased PR. A decrease in PT efficiency forces an increase in the ITT and temperature drop across it. An increase in ITT requires an increase in the gas generator power output, which results in the rise in the fuel flow, PR and engine mass flow.

The fault signature generated through the assumption of constant engine SHP reveals that the changes in the more commonly measured engine parameters are different than if a constant gas generator spool speed had been assumed. Therefore, this fault signature increases the quantity of useful information for the diagnostics of engine faults. Another look at the CDT appears to provide a method to differentiate the effects of a compressor efficiency drop from an HPT efficiency drop as the trends are different for each. Once again, however, the total variation involved is small and it would be difficult to detect in practice until the engine damage has proceeded to an excessive amount.

4.2.3 Fault Signatures with Constant ITT

As a final investigation, it is desired to examine a fault signature determined by setting the corrected ITT constant. This is of interest because pilots monitor the ITT against a maximum limit. The gas generator spool speed range set for these tests are the same as for the previous two fault signatures discussed. The results of this check are as in Figure 31 below:

Figure 31 - Off Design Effects Averaged over $0.9 < N_{hp} < 1.0$ for Constant ITT

Figure 31 reveals that if the ITT/Θ_2 is held constant, the changes to all of the measured parameters are in the same direction except for the case of an increased PT flow function. As a result, given a set of changes in the measured parameters from the undamaged state, it would be difficult to determine which of the above faults were responsible using Figure 31. The usefulness of this fault signature is therefore very limited indeed. Therefore, we will not discuss it any further.

4.3 Use of the T400 Fault Signatures for Fault Detection

4.3.1 Compressor Faults

Having examined the effects of single faults above, it is now practical to consider the effect of flow and efficiency degradations in combination to see if the superposition of individual faults yields the same changes on the measured parameters as a multiple fault calculation. The procedure followed is similar to that employed by Dupuis, Saravanamuttoo and Rudnitski (1986) who studied the effects of different proportions of individual faults on overall engine performance. Various efficiency and flow degradations are applied to each component to determine if the combined effects of one could be determined from the individual effects. Tables 10 and 11 below depict the percent change from the undamaged condition for the indicated variables for the axial and centrifugal compressor sections respectively. The ITT and EGT changes are in degrees R. These numbers are an average of the results obtained from the normal operating range of the engine for which $N_{hp}/\sqrt{\Theta_2}$ is greater than 0.9 and less than 1:

Table 10 - Changes with Axial Compressor Faults - Constant $N_{hp}/\sqrt{\Theta_2}$

$\Delta\eta$ (%)	ΔW (%)	Corr SHP or TRQ (%)	Corr W_f (%)	Corr ITT (Deg R)	Corr EGT (Deg R)	Corr W_2 (%)	Corr PR (%)
-5.0	0.0	1.1	3.2	52	46	-1.5	-0.3
-5.0	-2.5	-0.6	1.9	45	42	-2.1	-1.1
-5.0	-5.0	-3.1	0.1	38	38	-3.2	-2.3
-2.5	-5.0	-4.4	-1.9	10	15	-2.8	-2.5
0.0	-5.0	-5.9	-4.1	-17	-8	-2.5	-2.9
Adding Rows 1 & 5		-4.8	-0.9	35	38	-4.1	-3.2

Table 11 - Changes with Centrifugal Compressor Faults - Constant $N_{hp}/\sqrt{\Theta_2}$

$\Delta\eta$ (%)	ΔW (%)	Corr SHP or TRQ (%)	Corr W_f (%)	Corr ITT (Deg R)	Corr EGT (Deg R)	Corr W_2 (%)	Corr PR (%)
-5.0	0.0	5.1	7.3	89	75	-1.2	1.3
-5.0	-2.5	3.5	6.1	83	71	-1.7	0.5
-5.0	-5.0	1.6	4.7	78	69	-2.5	-0.4
-2.5	-5.0	-1.0	1.0	32	31	-1.9	-1.1
0.0	-5.0	-3.6	-2.5	-10	-5	-1.5	-1.8
Adding Rows 1 & 5		1.5	4.8	79	70	-2.6	-0.5

Of interest here is the predicted response of the different measured parameters to the various fault combination scenarios. A decrease in efficiency increases the values for the torque, fuel flow and ITT, while a decrease in flow does the opposite. For each compressor section, efficiency and flow degradations both act to reduce the corrected flow into the engine. In the axial section these two faults act together to reduce the engine PR developed, while in the centrifugal section they counter each other. When the effects of efficiency and flow degradations counter each other, there is a point at which they will cancel themselves out. For each of the torque, ITT and fuel flow, this point occurs at a different ratio of efficiency and flow degradation. As a result, by comparing the changes in the measured parameters it should be possible to determine the ratio of the efficiency drop to the corrected flow drop. In each table, rows one and five have been added to determine if the superposition of individual faults provide an accurate reflection on the engine with both faults in effect. As can be seen the matches as compared to row 3 are not exact, but the trends and magnitudes are similar. The superposition process appears adequate for performance trending applications with respect to the compressor.

A comparison between Tables 10 and 11 reveals that the trends of the effects of efficiency or flow degradations in each compressor section are the same. As the centrifugal section performs more work on the air being compressed than the axial, changes in its performance exert greater changes on engine performance. However, it is the trends which are important here, and it is unlikely that an engine user could isolate a fault to one compressor section or another. The best that could be expected is to be able to determine

that a fault exists somewhere in the compressor, and an estimate of the ratio of the efficiency to flow degradation involved.

4.3.2 Use of the T400 Fault Matrix for HPT Faults

Now we will examine the HPT using the same process as that used for the axial compressor section. The one difference is the reduction in the extent of the component faults implemented to 2% from 5%. The engine performance is very sensitive to changes in the HPT condition, and this leads to large increases in the ITT and EGT. With 5% degradations in the HPT, we will exceed the maximum ITT limits by a considerable margin, and the results would have little meaning. When the maximum ITT limiter is active, it has the effect of forcing the engine to operate at lower power settings. With such a severe HPT fault, it would not be possible to operate the engine in the gas generator spool speed range of $0.9 < N_{hp}/\sqrt{\Theta_2} < 1.0$. The results of these runs are shown in Table 12.

Table 12 - Changes with HPT Faults - Constant $N_{hp}/\sqrt{\Theta_2}$

$\Delta\eta$ (%)	ΔW (%)	Corr SHP or TRQ (%)	Corr W_f (%)	Corr ITT (Deg R)	Corr EGT (Deg R)	Corr W_2 (%)	Corr PR (%)
-2.0	0.0	4.1	5.0	66	55	-0.7	0.8
-2.0	-1.0	6.2	6.9	84	69	-0.4	0.5
-2.0	-2.0	8.2	8.8	103	83	-0.2	0.2
-1.0	-2.0	6.1	6.1	69	55	0.2	-0.2
0.0	-2.0	3.9	3.5	36	27	0.5	-0.7
Adding Rows 1 & 5		8.0	8.5	102	82	-0.2	0.1

Here, we see clearly the extent of the influence that the HPT efficiency has on the T400 engine performance. The effects of efficiency degradation and turbine erosion on the torque, fuel flow and ITT combine to produce very large changes in the overall engine performance. These three parameters all increase as the turbine condition worsens and show nearly identical trends. The engine PR and air flow are the only parameters commonly measured which are affected differently by degradations in efficiency and

corrected flow. A decrease in HPT efficiency increases the overall PR, while an increase in turbine swallowing capacity acts to decrease it. The opposite applies to the mass flow. As the mass flow is not commonly measured, changes in the PR provide the principle manner in which the ratio of efficiency to corrected flow degradation may be estimated.

Due to the large changes in engine performance as a result of HPT faults, it should not be a problem to determine if a problem exists in this component. The main exception is the compressor efficiency as we shall see later. As most of the trends of the changes above are in the same direction, it is difficult to isolate whether it is an efficiency or flow degradation based on the trends alone. Generally, it is the turbine efficiency that is affected, and this may serve as a starting point for a fault investigation. A brief look at the summation of the effects of the efficiency and flow degradations by comparing the shaded rows reveals that the principle of superposition of single faults is again sufficiently accurate in this case.

As a final note, Table 12 indicates large increases in ITT and SHP for a given spool speed. It must be remembered that this will not translate into a significant increase in the maximum power output of the engine, as there are limits on the maximum engine torque, SHP, mechanical N_{hp} and ITT. If the engine is held within these limits, it follows that the power setting of the engine must be reduced. The result of this will most probably be a reduction in the maximum engine power which may be obtained in practice.

4.3.3 PT Faults

As can be seen from Table 13, it is not very difficult to understand what is happening within the PT. Faults involving the PT efficiency affect the SHP and EGT temperatures only. If the SHP is dropping and the EGT is rising, with no other variable changing, a degradation in the PT efficiency is a likely suspect.

Table 13 - Changes Due to PT Faults - Constant $N_{hp}/\sqrt{\Theta_2}$

$\Delta\eta$ (%)	ΔW (%)	Corr SHP or TRQ (%)	Corr W_f (%)	Corr ITT (Deg R)	Corr EGT (Deg R)	Corr W_2 (%)	Corr PR (%)
-5.0	0.0	-5.9	0.0	0	17	0.0	0.0
-5.0	-2.5	-11.2	-4.0	-52	-20	0.5	-0.7
-5.0	-5.0	-16.2	-7.6	-99	-54	0.9	-1.4
-2.5	-5.0	-13.6	-7.6	-99	-61	0.9	-1.4
0.0	-5.0	-11.0	-7.6	-99	-69	0.9	-1.4
Adding Rows 1 & 5		-16.8	-7.6	-99	-52	0.9	-1.4

An increase in the swallowing capacity of the PT will have the effect of lowering all parameters above except for the engine air mass flow which changes only imperceptibly. This is a fairly unique signature. A decline in the compressor flow function has a similar effect on the engine performance, although the changes in the corrected ITT and EGT are much greater for the PT fault. Also, if the engine air flow is measured, this would reveal the difference, as for the compressor this parameter would drop as opposed to increasing for a PT fault.

4.3.4 Multiple Faults

Next, an examination of faults from different components will be performed to determine if the principle of the superposition of individual component faults may be applied throughout the engine. In practice, the axial compressor flow is more affected than the efficiency for faults such as compressor fouling, as shown by Saravanamuttoo and Lakshminarasimha (1985), while the turbine corrected flow does not generally vary to a great extent. Therefore, it has been decided to examine the case of a 2% reduction in the axial compressor section corrected flow and a 2% reduction in the HPT efficiency. These lower values have been chosen to keep the ITT within a reasonable limit. The result of this check is shown in Table 14.

Table 14 - Changes Due to Axial Compressor Section and HPT Faults - Constant $N_{hp}/\sqrt{\Theta_2}$

HPT $\Delta\eta$ (%)	Axial ΔW (%)	Corr SHP or TRQ (%)	Corr W_f (%)	Corr ITT (Deg R)	Corr EGT (Deg R)	Corr W_2 (%)	Corr PR (%)
-2.0	0.0	4.1	5.0	66	55	-0.7	0.8
-2.0	-1.0	3.4	4.5	63	53	-1.0	0.5
-2.0	-2.0	2.6	3.9	61	52	-1.3	0.1
-1.0	-2.0	0.5	1.4	27	24	-1.0	-0.3
0.0	-2.0	-1.6	-1.1	-5	-2	-0.7	-0.8
Adding Rows 1 & 5		2.5	3.9	61	52	-1.4	0.0

As can be seen above, changes in the HPT efficiency and axial compressor flow function act in opposite directions for most of the parameters. Therefore, it should not be a problem to estimate the relative proportion of each fault present if it is known that damage is confined to the HPT and the compressor. The trends due to degradations in HPT efficiency are similar to those involving compressor efficiency. The larger increases in fuel flow, SHP and ITT as compared to the engine PR or corrected mass flow for the HPT fault seem to offer a way of distinguishing the two.

A check involving the addition of the fault signatures for the axial compressor flow fault and the HPT efficiency fault indicates that the principle of superposition of faults is again reasonable in this case, with the hot section temperatures showing the best agreement.

Another case of interest involves differentiating between efficiency reductions in the compressor and the HPT. Following the same process above, the same efficiency reduction was implanted in both the axial and centrifugal compressor sections. This is done to examine a situation which will be encountered in Chapter 5. The results of this study are in Table 15.

Table 15 - Changes Due to Compressor and HPT Efficiency Reductions - Constant $N_{hp}/\sqrt{\Theta_2}$

Comp. $\Delta\eta$ (%)	HPT $\Delta\eta$ (%)	Corr SHP or TRQ (%)	Corr W_f (%)	Corr ITT (Deg R)	Corr EGT (Deg R)	Corr W_2 (%)	Corr PR (%)
-2.0	0.0	2.4	4.0	54	46	-1.0	0.4
-2.0	-1.0	4.4	6.5	88	74	-1.4	0.8
-2.0	-2.0	6.5	9.2	123	104	-1.8	1.1
-1.0	-2.0	5.3	7.1	94	79	-1.2	1.0
0.0	-2.0	4.1	5.0	66	55	-0.7	0.8
Adding Rows 1 & 5		6.5	9.0	120	101	-1.7	1.2

As can be seen, the fault signatures for the two faults are essentially the same. They are so close to each other that it would be nearly impossible to isolate an efficiency reduction to the component level. The best which could generally be achieved is to detect that an efficiency reduction somewhere in the gas generator section of the engine has occurred.

4.3.5 Handling Bleed Valve leakage in Combination with Other Faults

One of the most common engine faults on the T400 is a leakage or faulty scheduling of the handling bleed valve. The handling bleed operation is as described in Figure 53 for the NRC T400 model. In the real engine, it is triggered by two pressures. Air is bled off from the compressor delivery and flows through a venturi tube to produce a control pressure on the back side of the handling bleed valve. The compressor inter-stage pressure P2.5 acts on the inside of the valve. It is the ratio of these two pressures which cause the actuation of the valve. Debris ingested into the engine may abrade the valve seal or alter the control pressure. This could cause a bleed leakage or a change in the handling bleed schedule. In either case, the result is that compressed air at the exit of the axial compressor section is bled off and re-injected at the compressor entrance. This both reduces the air mass flow through the engine after the axial compressor and increases the intake temperature. Here, we shall examine the effect of such a leakage in combination with faults in the axial compressor or HPT.

4.3.5.1 Axial Compressor and Handling Bleed Faults

In Tables 16 and 17 below, we repeat the process used above to examine a combination of a handling bleed valve leakage and an axial compressor fault. The resulting changes in the parameters tabulated are each unique to their respective combination of faults, and should therefore be readily recognizable.

Table 16 - Handling Bleed and Axial Flow Faults - Constant $N_{hp}/\sqrt{\Theta_2}$

Axial ΔW (%)	Δ Bleed/ W_2 (%)	Corr SHP or TRQ (%)	Corr W_f (%)	Corr ITT (Deg R)	Corr EGT (Deg R)	Corr W_2 (%)	Corr PR (%)
-5.0	0.0	-5.9	-4.1	-17	-8	-2.5	-2.9
-5.0	2.5	-9.8	-6.1	-18	-3	-2.3	-5.1
-5.0	5.0	-14.4	-8.7	-23	0	-2.3	-7.6
-2.5	5.0	-8.4	-4.2	0	12	0.3	-4.6
0.0	5.0	-3.2	-0.5	19	22	2.5	-2.1
Adding Rows 1 & 5		-9.1	-4.5	2	14	-0.1	-5.0

Table 17 - Handling Bleed and Axial Efficiency Faults - Constant $N_{hp}/\sqrt{\Theta_2}$

Axial $\Delta \eta$ (%)	Δ Bleed/ W_2 (%)	Corr SHP or TRQ (%)	Corr W_f (%)	Corr ITT (Deg R)	Corr EGT (Deg R)	Corr W_2 (%)	Corr PR (%)
-5.0	0.0	1.1	3.2	52	46	-1.5	-0.3
-5.0	2.5	0.6	3.7	64	58	0.2	-0.8
-5.0	5.0	-0.4	4.0	78	73	1.6	-1.5
-2.5	5.0	-1.8	1.8	48	47	2.1	-1.8
0.0	5.0	-3.2	-0.5	19	22	2.5	-2.1
Adding Rows 1 & 5		-2.1	2.7	71	68	1.0	-2.4

For Table 16, the corrected SHP and fuel flow are reduced both by the handling bleed and the compressor flow reduction. These faults are additive. However, the axial compressor section flow reduction causes the ITT and EGT to drop, while the handling bleed does the opposite. From this, it is possible to roughly estimate the proportion of the axial compressor flow reduction to the handling bleed flow. Superposition does not seem to work here for the ITT or the EGT. However, the changes in both are fairly small, and in

the opposite directions for each of the faults considered. As such, this is not of great significance.

In Table 17, we see that when we have an axial compressor efficiency reduction simultaneously with a handling bleed leakage, the resultant fault signature is different than that for the axial section flow reduction. In this case, both effects cause the ITT and EGT to rise significantly. Decreases in the axial compressor efficiency act to increase the SHP and fuel flow, while increases in the handling bleed do the opposite.

4.3.5.2 Handling Bleed Leakage and HPT faults

As a final step, we now examine the fault combination closest to that of Table 17. Here, a handling bleed valve leakage is combined with a reduced efficiency for the HPT. The resulting fault matrix is quite similar due to the fact that the trends for a compressor or HPT efficiency reduction are in the same directions. Superposition works very well in this case. For the HPT efficiency reduction, the changes in SHP and fuel flow tend to be somewhat larger compared to the changes in the PR. However, in the field it would be difficult to distinguish the two combinations of faults.

Table 18 - Handling Bleed and HPT Efficiency Reduction - Constant $N_{hp}/\sqrt{\Theta_2}$

HPT $\Delta\eta$ (%)	$\Delta\text{Bleed}/$ W_2 (%)	Corr SHP or TRQ (%)	Corr W_f (%)	Corr ITT (Deg R)	Corr EGT (Deg R)	Corr W_2 (%)	Corr PR (%)
-2.0	0.0	4.1	5.0	66	55	-0.7	0.8
-2.0	-1.0	3.9	5.2	70	59	0.0	0.6
-2.0	-2.0	3.5	5.3	75	64	0.6	0.3
-1.0	-2.0	1.4	2.7	42	36	0.9	-0.1
0.0	-2.0	-0.7	0.2	9	9	1.2	-0.5
Adding Rows 1 & 5		3.4	5.2	75	64	0.5	0.2

4.4 Differentiating Between Difficult to Isolate Faults

From the faults identified above, there are a few which can be seen to be difficult to differentiate. These include the compressor and HPT efficiencies, and the HPT corrected flow. The reason for this is that the trends in the measured parameters are the same for each of them. The relative magnitudes of the fault signatures of one fault as compared to another are of no use, because a 2% reduction in the compressor efficiency might give an identical signature to a 1% reduction in the HPT efficiency. The only other method by which one of the above faults may be isolated from the others is through the examination of the relative changes of one parameter as compared to another. For example, if the SHP increases by 1% from its nominal value and the fuel flow increases by 2%, we have a 1:2 ratio between these parameter changes. This ratio may be helpful in isolating one component fault from another.

To pursue this premise further, Figures 32 and 33 are presented below. In these two figures, the temperatures have been normalized by dividing by the corrected ITT change, and all other parameters have been normalized by dividing by the corrected fuel flow percentage change. These parameters were chosen because the changes due to the various faults above are fairly uniform. These figures present data obtained from model runs with $0.9 < N_{hp}/\sqrt{\Theta_2} < 1.0$.

Figures 32 and 33 indicate that one should be able to distinguish an increase in the HPT swallowing capacity from efficiency degradations in the compressor or the HPT. The results obtained when $N_{hp}/\sqrt{\Theta_2}$ is held constant are similar except for the difference in the trends in the PR and intake air flow for the HPT flow increase. The constant SHP results are more definitive as for the HPT flow increase as we see a large increase in the change in the PR as compared to the other parameters. Due to the comparatively large parameter changes due to faults in the HPT, this difference in the ratios between the various parameter changes should be detectable.

Figure 32 - Changes in Parameters for Constant Corrected N_{hp} Normalized by % Change in W_f and ITT Temperature Change

Figure 33 - Changes in Parameters for Constant Corrected SHP Normalized by % Change in W_f and ITT Temperature Change

The unfortunate results are that degradations in the compressor efficiency and the HPT efficiency both cause the same trends in the parameter changes and the same relative magnitudes between these parameter changes. There seems to be no easy way to isolate these faults on a steady state off design thermodynamic analysis alone. In the constant

$N_{hp}/\sqrt{\Theta_2}$ plot, there seems to be a reversal in the PR trend between axial and centrifugal compressor sections. This trend is very small, and is unlikely to be measurable in practice.

4.5 Conclusions - Thermodynamic Fault Study

From the results discussed with multiple faults, the following general conclusions may be made. It appears to be possible for compressor faults to isolate the relative ratio of a flow function degradation from an efficiency drop. However, it is not readily possible to isolate such a fault to the axial or centrifugal compressor sections. Furthermore, while it seems that compressor flow degradations give a unique signature, compressor efficiency reductions show the same trends as for an HPT efficiency reduction. Hence, it would be difficult to distinguish these two faults from each other based on thermodynamic means alone.

An examination of the magnitudes of the parameter changes reveals that the engine is less sensitive to faults when the SHP is held constant than if the N_{hp} is held constant. Therefore, it is recommended that the fault signature for constant N_{hp} be consulted first by the engine user as faults will show up here earlier. From the studies which have been performed, it does not seem that the CDT is a particularly useful parameter for the purpose of fault detection.

The T400 engine is most sensitive to faults in the HPT. HPT efficiency and flow faults are not readily distinguishable from each other as for most of the measured parameters these effects add. For the PR, these two faults do act in opposite directions with efficiency faults causing an increase, and an increase in the flow function causing a decrease in the PR. From experience in the field, the probability of an efficiency reduction in the HPT is far greater than a flow increase. As such, it is usually most effective to investigate an efficiency reduction first. The large changes due to HPT faults may allow a problem to be localized to it, but this cannot be guaranteed as compressor and HPT efficiency reductions

have similar fault signatures. It would be difficult, but possible, to diagnose whether a problem is due to a flow change or an efficiency reduction in the HPT.

For PT faults, it has been found that their fault signatures are fairly unique, and it should not be difficult to either isolate a fault to this component or estimate the ratio of efficiency reduction to flow change. As damage to this component is not common, these facts are of limited value.

Handling bleed leakages may be readily distinguished from other faults which may occur in the turbomachinery due to their unique fault signature.

Finally, the principle of superposition of individual fault signatures at part power seems to be a valid one in performance trending, based on trends observed through the use of a multiple fault simulation in the NRC T400 model.

4.6 Fault Diagnosis in the T400 Engines Under Test at the NRC

Using the fault signatures developed and discussed above, it is now desired to examine the T400 engine presently under test here at the NRC. Each power section will be examined separately. The normal procedure would be to compare the engine fault signature against a baseline set of data taken immediately after the most recent overhaul of the unit. This would isolate changes in the engine performance due to degradation since that overhaul. Unfortunately, this baseline is not available within the engine log books. Therefore, we shall use the nominal NRC T400 model as our baseline. While the NRC T400 model is not as useful as test data immediately after overhaul, it will allow the comparison of the tested engine performance with the minimum guaranteed ratings. Also, as the same baseline will be used for both power sections, a comparison of the states of the two power sections will be possible.

The procedure used is fairly simple in nature. These runs were performed using the stock Bell 212 installation with the exception of the stock oil coolers not being used. Figure 49 shows some of the details of this installation. For the measured parameters, we have obtained the SHP, W_f , W_2 , ITT, and the compressor delivery pressure. The mechanical N_{hp} and N_{pt} , and compressor inlet temperatures have also been measured and used to set the engine operating state in the NRC T400 model. These data have been corrected to MSL, ISA conditions. The NRC T400 model with no faults implemented has then been used to predict the above performance variables corrected to MSL, ISA conditions for a nominal engine. The differences between the data obtained from the test stand and the NRC T400 model predictions provides us with a deviation signature of the engine with respect to the nominal engine ratings. Test Runs 20, 21 and 22 were used to assess the measured engine performance.

4.6.1 Power Section 1 - Serial Number 78095

Figure 34 below reveals the performance of power section 78095 as compared to that of the NRC T400 model engine.

Figure 34 - Performance of Power Section 78095 as Compared to NRC T400 Model

As can be seen in Figure 34, all of the measured parameters considered are lower than the NRC T400 baseline. Based on the results of this chapter, we may point to a list of faults which may be contributing to this situation. A reduction in compressor or HPT flow, or an increase in the PT flow, will cause a fault signature as shown in Figure 34. A handling bleed valve leakage will act to lower the SHP and PR, but will cause an increase in the other three parameters.

4.6.2 Power Section 2 - Serial Number 78117

In Figure 35, power section 78117 shows a similar set of trends as compared to the NRC T400 model as power section 78095. The main difference is that for this run the ITT is reduced only by a small amount. The reduction is nearly within the 9°R accuracy of the ITT measurement system. A glance at Figure 14 in Chapter 3 reveals that the measured ITT for this engine has increased. This is because for the engine runs displayed in Figure 14 a much simpler inlet system with only a bellmouth was used to measure the flow. This caused a slight installation variation between the results of runs used in Chapter 3, and those in Chapters 4 and 5.

Figure 35 - Performance of Power Section 78117 as Compared to NRC T400 Model

4.6.3 Analysis of Results

As mentioned earlier, Lakshminarasimha, and Saravanamuttoo (1985) have shown that fouling of a compressor acts primarily to reduce flow, and has only a minor impact on the efficiency. As such, it would seem at first that this could be a possible explanation. However, both power sections were washed thoroughly when they arrived at the NRC. Furthermore, the test cell is located on a fairly unpolluted area in the Montreal Road NRC campus and the engine has accumulated perhaps 20 hrs of testing time since it was washed. As such we may assume that fouling is not a significant factor.

There are also installation losses in effect for the tested T400 engine which are not implemented in the nominal NRC T400 model. An installed T400 engine uses exhaust air in an ejector to move a flow of air around the engine. This induced air flow is used for the purpose of inertial separation. As a result of the operation of this device, some back pressure is created on the exhaust nozzle of the engine. Unfortunately, no “hard” data are available on the magnitude of this loss, but Davis Engineering (1997) indicates that the losses due to this are roughly from 5 to 20 SHP. A negligible loss in intake pressure at the compressor face is indicated, while only minor losses are indicated in the exhaust. This situation will have the primary impact of reducing the SHP and increasing the ITT. To account for what has been observed, we must look farther.

Both power sections have been in service for almost 4000 hrs each since their last overhaul. Power section 78117 has spent much of this time in the Sinai peninsula. It is plausible that sand ingestion and regular in service degradation has affected the observed engine performance.

Turyk (1989) discusses three possible modes of damage to turbomachinery which correspond to this type of damage. He states that one possible mode of damage is a compressor tip clearance increase, for which the major impact on component performance involves the reduction of pressure rise capability and efficiency. Essentially, this translates

to a shifting of the compressor map to the left. A second mode of damage discussed is increased surface roughness. This will cause a reduction in the mass flow, pressure ratio and efficiency of the component. The third mode discussed is blade leading edge erosion. A blunt leading edge will cause a significant pressure increase on the suction surface, which may cause boundary layer separation on the blade. Testing on a J57 engine showed a 4% reduction in the air mass flow through the engine after 346 kg of dust had been ingested (Dunn et al., 1987).

From our discussion, we can see that there are forms of engine damage which will cause performance changes which correspond to what has been observed for the two power sections examined here. Unfortunately, it is not possible to make firm conclusions about what mode of damage has actually occurred without more information on the life history of the power sections in question. We are able to isolate damage to section of the engine such as the compressor or HPT, but cannot go on to say what type of damage occurred within the component. More study is required to allow a consistent linkage of such damage to observed changes in engine component performance.

Chapter 5

Power Assurance and the Topping Test

As seen above, the creation and usage of fault matrices can be an important way to locate faults in the various components of an engine. However, the primary concern of field personnel is to ensure that the engine in question will produce an adequate power output under any conditions that a helicopter may encounter in flight. While locating a fault enables the repair of the component in question, the decision to do so will depend to a large degree on the results of power assurance testing carried out on the engine.

Therefore, a complete picture of engine health should provide an indication of the maximum output power of the engine. A process has been developed in which the NRC T400 software will be able to match the performance of an engine under test through the manipulation of the component characteristics. Once this has been achieved, further “testing” may be performed to obtain an estimate of the maximum power output of this tested power section using a computer model as opposed to the actual engine.

The discussion to follow will involve the examination of the effect of limits placed upon the maximum mechanical N_{hp} , ITT, and torque (TRQ). Combinations of faults of various severity will be applied to the NRC T400 model to determine their impact on the maximum power section power output under various ambient conditions. The procedure of the Canadian Forces Topping test will be explained and a substitute for it using the NRC T400 model will be developed. This NRC T400 Topping procedure will then be applied to faulted engines generated by both computer modeling and from test data obtained from the T400 engine at the NRC.

5.1 Engine Limiters and Faults

In practical applications, there are a variety of factors which act to limit the maximum power output of a gas turbine engine. The gas generator mechanical spool speed must

remain within limits so that stresses within the disks and blades remain at safe levels. The TIT and hence the ITT must be controlled to avoid over-temperatures which may melt or weaken the turbine section of the engine. Also, the gearbox and transmission on the engine have maximum limits on the amount of torque which may be transmitted without causing damage. For the T400 engine as installed on the Bell 212 helicopter, the most important limits with respect to the topping test are as in Table 19 (CFTO C-14-300-000/MN-000, 1992).

Table 19 - Engine Limiters Affecting Topping Test

Limiter	Maximum Rating	Absolute Mechanical Limits
TRQ	800 lb·ft	857 lb·ft
N_{hp}	37,800 RPM	38,100 RPM
ITT	1950 °R (Trimmed)	2040 °R (Actual)

The trimming of ITT values has been mentioned in Table 19. In reality, small differences from engine to engine mean that the measured ITT will vary for a given power setting. This would be confusing to the pilots who need fixed values for monitoring purposes. Therefore, an ITT trim limiter box is installed which corrects the measured ITT to the rated values of ITT for the engine power setting. These corrections may be summarized by the following two equations (P&WC, 1996):

$$\frac{ITT_{Trimmed}}{\Theta_{amb}} = \frac{ITT_{Thermodynamic}}{\Theta_{amb}} - 60^{\circ} R$$

$$ITT_{Trimmed} = ITT_{Measured} - \Delta T_{Trim}$$

The first equation refers to the setting of the trimmed ITT with respect to the thermodynamic ITT. The thermodynamic ITT is determined though the measurement of the power section EGT, SHP, fuel flow and air mass flow. From these, conservation of

work may be applied to the power turbine to find the thermodynamic ITT. On a production engine, a trimming adjustment ΔT_{trim} is applied to set the measured ITT equal to this standard thermodynamic ITT-60 °R. For the results to follow, the thermodynamic ITT may be assumed unless indicated otherwise.

As a final note, the ratings in Table 19 are for emergency power from one power section if the other fails. The maximum torque rating of the Bell 212 gearbox of 1028 lb-ft effectively limits the engine power output for normal dual power section operation.

These limiters apply to the T400 engine and combining gearbox with single power section operation. With standard GASTURB features, NRC T400 is capable of modeling the engine with these limiters active. The power setting of the engine can only be increased until one of the above limiters is reached. It will then determine the maximum output SHP the engine is capable of producing at this point, and indicate which of the above limiters is active.

5.2 Maximum Obtainable Engine Power Output for Single Faults

To understand the behavior of a faulted engine with respect to maximum power output, it is useful to examine a series of engines using the NRC T400 model. Each engine has an implanted fault of varying severity. By performing the above procedure using the NRC T400 model, it will be possible to determine the mechanism by which each engine fault examined in Chapter 4 will reduce or increase the maximum engine power available. We will also determine the sensitivity of this maximum power to the fault severity, ambient conditions of temperature and pressure, and the ratios of the various performance degradations which may be present. Each of the faults examined in Chapter 4 has been examined individually here. The one exception is the compressor. Here, the two compressor sections have been combined and the same faults are applied to both simultaneously.

5.2.1 Maximum Power at MSL, ISA

In Figure 36 the maximum power output of the engine has been plotted with respect to the fault severity at MSL, ISA conditions. These faults include the efficiency of the compressor, and the flow functions of the HPT and centrifugal compressor section. The plot is normalized with respect to the rated power of 900 SHP for each power section under these conditions. It should be noted that the model predicts slightly more than 900 SHP with no implanted faults. The limiter which is responsible for the power reduction for each fault is specified in the legend. An interesting result of this investigation is that three of these faults actually act to increase the maximum engine power obtainable.

Figure 36 - Maximum SHP with Respect to Fault Severity, MSL, ISA Conditions

In examining Figure 36, we must remember that the NRC T400 model with no faults implemented represents the minimum guaranteed performance of the T400 engine to be expected in service. It does not take installation effects such as running the inertial particle separators or oil cooling fans into account. The Maximum Rating limiters of Table 19 have been used with the power turbine mechanical speed at the design value. For the minimum guaranteed engine performance at MSL, ISA conditions we never reach

the TRQ limit on either the T400 or Bell 212 gearboxes. This limiter therefore doesn't play a role in this case. As a final note, only the mechanical N_{hp} and N_{pt} have speed limits for which there is automatic limiting by the speed governors. The N_{pt} is limited at a design speed of 33,000 RPM. The remaining variables are displayed in the Bell 212 cockpit and are held within limits by the pilots.

In Figure 36, the engine power with no implanted faults is limited by N_{hp} . The faults which act primarily to increase the N_{hp} for a given output SHP will reduce the SHP obtainable before this limit is reached. For these faults the maximum SHP lines show a linear decline as the fault severity increases. Degradations in the compressor and HPT efficiency and the HPT flow act primarily to increase the ITT for a given SHP. As a result, when these faults are of a small magnitude the N_{hp} is still the active limiter. The increase in the ITT which these faults cause acts to increase the SHP of the engine. Eventually, the trimmed ITT limit is hit, and engine power output then must drop with increasing fault severity to maintain it within limits.

5.2.2 Maximum Power at 10,000 ft, ISA

When the performance of an engine component is degraded, one is not only concerned with the engine performance at MSL, ISA conditions. The ambient temperatures and pressures at the compressor intake will vary to a large degree over the flight envelope of a typical helicopter. To examine the engine behavior at altitude, Figure 37 has been plotted for operation at 10,000 ft, ISA in a similar manner as Figure 36. The peak power output of the engine has dropped due to the drop in air density at altitude. For a given engine operating state, a lower mass flow of air is moving through the engine, and so a lower power output is obtained. The active limiter for the nominal NRC T400 at 10,000 ft ISA is the ITT. As such, any fault which acts to increase the ITT for a given fault, even if this effect is a minor one, will serve to reduce the available engine power for the limiting ITT.

A reduction in the compressor corrected flow increases both N_{hp} and the ITT. When this fault is small in magnitude, the increase in ITT caused by it dominates in the power reduction as we started out being limited by this parameter. However, the N_{hp} is increasing faster than the ITT, and we eventually hit this limiter. The result is the “kink” in this line in Figure 37 when a 4.5% reduction in the flow has been reached.

An increase in the PT corrected flow acts to rapidly increase N_{hp} . As such, it demonstrates the same behavior in Figure 37 that the compressor and HPT efficiencies do in Figure 36.

Figure 37 - Maximum SHP with Respect to Fault Severity, 10,000 Ft, ISA Conditions

5.2.3 Maximum Power on Hot Day Conditions

Figure 38 examines the case of a hot day which is 45°R above MSL, ISA or 40°C at sea level. Again, the higher ambient temperature acts to reduce the density of the air entering the engine. For a given corrected intake flow, the actual mass flow decreases. As can be

seen, an increase in ambient temperature has a similar effect on the maximum engine power output as a decrease in ambient pressure. Once again, it is a high ITT which is the limiting factor on power output for an undamaged engine. However, for this case the power reductions are less severe than those experienced at 10,000 ft. For all of the flow degradations except for that of the HPT, the gas generator mechanical spool speed becomes the limiting factor as the airflow must be maximized to maintain power. One might expect that a reduction in the axial compressor efficiency would affect the engine power in a similar manner as that for the centrifugal compressor or HPT. However, the greatest impact of this axial compressor fault is an increase in the gas generator spool speed. Two thirds of the compression work is performed in the centrifugal compressor section. A decrease in axial compressor efficiency will cause an increase in the air temperature entering the second compressor section. This will increase the corrected flow in this section of the engine for a given actual mass flow. To keep the actual mass flow up, the gas generator spool must spin faster.

As the ambient temperature drops, we see a change from the ITT to the N_{hp} as the primary limiter. Also, the output power of the engine increases above the rated power at MSL, ISA. The case for a hot day has been illustrated because it is a “worst case” scenario at sea level in terms of power output. Throughout Figures 36 to 38, we have seen that the effect of an HPT efficiency reduction is almost identical to that of a compressor efficiency reduction. Also, the maximum engine SHP becomes more sensitive to component decay at higher altitudes or temperatures. This is a reflection of the lower power outputs obtainable under such conditions. If a high ambient temperature increases the compressor work required, a loss of compressor efficiency will aggravate this problem.

Figure 38 - Maximum SHP with Respect to Fault Severity, +45°R Above MSL, ISA

5.3 Multiple Component Faults and Maximum Power Output

As a next step, we shall examine the effects of multiple faults on the maximum power output. Three fault combinations have been investigated. The first two include a handling bleed valve leakage in combination with either an HPT efficiency reduction or a compressor flow reduction. The third case involves a combination of a compressor flow and HPT efficiency reduction. These three fault combinations which have been modeled case the failure of the Topping test by a considerable margin. The purpose of this investigation is then to determine how combinations of well established faults will interact together to determine the maximum engine power output.

5.3.1 Compressor Flow and HPT Efficiency Degradations

Some combinations of faults may produce considerably different results than another combination of the same two faults. Figure 39 illustrates this point.

Figure 39 - Effect of Compressor Flow and HPT Efficiency Reduction on Maximum SHP at MSL, ISA

In Figure 39, a close examination reveals that the superposition process used in Chapter 4 no longer is valid. The power reduction for the 6% compressor flow and 6% HPT efficiency faults acting together is not the same as the sum of the two as in Figure 36. The peak for the maximum SHP curve of Figure 39 does not correspond to the same HPT percent degradation as in Figure 36. Also, in Figure 36 we never see the maximum SHP increasing as the compressor flow fault severity increases.

This complex behavior results because each of these faults acts to limit the engine power in a different way. An HPT efficiency reduction acts primarily to increase the ITT, while a compressor flow reduction acts to increase N_{hp} . As the engine is more sensitive to the HPT efficiency than the compressor flow, the effect of the HPT efficiency dominates. When this is so, the active limiter will be the ITT. Towards the left hand side of Figure 39, the HPT efficiency is dominant, and the compressor flow reductions imposed act both to reduce the flow through the engine and the ITT. The flow reduction acts to reduce engine power, while the reduction in the ITT resulting from this counteracts the action of

the HPT fault to increase the ITT. This would serve to increase the maximum engine power obtainable before the ITT limit is hit. The conflict between these two processes is responsible for the flat curve, and makes the process of superposition of the effects of the two invalid.

The process of superposition assumes that the two effects being added are linearly independent of each other. In Chapter 4, this was essentially the case. The process of placing maximum limits on certain variables and running the engine until one of these limits is hit forces a change in the engine power setting in addition to the changes due to the faults themselves. Essentially, we are adding the effects of the two faults and then “chopping” the result using a maximum power limit. This “chopping” is a non linear effect.

5.3.2 Handling Bleed Leakage and Compressor Flow Reduction

A somewhat different scenario emerges when a combination of a handling bleed leakage and a compressor flow reduction is investigated. Both faults act to increase the mechanical N_{hp} required for a given power output, and the effects of these two faults in combination are additive as seen in Figure 40.

A handling bleed leakage acts to reduce the flow through the hot section of the engine, and in the centrifugal section of the compressor. The result is that the gas generator must spin at a faster rate to maintain the engine mass flow required to maintain power. A further reduction in the air mass flow due to an axial compressor section flow reduction will reinforce this trend to provide the results as seen in Figure 40. It should be noted that the apparent validity of adding the effects of the two independent faults in this case is due only to the fact that they act on the N_{hp} and ITT in a similar manner for a given SHP. In general, this will not be the case.

Figure 40 - Effect of Handling Bleed Leak and Compressor Flow Reduction on Maximum SHP

5.3.3 Handling Bleed Leakage and an HPT Efficiency Loss

In our final case, we examine a combination of a handling bleed valve leakage and an HPT efficiency reduction. The results of this case are plotted in Figure 41.

In this case, we have two faults which, when acting independently, limit the maximum power through different limiters. An HPT efficiency reduction primarily acts to increase the ITT, while a handling bleed leakage increases both the N_{hp} and the ITT. For the left hand side of Figure 41 the two faults act in an additive manner as in Figure 40, as opposed to countering each other as in Figure 39. However, on the right hand side they do not. If they did, we should see a peak in the curve as in Figure 36 for decreases in the HPT efficiency. On the left hand side of Figure 41, the trimmed ITT is the active limiter and remains so as the handling bleed is varied. In this condition, the handling bleed acts simply

Figure 41 - Effect of Handling Bleed Leak and HPT Efficiency on Maximum SHP

to reduce the flow through the power turbine, and hence the available SHP. This reduction in the hot section mass flow acts to increase the ITT as a means of maintaining output SHP. On the right hand side of Figure 41 with no HPT fault active, the effect of the handling bleed has been to reduce the gap between the maximum SHP available when the active limiter is the N_{hp} or the trimmed ITT. Therefore, even a small HPT efficiency reduction causes the trimmed ITT limit to be reached, and the power output is reduced.

5.3.4 Superposition of Faults

As we have seen, the interaction of engine faults and power limiters is quite complex. Factors which may decide whether an engine passes or fails the Topping test include the severity of individual faults, the nature of individual faults in combination, and the ratio of the degradations involved in two or more faults. The maximum power obtainable may also vary greatly with the ambient temperature and pressure. As a result, one cannot use the superposition of the effects of multiple faults in the evaluation of the Topping test. Such principles which work in fault trending do not necessarily apply to power assurance. To

predict with any accuracy the maximum engine power available without performing an engine test, it will be necessary to use a thermodynamic performance model such as NRC T400 which is capable of taking all of the significant variables into account. The user of such software should still examine the results, and should be given clear guidance towards an intuitive understanding of the outcome. The user will have to decide on maintenance action, so an understanding is essential.

5.4 The “Topping” Test Procedure

Now that we understand the engine performance with faults near rated power, we can investigate the actual test used for power assurance. The Topping test is a procedure used by the Canadian Forces on their Bell 212 helicopters and is their version of the “maximum power available” test (CFTO C-14-300-000/MN-000). It involves flying the helicopter at approximately 60 knots in horizontal flight. One power section is reduced to idle power, while the other power section to be tested is powered up with its alternator and compressor bleeds shut down. The pilot increases the pitch of the rotor blades so as to increase the torque on the tested engine until either N_{hp} or the trimmed ITT reaches its maximum value with the power turbine mechanical speed at 97% of its design value. This speed corresponds to 32010 RPM. The torque of the power section tested is then divided by the 1028 lb-ft maximum torque that the Bell 212 transmission is capable of carrying to obtain a percentage of the maximum Bell 212 transmission torque. The torque obtained is plotted on a Topping chart for the measured pressure altitude and temperature at which the engine was tested. This entire process is repeated for the other power section. Running the engines to maximum power consumes engine life. In addition, flight tests are required, so the Topping test is used only after a significant overhaul of the engine is performed.

To allow for variations in the ambient conditions for the Topping test, a chart of the maximum torque output with respect to the ambient conditions is used as described above. It is as shown in Figure 42. The NRC T400 torque values shown in Figure 42 are

calculated as below for the points shown in Table 20. This may not be the equation used for the Canadian Forces Technical Order (CFTO).

$$\%TRQ = \frac{(SHP - 85 \cdot \sqrt{\Theta_2}) \cdot 60}{6600 \cdot 2 \cdot \pi \cdot 0.97 \cdot 1028}$$

The SHP is the thermodynamic engine power obtained from a minimum guaranteed performance thermodynamic computer model of the T400. Installation losses are assumed to be 85 SHP at MSL, ISA conditions.

Table 20 - NRC T400 Data Points Plotted in Figure 42

Pressure Altitudes (ISA - ft)	Ambient Temperature (°C)
MSL	-50
2500	-20
5000	0
7500	15
10000	20
	30
	40

As can be seen, these data points show a good agreement with the rest of Figure 42. This is to be expected because Figure 42 was originally produced from the P&WC T400 performance model to which the NRC T400 model was compared in Chapter 3. The only significant variation occurs for hot days at low altitudes. Under these conditions, the NRC T400 model over predicts the maximum power available by around 2.5 percentage points. No definitive explanation could be obtained, and more work should be done in the future to clarify this issue. As the agreement for the rest of Figure 42 is good, the ambient pressure and temperature effects on the Topping test may be assessed with the NRC T400 model. Details of the preparation of Figure 42 should still be acquired, if possible.

MODEL CH135 T400-CP-400
 SINGLE POWER SECTION OPERATION AT INTERMEDIATE RATING
 REFERENCE INSTALLATION POWER LOSS: 85 SHP, @ SLS, ISA, 97% η_f
 HOVER CONDITIONS, $\eta_f = 97\%$ (100% = 6800 RPM)
 100% TORQUE = 1028 LB-FT

Figure 42 - Topping Test Chart, Maximum Power Available (From DND CFTO C-12-135-000/MB-000, 1981)

To do the Topping test, another modification is required involving the original GASTURB code. When power limiting calculations are performed, N_{hp} becomes another guessed variable in the component matching process in addition to β_{LPT} , β_{HPC} , β_{PT} , and P_8 as discussed in Chapter 2. For each power limiting parameter such as ITT, a power limiter error is calculated as a fractional difference between the present value of the parameter and its maximum allowable value. The error associated with N_{hp} is typically the largest of these power limiter errors. The power limiting calculation is performed simultaneously with the component matching procedure. The modification of the code is simply to repeat this calculation twice. The first is to determine the maximum available power from the actual cycle of interest. This requires a knowledge of the engine faults which are present and the component characteristics of the engine. The latter are part of the NRC T400 model, while the former must be found through other means. The second calculation is for the nominal NRC T400 engine. Both calculations are performed for the same ambient conditions under which it is desired to perform our simulated Topping test. If the % TRQ results of the first calculation are equal to or greater than that of the second minus 2%, the power section “tested” will pass the Topping test.

5.5 Development of the NRC T400 Performance Matching Procedure

For the results of the topping test to be useful, it will be necessary to determine how a typical engine responds to various faults as the altitude and gas generator spool speed change. A possible procedure for the Topping test involves the extrapolation of performance results from more benign operating conditions. It is assumed implicitly that the fault signatures used for the extrapolation don't change significantly. As seen in Chapter 4, this is essentially the situation which exists. As there is some variation of the fault signatures with varying $N_{hp}/\sqrt{\Theta_2}$, it is recommended that the measured engine parameters be obtained at moderate to high engine power.

As already mentioned, the Topping test procedure as performed in the NRC T400 model requires that the engine condition be known. This means that the engine faults present

must be identified and their severity quantified. The determination of these faults is the principle problem to be encountered in the overall computer-modeled Topping test. The need for this application is to predict the engine performance with good accuracy. Therefore, it will be sufficient to use the existing NRC T400 model as a baseline, and determine appropriate scaling factors to be applied to the various component characteristics so that the predicted performance of the model most closely matches that of the engine under test. It is desired to load into the model an input data file containing test results. The analysis tool in the model would then alter the nominal component characteristics until the performance predictions agree with the test data. The procedure for this is similar to that described in Lambiris et al (1991).

The measured variables in the input must include the “mandatory” parameters listed below, and several of the items in the “variables to match” parameter list:

Mandatory

gas generator and power turbine spool speeds
ambient temperature and pressure

Variables to Match

fuel flow, ITT, EGT, compressor delivery pressure
output torque, engine inlet air mass flow, CDT, compressor inlet temperature for handling bleed leakages

The mandatory parameters specify the ambient conditions and engine power setting. The variables to match are a list of variables which may be measured along the gas path of the engine. They are dependent both on the mandatory parameters and the component characteristics in Table 21 which we are attempting to determine. All of the variables being passed between the NRC T400 model and our new solution algorithm fit into these three categories. The mandatory variables and the component characteristics may be

thought of as the independent variable sets, while the variables to match are dependent upon the other two groups of variables.

5.5.1 Component Performance Scaling Procedure

An optimization routine based on the Nelder Mead Simplex algorithm (Press et al., 1989) has been developed which varies the compressor and turbine efficiency and flow functions to allow the above variables to be matched between the model results and the test data. At least one component efficiency or corrected flow must be altered for each variable that is to be matched to arrive at a unique solution. When this process is repeated for a number of test data points, the changes in component efficiencies and corrected flows may be determined which provide the best fit between the model predictions and the test data. With this information, it is possible to readily repeat the Topping test using the NRC T400 model by running an off-design point to find the predicted engine power at the ITT, mechanical N_{hp} , TRQ, or SHP limit.

The simplex method is a routine which is capable of finding a minimum value for a multidimensional function. It has been chosen for this application for a variety of reasons. The first is that it requires only function evaluations, not derivatives. This allows the implementation of non-smooth penalty terms which are useful in keeping the calculated component characteristic scaling factors realistic. For instance, we cannot have a compressor with an efficiency of greater than 100%, so a penalty function may be utilized to prevent such values from being calculated. Also, penalty functions allow for the control of the solution process. Calculated values of the efficiency and flow scaling factors may be kept within certain reasonable bounds. It is not likely that degradations of greater than 10% will occur.

Other advantages of the Simplex method include robustness and simplicity. It is robust in that the calculation process is stable in terms of convergence. The compactness of the

algorithm also enable this method to be coded and made functional with a minimum of problems.

The component characteristics which are to be modified in our attempt the match the model performance to the tested engine performance are as in Table 21. As we can see, there are seven variables. This means that we will be implementing a seven dimensional simplex algorithm.

Table 21 - Component Characteristics to be Modified

Variable #	Variable to be Scaled	Nature of Scaling
1	Compressor Efficiency	Additive factor applied to both compressor sections
2	Compressor Flow	Multiplicative factor applied to both compressor sections
3	HPT Efficiency	Additive factor
4	HPT Flow	Multiplicative factor
5	PT Efficiency	Additive Factor
6	PT Flow	Multiplicative Factor
7	Handling Bleed (W_{hb}/W_2)	Additive Factor

For an N dimensional function, the simplex consists of a geometric figure in N dimensional space with N+1 vertices. At the beginning of the solution process, a starting point is

chosen and assigned to one of these vertices. For our application, an engine with modifications to its component characteristics has been chosen for this purpose. For convenience, let us call this point P. Each point P will have N dimensions, one for each of the component characteristic scaling factors as in Table 21. The other N vertices are arranged around point P. For our purposes, each of these N vertices corresponds to faults in the component characteristics in Table 21. For instance, one point is assigned only a 4% decrease in compressor efficiency. Another is assigned a 4% increase in HPT flow. It is initially guessed that the turbine flows have increased, while all other efficiencies and flows have decreased by 4%. For each of these N+1 vertices, a corresponding value from a cost function is calculated. For our purposes, this cost function has been defined as follows:

$$Cost = 2 \sum_{i=1}^N \frac{|\text{Measured Parameter} - \text{Calculated Parameter}|}{|\text{Measured Parameter}| + |\text{Calculated Parameter}|}$$

The measured and calculated parameters correspond to the engine performance variables such as SHP or ITT which are typically measured on the engine. The calculated parameter is the value as estimated by the NRC T400 model, while the measured value is that measured on the tested engine. This cost function then finds a fractional difference between these two values and sums up all of these differences for all of the engine parameters examined. It is this sum which the simplex algorithm will seek to minimize.

The simplex minimization routine begins to manipulate the vertices of the initial simplex above. The algorithm will examine the cost function of each vertex and determine the minimum and maximum values. Most steps involve a reflection of the highest vertex through the opposite face of the simplex in search of a lower point. The minimization routine will expand the simplex as it makes this reflection if it can do so to speed the solution process. If the simplex has to pass through a “valley floor” in N dimensional space, the algorithm will contract the simplex to allow it to squeeze into this valley. If the simplex must pass through an extremely tight space, it will contract itself in all dimensions around the smallest vertex. This process of expansion, contraction, and reflection of the vertices of the simplex to obtain lower values of the cost function will eventually converge

to a minimum. A printout of the code used in this minimization routine may be found on pages 170 to 208.

5.5.2 Difficulties Encountered

It must be noted that the Nelder Mead simplex algorithm is not capable of consistently finding the lowest minimum if there are multiple minima present. It will simply converge to the first minimum that it arrives at. Therefore, to have an exact solution with only one minima present, we must ensure that the number of independent parameters to match is greater or equal to the number of component characteristics being modified. This is simply stating that there must be as many equations to be summed in the cost function as there are unknown component efficiencies to be determined. As we shall see, the specification of independent parameters is critical, as some of the parameters in the variables to match category are in fact not independent. This, in combination with the fact that there are not a large number of parameters typically measured means that the number of component characteristics which may be manipulated at one time is limited if a unique solution is to be obtained.

Some remedies to this problem include a process of differential gas path analysis (Stamatis et al, 1991). However, such a method requires the use of data sets of measured engine parameters collected for several operating points of the engine. In a test cell this may be a practical option, but in the field it is highly unlikely that ground crews will significantly increase their workload to obtain the extra data. For the NRC T400 model to be useful in power assurance, it must be used by the ground crew. As such, care must be taken to ensure that maximum benefit will be obtained using this computer model while imposing a minimum of extra effort on those who will use it. Therefore, it has been decided to limit ourselves to the use of single data sets for each matching of the NRC T400 model to the test engine. If multiple points are collected, this process should find similar component scaling factors for each data set. If it does not, this will provide an indication of faulty data points due either to faulty instruments or misread readings.

Preliminary work has involved the implanting of typical component degradations into the NRC T400 model. By applying the above process to these data, one should arrive at the component changes which were implanted. For a considerable period of time, this was not the case. A numerical problem existed which prevented the solution from achieving complete convergence. In many of the fault scenarios examined, it has been found that the N dimensional topography is quite flat. As a result, the change in the cost function for each step being taken by the simplex algorithm became small as the solution was approached. The problem arose when the step size taken by the simplex routine reached the repeatability of the NRC T400 core model. In Chapter 2, we observed that the component matching process performed by GASTURB minimizes the sum of the squares of four errors. These include the β values of each compressor section, the PT and the pressure drop across the exhaust nozzle. When these errors are eliminated, we have matched the components so that the principles of conservation of work and flow are obeyed for steady state operation. As purchased, GASTURB stops the component matching procedure when the sum of the squares of these errors becomes smaller than 1×10^{-8} . This is adequate for the core model alone. However, due to the flatness of the solution domain the errors left in the measured parameters at the completion of the component matching process are significant to the simplex algorithm. A partial fix to this problem has been implemented by reducing the stopping criterion in the core model to 1×10^{-14} . This has greatly improved the simplex algorithm solution process. Unfortunately, there are limitations to the extent to which the stopping criterion error may be reduced, with effects on the accuracy of the simplex algorithm. This is because the component characteristics for the compressors and power turbine are interpolated linearly in GASTURB. Also, the original component characteristic files were created through the use of linear interpolation. The use of linear interpolation means that at the junction between line segments there will be a discontinuity in slope. These kinks confuse the Newton-Raphson routine used in GASTURB for very small values of the stopping criterion. As a result, it can only be dropped to 1×10^{-14} without causing convergence problems.

While we are thus limited in the solution accuracy obtainable, as we shall see we shall still be able to detect component performance changes of as small as 0.5%.

5.6 Evaluation of Performance Matching with Implanted Faults

With the above changes implemented, a series of component faults were implanted into the NRC T400 model. The relevant performance parameters were saved to disk and used to create input files for the performance matching process. These became input for the performance matching routine. The scaling factors as found by this routine were again written to disk and compared to the implanted fault. With the seven possible faults in Table 21, there are obviously many possible fault combinations which may be attempted. For each case, a series of five different mechanical gas generator spool speeds have been run to isolate any effects that this parameter may have on the process. As the CDT is not generally measured on the engine and is not available from the NRC T400 test stand, it has been neglected as a parameter. The remaining seven variables in the “parameters to match” list have initially been selected. The results for each case are presented in tabular form, with the final cost function defined above in decimal form in the last column. Smaller values of the cost function mean that the NRC model performance has been matched more closely to the engine performance.

5.6.1 Linear Dependence of EGT and SHP

The first problem encountered is an apparent relationship between the EGT and the SHP. This relationship is the most prevalent for HPT efficiency faults. An examination of Figure 29 in Chapter 4 will help to illustrate this issue. It is noticeable in this figure that the EGT and SHP trends are similar for reductions in HPT or compressor efficiency. If the typical situation of no PT damage exists, then the trends for the EGT and SHP will be close enough that the two will not longer be effectively independent of each other. To illustrate this point, Table 22 below illustrates a performance matching run for which all

seven component characteristics have been scaled, and seven performance parameters have been used.

Table 22 - Component Scaling Results for a 2% HPT Efficiency Reduction

N_{hp}	ΔW_c	$\Delta \eta_c$	ΔW_{HPT}	$\Delta \eta_{HPT}$	$\Delta \eta_{PT}$	Hand. Bld.	Cost Function
1.000	0.53	-1.55	0.15	-0.55	0.02	0.01	1.00E-04
0.975	0.29	-0.87	0.09	-1.21	0.00	0.00	1.00E-04
0.950	-0.21	-0.26	0.32	-1.62	0.04	0.00	3.50E-03
0.925	0.04	-0.08	0.00	-1.92	0.02	0.00	2.00E-04
0.900	0.36	-0.65	-0.13	-1.42	0.40	0.04	9.00E-04

Table 22 shows significant scaling being applied to the PT flow and efficiency functions, even though no such fault exists in the “model” engine being examined. Again, an examination of Table 15 in Chapter 4 is useful. Table 22 shows inconsistent behavior at different gas generator spool speeds, especially for an N_{hp} of 0.975. From Table 15 in Chapter 4, we see that a decrease in the PT flow function will act to increase most of the measured parameters, especially SHP and Wf. The decrease indicated for the PT efficiency will counter the effect of PT flow decrease. The decrease in the HPT and compressor efficiencies have changed to compensate in part for the change in both the SHP and the other variables affected by the PT flow decrease. In short, the simplex algorithm has converged to a local minimum. This minimum is not the global minimum and is not the correct answer.

Therefore, we may conclude that with the engine parameters available, we must reduce the number of component efficiencies by at least one to get a unique solution. On the examination of Table 22, the most significant wrongly deduced parameter is W_{HPT} . As mentioned in Chapter 4, when turbines are damaged we are most likely going to see efficiency reductions with a much smaller effect on flow. Due to the lower temperatures in the vicinity of the PT, we would expect less damage there than for the HPT. Therefore, it seems reasonable to neglect changes in the PT flow function. Once the engine is in

service, we should not experience significant changes over time with this characteristic anyway.

With further experimentation, it has been found that the addition or removal of the EGT as a parameter to match makes little difference to the results. From the arguments above, this is to be expected. Therefore, we now proceed without the EGT or the PT flow in consideration. As we shall see, from a performance perspective these changes shall provide the results for which we are searching.

5.7 Single Component Faults

With the modifications above implemented, we now return to the task of testing the performance matching algorithm. We will begin with the detection of a series of single implanted faults. This will provide us with an indication of if the performance matching algorithm is working while keeping the solutions obtained as simple as possible.

5.7.1 Compressor Faults

Here, we examine the cases of a 2% degradation in the compressor flow or efficiency. In Table 23, the 2% reduction the compressor flow has been detected with surprising accuracy. As discovered in Chapter 4, it is a fairly unique fault, and therefore did not provide a significant problem for the performance matching algorithm.

Table 23 - Component Scaling Results for a 2% Reduction in Compressor Flow

N_{hp}	ΔW_c	$\Delta \eta_c$	ΔW_{HPT}	$\Delta \eta_{HPT}$	$\Delta \eta_{PT}$	Hand. Bld.	Cost Function
1.000	-1.96	-0.28	0.02	0.24	0.00	0.00	1.00E-04
0.975	-1.94	-0.23	0.01	0.21	0.02	0.01	3.00E-04
0.950	-2.05	0.19	-0.01	-0.18	-0.02	0.00	5.00E-04
0.925	-1.90	-0.28	0.01	0.25	0.04	0.02	8.00E-04
0.900	-1.99	-0.04	-0.01	0.03	0.02	0.00	1.00E-04

An important point must be made concerning the compressor and HPT efficiencies. As found in Chapter 4, these two faults have essentially the same impact on the engine performance. As a result, when we are attempting to detect the engine condition through the use of performance parameters, it is difficult to isolate the two faults. As can be seen in Table 23, the compressor and HPT efficiency changes are nearly equal in magnitude and opposite in sign. Their influence therefore cancels out. The cost function is much smaller than in Table 22, and we can expect that the performance of this engine will be very close to an engine with a single 2% reduction in compressor flow.

Table 24 examines the case of a 2% reduction in the compressor efficiency. Again, the method has been successful in finding the state of the engine.

Table 24 - Component Scaling Results for a 2% Reduction in Compressor Efficiency

N_{hp}	ΔW_c	$\Delta \eta_c$	ΔW_{HPT}	$\Delta \eta_{HPT}$	$\Delta \eta_{PT}$	Hand. Bld.	Cost Function
1.000	0.01	-1.83	0.08	-0.09	-0.05	0.05	2.30E-03
0.975	-0.01	-1.93	-0.04	-0.08	0.05	0.03	4.00E-04
0.950	-0.04	-1.90	0.00	-0.10	-0.03	0.00	2.00E-04
0.925	0.00	-1.99	0.00	-0.01	0.00	0.00	1.00E-04
0.900	-0.24	-1.58	0.07	-0.40	-0.24	0.00	7.00E-04

5.7.2 Turbine Faults

Here, we will examine the case of an HPT swallowing capacity increase, and an efficiency reduction. Finally, an LPT efficiency reduction will be tested. In Table 25, we once again arrive at the correct solution. In this case, the performance matching algorithm appears to be indicating a compressor efficiency improvement as compared to the NRC T400 model standard which is not actually there. However, the changes in the HPT efficiency counteract these changes and will almost completely cancel them out.

Table 25 - Component Scaling Results for a 2% HPT Flow Increase

N_{hp}	ΔW_c	$\Delta \eta_c$	ΔW_{HPT}	$\Delta \eta_{HPT}$	$\Delta \eta_{PT}$	Hand. Bld.	Cost Function
1.000	0.04	0.15	1.70	-0.24	0.41	0.30	4.00E-03
0.975	-0.10	0.35	1.97	-0.32	0.00	0.00	1.00E-04
0.950	-0.14	0.47	1.99	-0.46	-0.13	0.00	1.10E-03
0.925	-0.22	0.60	1.95	-0.56	-0.06	0.00	1.70E-03
0.900	-0.26	0.78	2.11	-0.68	-0.38	0.00	1.10E-03

It is in Table 26 where the difficulty in separating HPT and compressor efficiencies becomes the most acute. An examination of this table reveals that the total combined magnitudes of the compressor and HPT efficiencies add up to approximately -2%. A 2% reduction in the compressor or HPT efficiency has essentially the same effect on the engine performance, and the ratio between the two is therefore unknown. Only the sum of the two is detectable. This reinforces the notion that the performance matching routine works effectively in its assigned task, but has significant weaknesses in the application of fault detection. As a final note, some variation has been predicted in both the compressor and HPT flow functions. However, an increase in the HPT flow counteracts a decrease in the compressor flow. Hence, the two are for the most part canceling each other out. In this sense, the HPT and compressor flows behave in a similar manner as the efficiencies. Fortunately, the fault signatures of the two are not as similar to each other as the efficiencies are, and therefore the magnitude for this “noise” is much less significant.

Table 26 - Component Scaling Results for a 2% HPT Efficiency Decrease

N_{hp}	ΔW_c	$\Delta \eta_c$	ΔW_{HPT}	$\Delta \eta_{HPT}$	$\Delta \eta_{PT}$	Hand. Bld.	Cost Function
1.000	0.53	-1.55	0.15	-0.55	0.02	0.01	1.00E-04
0.975	0.29	-0.87	0.09	-1.21	0.00	0.00	1.00E-04
0.950	-0.21	-0.26	0.32	-1.62	0.04	0.00	3.50E-03
0.925	0.04	-0.08	0.00	-1.92	0.02	0.00	2.00E-04
0.900	0.36	-0.65	-0.13	-1.42	0.40	0.04	9.00E-04

As discovered in Chapter 4, the PT efficiency has a fairly unique fault signature. As such, one would expect the isolation of such a fault to be readily achievable in practice. Table 27 validates this notion in a quantitative manner. All of the changes in the component characteristics are small except for the PT efficiency, which has changed to match that of the fault which was implanted into the “model” engine.

Table 27 - Component Scaling Results for a 2% PT Efficiency Decrease

N_{hp}	ΔW_c	$\Delta \eta_c$	ΔW_{HPT}	$\Delta \eta_{HPT}$	$\Delta \eta_{PT}$	Hand. Bld.	Cost Function
1.000	0.01	-0.04	0.00	0.03	-1.99	0.00	1.00E-04
0.975	-0.01	0.11	-0.05	-0.13	-1.96	0.06	6.00E-04
0.950	0.05	-0.12	-0.03	0.09	-1.93	0.04	1.00E-04
0.925	-0.04	-0.15	-0.07	0.08	-1.80	0.03	2.00E-03
0.900	0.08	-0.19	-0.04	0.16	-1.88	0.02	2.00E-04

5.7.3 Handling Bleed Valve Leakage

Occasionally, the seal on a handling bleed valve will become damaged and leak air from the back of the axial compressor into the engine intake. When this occurs, the air flow through the remainder of the engine aft of the axial compressor section will be reduced. Also, the intake temperature at the compressor face will be increased due to the mixing of this bleed air with the incoming ambient air. A fault was implanted into the NRC T400 model assuming that complete and even mixing of the handling air and the ambient air occurred at the compressor inlet. As this fault has been shown to have a unique signature on the performance of the engine in Chapter 4, we expect a well defined solution here. As shown in Table 28, this is indeed the case.

Table 28 - Component Scaling Results for a 2% Handling Bleed (W_{hb}/W_2) Leakage

N_{hp}	ΔW_c	$\Delta \eta_c$	ΔW_{HPT}	$\Delta \eta_{HPT}$	$\Delta \eta_{PT}$	Hand. Bld.	Cost Function
1.000	-0.01	0.05	-0.01	-0.05	-0.01	2.00	1.00E-04
0.975	-0.16	0.55	-0.08	-0.51	0.04	2.01	5.00E-04
0.950	0.08	-0.19	-0.05	0.14	0.12	2.07	2.00E-04
0.925	-0.11	0.22	0.05	-0.18	-0.13	1.92	3.00E-04
0.900	-0.06	0.16	0.04	-0.14	-0.10	1.98	2.00E-04

5.8 Multiple Faults

Having successfully validated the performance matching test for single engine faults, we shall now challenge the algorithm with a few multiple faults. Four cases will be examined. The first case will deal with a fouled compressor with a 5% reduction in flow and 2% reduction in efficiency. The second and third will deal with a combination of a handling bleed valve leakage and either a compressor flow or HPT efficiency reduction. Finally, the fourth fault case will be a triple fault combining the first three cases.

5.8.1 Compressor Fouling

In Table 29, a compressor fouling situation is examined. In light of the results above, we see that the performance matching algorithm has indeed been able to isolate this situation. The scaling in the compressor flow has been isolated to 5%, and the combination of the compressor and HPT efficiency decreases are roughly equivalent in performance terms to a 2% reduction in compressor efficiency. One interesting result is the loss of accuracy in these results as we move farther from the engine design point. The HPT flow and PT efficiency both move away from their correct values of zero. In Figure 25 in Chapter 4, we can see what happens to the fault signature of a typical engine as the gas generator spool speed is reduced. The SHP and fuel flow increase with respect to the PR and air mass flow. As a result, the information contained in the latter two parameters tends to get swamped by the larger SHP and fuel flow variations as the power is reduced. As we

would be conducting this performance matching test within the speed range of Table 29, this effect should not be a serious problem.

Table 29 - Component Scaling Results for a Fouled Compressor - 5% Reduction in Flow, 2% Reduction in Efficiency

N_{hp}	ΔW_c	$\Delta \eta_c$	ΔW_{HPT}	$\Delta \eta_{HPT}$	$\Delta \eta_{PT}$	Hand. Bld.	Cost Function
1.000	-5.1739	-0.8026	-0.1247	-1.1193	-0.0040	0.0000	1.00E-04
0.975	-5.0517	-1.7700	-0.0227	-0.2112	0.0025	0.0000	1.00E-04
0.950	-5.1188	-1.3664	-0.0120	-0.6337	-0.1813	0.0000	1.40E-03
0.925	-5.3858	-0.2656	-0.1301	-1.6213	-0.2011	0.0000	4.90E-03
0.900	-5.4221	-0.1711	0.2518	-1.6133	-0.9095	0.0002	2.70E-03

5.8.2 Handling Bleed Leakage and Compressor Flow Reduction

In Table 30, a handling bleed valve leakage has been combined with a reduced flow compressor fault. As can be seen, the convergence proceeds extremely well as both faults have fairly unique fault signatures. Once again, small deviations exist in the compressor and HPT efficiencies which act to cancel each other out.

Table 30 - Component Scaling Results for a 2% Handling Bleed in Combination with a 2% Reduction in Compressor Flow

N_{hp}	ΔW_c	$\Delta \eta_c$	ΔW_{HPT}	$\Delta \eta_{HPT}$	$\Delta \eta_{PT}$	Hand. Bld.	Cost Function
1.000	-1.97	-0.30	0.04	0.28	0.00	1.99	1.00E-04
0.975	-1.96	-0.31	0.03	0.28	0.00	2.00	1.00E-04
0.950	-2.10	0.37	0.09	-0.29	-0.23	1.86	5.00E-04
0.925	-2.07	0.19	0.05	-0.15	-0.12	1.93	2.00E-04
0.900	-2.10	0.34	0.08	-0.28	-0.21	1.96	4.00E-04

5.8.3 Handling Bleed and HPT Efficiency Reduction

In Table 31, a handling bleed valve flow reduction is combined with an HPT efficiency reduction. Once again the “goodness” of the fit seems to decay slightly as the spool speed

is reduced. However, this is a small effect, and the net result is essentially a superposition of the handling bleed and HPT efficiency faults examined separately above. Also, small but significant variations in the compressor and HPT flow are predicted which are not actually there.

Table 31 - Component Scaling Results for a 2% Handling Bleed in Combination with a 2% Reduction in HPT Efficiency

N_{hp}	ΔW_c	$\Delta \eta_c$	ΔW_{HPT}	$\Delta \eta_{HPT}$	$\Delta \eta_{PT}$	Hand. Bld.	Cost Function
1.000	0.3822	-1.4296	0.1400	-0.6802	0.0233	2.0134	2.00E-04
0.975	0.4986	-1.5755	0.1784	-0.5245	-0.0040	1.9810	3.00E-04
0.950	-0.0887	-0.0222	0.0866	-1.9476	-0.0260	1.9535	1.20E-03
0.925	0.6231	-1.1149	-0.2805	-1.0853	0.7128	2.4271	1.50E-03
0.900	-0.3259	0.7623	0.1255	-2.6596	-0.4089	1.9816	1.20E-03

5.8.4 Handling Bleed Leakage with Compressor Flow and HPT Efficiency Reduction

As a final check, a triple fault was implanted into the NRC T400 model. This fault consisted of a 2% handling bleed valve leakage, a 2% reduction in the compressor flow capacity, and a 2% reduction in the HPT efficiency. As can be seen in Table 32, these faults have for the most part been detected. It can be seen that the variability of the results has increased as we have proceeded from single to double to triple faults. It is speculated that as more faults are implemented the N dimensional space through which the simplex algorithm must navigate becomes more complex. This would increase the difficulty of the solution process and might affect the convergence to the final solution.

Table 32 - Component Scaling Results for a 2% Degradation in the Handling Bleed Valve, Compressor Flow and HPT Efficiency

N_{hp}	ΔW_c	$\Delta \eta_c$	ΔW_{HPT}	$\Delta \eta_{HPT}$	$\Delta \eta_{PT}$	Hand. Bld.	Cost Function
1.000	-1.68	-1.61	0.17	-0.51	0.02	2.01	2.00E-04
0.975	-1.55	-1.60	0.16	-0.53	0.02	2.01	2.00E-04
0.950	-1.56	-1.16	-0.30	-1.10	0.82	2.45	2.50E-03
0.925	-1.93	-1.10	0.40	-0.79	0.28	2.01	6.00E-03
0.900	-1.60	-1.48	0.00	-0.54	0.48	1.72	3.20E-03

5.9 Verification of Performance Matching Routine

Now that results have been obtained from our performance matching routine, the next step is to examine a couple of cases above to verify that the output SHP is indeed predicted accurately with the usage of the component characteristic scaling factors which have been calculated. We can say with confidence that those fault conditions which were isolated to the component level to match the original implanted faults will yield the same engine performance. Therefore, we will show this particular check for a multiple fault case which we have already examined. It involves a fouled compressor with a 5% flow and 2% efficiency reduction.

5.9.1 SHP -vs- N_{hp} Curve

This check is quite simple in nature. The NRC T400 model has been run with the scaled component characteristics originally implanted into the model, and again with those found using the performance matching routine. For each fault combination, a plot with respect to N_{hp} has been made for the error between the SHP as calculated using the performance matching scaling factors and the SHP found using the implanted fault scaling factors. The scaling factors derived at values of N_{hp} of 0.9, 0.95 and 1 are used. For the simulated compressor fouling fault, the results are as in Figure 43.

Figure 43 reveals the accuracy of the performance matching process, with typical errors of less than 0.6%. The maximum error encountered throughout the useful operating range of the engine is 1%. This 1% error occurs for the line plotted using the scaling factors obtained at $N_{hp} = 0.9$. Table 29 reveals a correlation between the cost function and the fit of the curves in Figure 43. The lower the cost function, the better the SHP fit. Therefore, the user should be able to select an appropriate scaling factor set which would provide better accuracy than 1% as seen in Figure 43. Also, doing the performance matching process at higher values of N_{hp} seems to give more accurate results. Any N_{hp} above 0.9 for this should be adequate.

Figure 43 - Percent Error Between Corrected SHP Calculated Using Compressor 5% Flow and 2% Efficiency Reduction and Corrected SHP Calculated from Performance Matching Scaling Factors at MSL, ISA Conditions

5.9.2 Topping Test using NRC T400

Next, the Topping test results for this fouled compressor scenario are presented for two ambient conditions. These are at +20°C and -20°C at the ISA pressure altitude of 5,000'.

As explained earlier, Figure 43 has been developed using the NRC T400 model with no installation effects implemented. As such, the standard Topping test installation effects of 85 SHP have been removed from the tested engine performance as outlined in the Topping test procedure.

The accuracy of the Topping test using the scaling factors as determined from the performance matching process is shown to be within 1 percentage point in Table 33. Once again, this error may be minimized by using a scaling factor set with a minimum corresponding cost function.

Table 33 - Topping Test Results for a Compressor 5% Flow and 2% Efficiency Reduction

Ambient Conditions: 5,000 ft ISA, +20°C	% TRQ	Error due to Performance Matching	% Margin of Failure
Required to Pass	49.3		
With Implanted Fault	44.7		-4.6
Derived at $N_{hp} = 1$	44.7	0	-4.6
Derived at $N_{hp} = 0.95$	44.4	-0.3	-4.9
Derived at $N_{hp} = 0.9$	43.9	-0.8	-5.4

Ambient Conditions: 5,000 ft ISA, -20°C	% TRQ	Error due to Performance Matching	% Margin of Failure
Required to Pass	61.9		
With Implanted Fault	61.6		-0.3
Derived at $N_{hp} = 1$	61.5	-0.1	-0.4
Derived at $N_{hp} = 0.95$	61.4	-0.1	-0.5
Derived at $N_{hp} = 0.9$	60.5	-1	-1.4

Ambient Conditions: 0 ft ISA, +20°C	% TRQ	Error due to Performance Matching	% Margin of Failure
Required to Pass	60.9		
With Implanted Fault	59		-1.9
Derived at $N_{hp} = 1$	59	0	-1.9
Derived at $N_{hp} = 0.95$	58.7	-0.3	-2.2
Derived at $N_{hp} = 0.9$	57.9	-1.1	-3

Another factor of interest is the percentage margin by which these faulted “imaginary” engines fail the topping test. This margin grows smaller as the ambient temperature grows colder. At -20°C our faulted power section is on the verge of passing the Topping test. This is to be expected because these faults are primarily limited by the Trimmed ITT under these ambient conditions. Higher ambient temperatures aggravate the elevated ITT situation caused by the engine faults, while low ambient temperatures reduce them. This leads us to the conclusion that the outcome of the Topping test may be dependent on the ambient conditions, even though they have been previously taken into account in the minimum guaranteed power projections. The same effect is observed for variation in altitude at a constant ambient temperature. To maintain power at lower ambient pressure, both N_{hp} and ITT must rise. The result of this is that the critical situation for the Topping test is “hot and high”. It is here where the power section to be tested will be the most adversely affected. If the simulated Topping test is passed under these conditions, we can be fairly certain that it will pass at all other ambient conditions as well.

5.10 Topping Testing on Power Sections 78095 and 78117

Now that the performance matching and Topping test procedures have been developed and verified, it is time to apply them to a real T400 engine. We will repeat the process twice for each of the two power sections on the engine. The first time will be using the same parameters as above. The second will be using an abbreviated list of parameters including the SHP, fuel flow, Trimmed ITT, N_{hp} and N_{PT} , P_{amb} , and T_{amb} . These are the engine parameters which are available in the Bell 212 cockpit. It would therefore be useful to examine if the performance matching process in a less detailed form could be useful for the Topping test procedure.

As mentioned earlier, the T400 engine under test at the NRC is fitted with the standard Bell 212 intake and inertial separation system which the nominal NRC T400 model does not take into account. Though typical power losses are between 5 and 20 SHP for this installation for each power section, no measurements have been made to this effect. As

the losses are fairly small compared to the total engine power output but the exact magnitudes are unknown, it has been decided to ignore these losses explicitly in the performance matching procedure. As no oil cooler blowers are installed in the tested configuration, the losses associated with will them will not affect the performance matching process.

The performance matching procedure matches the performance of the engine with all of the associated installation effects included. As such, the engine tested at the NRC includes all of the installation effects with the exception of the oil cooler blowers which themselves have a very minor impact on the overall engine performance. The blower losses should technically be accounted for in the Topping procedure, but as they are quite small and are also not precisely known, neglecting them will not significantly alter the results. The inertial separator losses will influence the operating state of the engine as tested, and hence the component scaling factors determined by the performance matching procedure. As the Bell 212 installation effects are for the most part already accounted for in the NRC test configuration, we will not deduct the installation effects as outlined in the Topping test procedure above. To do so would be to make the same correction twice.

5.10.1 Full NRC Instrumentation

We first address the full parameter list case as all of the parameters used above are available in the NRC test stand. The compressor delivery pressure is a static value, and therefore the NRC T400 total compressor delivery pressure has been corrected as described in Chapter 2. This correction is not an exact one as a flow area had to be assumed, making the PR a less exact variable. The compressor intake mass flow is not measured directly on the test configuration. In some preliminary calibration, it has been correlated using a bellmouth mass flow meter with respect to the gas generator spool speed. For the remaining runs, the intake mass flow has been obtained from this calibration. All of the other remaining parameters have been measured directly on the

engine during the tests. Engine data from NRC test run 20 has been used. This run has been performed for the stock engine configuration as discussed above.

A minor modification has been introduced to the performance matching routine with respect to handling bleed flow determination. On further examination of the situation, it has been found that the handling bleed flow may be determined directly through a mixing calculation. Ambient air and compressed air from the exit of the axial compressor section are mixed at the compressor inlet plane. It is possible to determine the amount of handling bleed air required to produce the required temperature increase from the ambient to the compressor face. The equation used is as follows.

$$\frac{\dot{W}_{hb}}{W_2} = \left(\frac{H_2 - H_{amb}}{H_{25} - H_{amb}} \right)$$

This change eliminates one variable from the Simplex routine, speeding up and simplifying the calculation. The above calculation reveals the total handling bleed flow present. The normally scheduled handling bleed flow is subtracted from this sum to give the values in Tables 34 and 36 below. This now represents the leakage from the valve. The above equation is a simplification of reality as perfect mixing does not actually happen in the engine. However, it is a reasonable relationship to use as discussed in chapters 3 and 4.

5.10.1.1 Power Section 78095

Below we see the scaling factors which the performance matching routine applied to the NRC T400 model to predict the performance of this power section. Both compressor and HPT flow reductions are indicated, as well as a reduction in efficiency in either the compressor or HPT. An increase in PT efficiency is indicated. The effects of the HPT and compressor flow reductions add up so that their combined effects remain roughly constant throughout the speed range tested. This effect is as discussed in Chapter 4.

Table 34 - Scaling Factors for Engine 78095 from NRC Test Stand

N_{hp}	ΔW_c	$\Delta \eta_c$	ΔW_{HPT}	$\Delta \eta_{HPT}$	$\Delta \eta_{PT}$	Hand. Bld.	Cost Function
1.006	-4.85	2.31	-6.09	-4.60	6.29	6.31	2.28E-02
0.981	-3.88	-6.74	-4.95	5.31	7.17	5.64	1.00E-04
0.956	-4.91	1.80	-6.40	-3.88	6.65	6.56	1.40E-02
0.927	-2.72	-9.50	-8.28	7.04	14.53	6.44	1.03E-02
0.902	-2.28	-6.00	-10.00	3.21	17.40	10.38	6.27E-02

When the handling bleed valve should be shut according to the handling bleed valve schedule, we see around 6% of the intake flow is being bled off according to our calculation. As mentioned in Chapter 3, there has been some difficulty in obtaining an accurate compressor entry temperature as only three thermocouples have been used to measure this temperature. It is suspected that at least for power section 78095 the measured compressor inlet temperature is higher than what actually exists. This would act to increase the apparent handling bleed leakage. An over-predicted handling bleed leakage would drop the predicted power output below that observed. To compensate, an increased power turbine efficiency is called for. This effect has also been observed in Table 34. Furthermore, our handling bleed calculations have been made with the assumption that all the temperature rise observed before entry into the compressor is due to mixing with the handling bleed air. It is possible that some of this temperature rise may be due to other factors such as conduction of heat onto the wire intake screen on which the thermocouples have been mounted.

As a final note, the cost function in Table 34 is larger than for the previous cases. This is because the measured data are not the thermodynamic average values due to the limitations of the instrumentation used. For instance, only one compressor delivery pressure probe is incapable of resolving the entire pressure distribution at the compressor exit.

Having examined the shortcomings of the performance matching process in this case, we shall see that the power output of this power section is still predicted with excellent accuracy.

Figure 44 - Comparison of Scaled NRC T400 Model Corrected SHP Obtained using Scaling Factors in Table 34 with Tested SHP of Engine 78095

As we can see in Figure 44, the actual power output of the power section tested is accurately predicted by the scaled NRC T400 model. As well, the success of the scaling process is relatively insensitive to the gas generator speed at which the power section was tested. This is due to the predicted engine faults remaining relatively constant over the speed range in Table 34. Knowing that good agreement between the predicted and actual power output has been obtained, we now perform the Department of National Defence Topping test in the manner described earlier in this chapter. The results are as in Table 35.

Table 35 - Topping Test Results for Engine 78095 - Full Performance Matching

Ambient Conditions: 5,000 ft ISA, +20°C	% TRQ	% TRQ Margin	Active Limiter
Required to Pass	49.3		
Performance Matching done at:			
$N_{hp} = 0.901$	53.1	3.8	N_{hp}
$N_{hp} = 0.955$	52.4	3.1	N_{hp}
$N_{hp} = 1.006$	53.1	3.8	N_{hp}

Once again, we see that the results of the maximum power predictions under the given ambient conditions are roughly constant for each of the various gas generator spool speeds at which the performance matching process was performed. As a final note, we can see that this engine has just barely passed the test. The DND Topping test allows for a 2% margin of error on the low TRQ side, and this error has already been taken into account in Table 35. This marginal passing of the Topping test is consistent with the 3600 hr TSO of the power section.

5.10.1.2 Power Section 78117

Now, we repeat the same process as above for the second power section of the tested T400 engine. The results of the performance matching run on this power section are as in Table 36:

Table 36 - Scaling Factors for Engine 78117 From NRC Test Stand

N_{hp}	ΔW_c	$\Delta \eta_c$	ΔW_{HPT}	$\Delta \eta_{HPT}$	$\Delta \eta_{PT}$	Hand. Bld.	Cost Function
0.981	-2.96	-1.47	-3.45	-1.23	2.72	2.52	2.00E-04
0.953	-5.23	1.94	-4.74	-4.59	4.43	3.40	1.00E-04
0.928	-6.45	2.11	-6.28	-5.80	6.20	5.02	1.00E-04
0.900	-7.63	-1.91	-10.28	-4.05	12.74	6.75	1.07E-02
0.876	-11.43	1.56	-12.55	-8.59	12.27	6.04	2.89E-02

From this test, we see a somewhat different pattern emerging in that the scaling factors on the component efficiencies show a large variation with respect to the gas generator spool speed of the test. The higher the gas generator speed used for the test, the smaller the indicated engine damage appears to be. Low values of the cost function indicate good agreement between the scaled model and the data point at which the performance matching has occurred. However, we should expect that the agreement may not be as good farther away from this matched point. To verify this, Figure 44 shows the SHP -vs- N_{hp} curve.

From Figure 45, we can see that our assumption is correct. Each engine output power curve gives excellent agreement with the test data at the gas generator speed at which it was matched. Overall, a value of $N_{hp} = 0.95$ seems to be the best speed for the performance matching process simply because it is in the middle of the normal engine operating speed range.

Figure 45 - Comparison of Scaled NRC T400 Model Corrected SHP Obtained using Scaling Factors in Table 36 with Tested SHP of Engine 78117

From Table 37, we see that the maximum TRQ available in the Topping test under the conditions indicated only varies by 1 percentage point across the different performance matching runs. This is less than the power variation indicated in Figure 45. The results for this power section are similar to the first in that this engine appears to marginally pass the Topping test. It also has accumulated a 3600 hr TSO.

Table 37 - Topping Test Results for Engine 78117, Full Performance Matching

Ambient Conditions: 5,000 ft ISA, +20°C	% TRQ	% TRQ Margin	Active Limiter
Required to Pass	49.3		
Performance Matching done at:			
$N_{hp} = 0.900$	52.7	3.4	Trimmed ITT
$N_{hp} = 0.953$	53.1	3.8	Trimmed ITT
$N_{hp} = 0.981$	53.7	4.4	Trimmed ITT

5.10.2 Bell 212 Instrumentation

As installed in the Bell 212 helicopter, the suite of engine parameters on the NRC test stand are reduced. The parameters involving engine performance available in the cockpit include N_{hp} and N_{pt} , the outside air temperature and pressure, ITT, TRQ, and W_f . As the compressor inlet temperature after the mixing of the handling bleed air is not measured in the helicopter, we must do the performance matching test run on the engine with the bleed valves shut. If there is no abnormal bleed valve leakage, a value of N_{hp} of 0.95 should achieve this.

The total number of component characteristics available for scaling amounts to 3 for the Bell 212 configuration. This is down from 7 in the NRC test setup. As such, there has been some doubt as to how a handling bleed leakage may be dealt with. The η_{PT} , η_{HPT} and W_c have been chosen for scaling as they appear to provide a low cost function. This leaves us one engine parameter short if we should be interested in dealing with a

compressor handling bleed leakage. For the most part, we shall assume that the handling bleed valve has been inspected and dealt with off line from our performance matching routine. We will assume that the nominal NRC T400 handling bleed schedule is in effect and that the compressor inlet temperature is found through uniform mixing of the handling bleed and ambient air. We will then account for the postulated fault in the case of power section 78095 and use the measured compressor entry temperature on the NRC test stand instead of the ambient temperature. This will reveal how sensitive the results will be to this parameter.

5.10.2.1 Power Section 78095

Using the instrument readings available in the Bell 212 cockpit, we arrive at a somewhat smaller list of component performance scaling factors. These are as in Table 38.

Table 38 - Scaling Factors for Engine 78095, Bell 212 Performance Matching

N_{hp}	ΔW_c	$\Delta \eta$ HPT	$\Delta \eta$ PT	Cost Function
1.006	-9.893	-0.078	3.224	1.00E-04
0.981	-10.284	-0.080	3.494	1.00E-04
0.956	-11.287	-0.451	3.978	1.00E-04
0.926	-12.985	-1.363	4.655	1.00E-04
0.902	-14.588	-2.205	3.917	1.00E-04

Once again, the variation in the component characteristics over the speed range is not excessive. Note the large compressor flow reductions which are indicated. With only three component characteristics to scale, the effects of faults in multiple engine components have been approximated through the use of large scaling factors in the faults which may be scaled. A flow reduction of 14% in the compressor is probably not present. The real test is in how well the predicted output power matches that measured on the power section. In Figure 46 we see a plot of Power -vs- N_{hp} .

Figure 46 - Comparison of Scaled NRC T400 Model Corrected SHP Obtained using Scaling Factors in Table 38 with Tested SHP of Engine 78095

From Figure 46, it can be seen that not only are the power predictions less accurate, but they do not match even on the data points for which the performance matching routine has been performed. The reason for this is simply that the performance matching routine was performed using the outside ambient temperature. The test data have been corrected using the measured compressor intake temperature. It is important for an accurate performance matching run that the compressor intake temperature is known. Despite this deficiency, the power predictions derived from the performance matching runs at $N_{hp} = 0.9553$ and 1.006 both give results with acceptable accuracy.

Let us now examine the impact of this inlet temperature problem on the Topping test maximum TRQ predictions for the engine. The results are as in Table 39.

Table 39 - Topping Test Results for Engine 78095, Bell 212 Performance Matching

Ambient Conditions: 5,000 ft ISA, +20°C	% TRQ	% TRQ Margin	Active Limiter
Required to Pass	49.3		
Performance Matching done at:			
$N_{hp} = 0.901$	48.1	-1.2	Trimmed ITT
$N_{hp} = 0.955$	50.7	1.4	N_{hp}
$N_{hp} = 1.006$	51.1	1.8	N_{hp}

As the outside air temperature was several degrees lower than the compressor entry temperature, using the outside air temperature instead of the compressor inlet temperature will result in an overestimation of engine decay. As can be seen in Table 39, the maximum power prediction made using the $N_{hp} = 0.901$ performance matching scaling factors predicts a failure of the Topping test. From our other results, we have already concluded that the engine will pass the test. The main reason for this is an elevated compressor intake temperature at $N_{hp} = 0.901$ which was not taken into account in the performance matching process. This unaccounted for high intake temperature caused an under estimation of the engine power output. The two maximum power predictions using component performance scaling factors obtained at higher values of N_{hp} are only around 1% low.

5.10.2.2 Power Section 78117

Let us now repeat the Bell 212 Topping test on power section 78117. In Table 40, we see a significant variation in the scaling factors with respect to the gas generator spool speed at which the performance matching routine was performed. This variation is consistent with that observed earlier. Figure 24 in Chapter 4 reveals a smaller elevation in the intake temperature for this power section than for power section 78095. Therefore, the effects due to inlet temperature errors should be less severe for power section 78117.

Table 40 - Scaling Factors for Engine 78117, Bell 212 Performance Matching

N_{hp}	ΔW_c	$\Delta \eta_{HPT}$	$\Delta \eta_{PT}$	Cost Function
0.981	-7.312	-1.548	2.539	1.00E-04
0.953	-9.743	-1.859	3.977	1.00E-04
0.928	-12.433	-3.003	4.946	1.00E-04
0.900	-14.681	-3.703	2.485	2.43E-02
0.876	-15.000	-3.159	3.227	1.30E-03

In Figure 47, we see that there is excellent agreement between the output power predicted using the two higher gas generator spool speeds indicated and the tested power. Once again, the results predicted using the scaling factors determined at $N_{hp} = 0.9$ are considerably low. Figure 24 in Chapter 4 reveals that at this speed the difference between the ideal NRC T400 compressor intake temperature and the measured value has increased from that at higher gas generator speeds.

Figure 47 - Comparison of Scaled NRC T400 Model Corrected SHP Obtained using Scaling Factors in Table 40 with Tested SHP of Engine 78117

The Topping test results in Table 41 show the same trend as for power section 78095. The maximum output power predicted using component performance scaling factors determined at lower speeds are not as accurate as those found at higher speeds. As in Figure 46, the results in Figure 47 for values of N_{hp} greater than 0.95 are reasonable. Once again, our power section passes the Topping test.

Table 41 - Topping Test Results for Engine 78117, Bell 212 Performance Matching

Ambient Conditions: 5,000 ft ISA, +20°C	% TRQ	% TRQ Margin	Active Limiter
Required to Pass	49.3		
Performance Matching done at:			
$N_{hp} = 0.900$	44.1	-5.2	Trimmed ITT
$N_{hp} = 0.953$	51.5	2.2	Trimmed ITT
$N_{hp} = 0.981$	52.5	3.2	Trimmed ITT

5.10.3 Bell 212 Test Setup Using Measured Compressor Intake Temperature

As a final check, the performance matching routine was repeated on power section 78095 using the Bell 212 instrument configuration. In this case, the measured compressor inlet temperature has been used in addition to the outside ambient temperature. The compressor inlet temperature has been set to the measured value, and the required handling bleed leakage in excess of the nominal bleed schedule required to produce the observed temperature rise has been calculated and used.

Table 42 - Scaling Factors for Engine 78095, Bell 212 Performance Matching Using Compressor Inlet Temperature

N_{hp}	ΔW_c	$\Delta \eta_{HPT}$	$\Delta \eta_{PT}$	Hand. Bld.	Cost Function
1.006	-1.522	2.095	3.274	6.258	1.00E-04
0.981	-2.374	1.960	3.542	6.012	1.00E-04
0.956	-2.738	1.534	4.688	6.671	1.00E-04
0.926	3.644	2.435	7.327	12.928	1.00E-04
0.902	2.817	2.817	2.817	18.771	2.41E-01

As seen in Table 42, the same handling bleed flows are predicted here as in the full NRC instrumentation case. However, here only three other component characteristics are altered. As a result, the performance algorithm has been unable to compensate for the large apparent bleed flow at the lower speeds in Table 42. Therefore, we see a sudden switch from a drop to a predicted increase in the compressor flow. It should be noted that it is highly unlikely that this change is actually occurring in the engine.

Figure 48 - Comparison of Scaled NRC T400 Model Corrected SHP Obtained using Scaling Factors in Table 42 with Tested SHP of Engine 78095

Using the scaling factors in Table 42, we may predict the power output of power section 78095 as shown in Figure 48. An accurate prediction of the power section power output for all of the values of N_{hp} for which the performance matching routine was used is revealed in this figure.

The Topping test results shown in Table 43 performed using the scaling factors in Table 42 reveal the same trend which has been observed all along. The performance predictions obtained through the use of engine test data taken at lower power settings tend to be low. However, the spread in the predicted TRQ is not excessive. Viewing the overall picture, we may conclude that the engine will marginally pass the Topping test.

Table 43 - Topping Test Results for Engine 78095, Bell 212 Performance Matching

Ambient Conditions: 5,000 ft ISA, +20°C	% TRQ	% TRQ Margin	Active Limiter
Required to Pass	49.3		
Performance Matching done at:			
$N_{hp} = 0.901$	47.7	-1.6	N_{hp}
$N_{hp} = 0.955$	51.0	1.7	N_{hp}
$N_{hp} = 1.006$	51.4	2.1	N_{hp}

Chapter 6

Conclusions and Recommendations for Further Work

6.1 Conclusions

From the work which has been done, the following conclusions may be arrived at:

1. The nominal NRC T400 aerothermodynamic model accurately predicts the performance of a T400 gas turbine as compared to the P&WC thermodynamic model P1520 and NRC test data.
2. The performance matching process developed in Chapter 5 is capable of accurately reproducing the performance of a tested T400 power section through the use of a computer model. This applies to both an engine on a test bed or a standard Bell 212 installation. This provides a quick method of estimating the engine performance over the flight envelope of the helicopter through the use of only a few test data points.
3. The Topping test procedure presently carried out by the Canadian Department of National Defence may be carried out using the alternative process developed in Chapter 5 without consuming engine life through high power operation. The original Topping test has to a large extent been discontinued for this reason, and therefore this new alternative test is capable of providing valuable engine power data which could not otherwise be obtained.
4. The NRC T400 model is useful for the purpose of component fault diagnosis and isolation in the T400 engine. At the present time there are no thermodynamic models of the T400 engine capable of modeling engine faults available to the users of the engine, and therefore NRC T400 would be a considerable contribution to engine health monitoring work.

5. To a first approximation, fault signatures of individual engine faults such as a compressor flow reduction or an HPT efficiency reduction may be added for part power operation. For maximum power operation, the effects of multiple faults do add, but the result is then “clipped” through the action of the maximum engine power limiters. As a result, this principle of superposition applies only at part power.

6. The temperature lapse rate exponents found using P1520 and NRC T400 data are in agreement for a wide selection of engine parameters.

The agreement between the NRC T400 and P&WC P1520 models has been verified in Chapter 3 for ambient temperatures of up to 37°C and altitudes of up to 10,000 ft

A greater number of measured engine parameters appears to improve the accuracy of the performance matching process. The performance matching process cannot include every possible fault which may occur in an installed T400 engine. Fewer engine parameters used will generally mean that a simplification of the actual engine faults will be arrived at. For instance, an intake blockage may be modeled by scaling down the compressor flow so as to match the engine performance. As a result, faults detected through the performance matching process must be verified through engine inspection. It would appear that obtaining the correct compressor entrance temperature is highly important for the performance matching process.

The temperature lapse rates found are generally different from the classical values, but their magnitudes are within a reasonable range. The tightness of the collapse of the engine performance data with temperature correction is not highly dependent on small changes in the temperature exponents.

6.2 Recommendations for Further Work

Through the work performed in the development and use of the NRC T400 model, areas where further work would be beneficial have been identified. It is believed that there are two main areas where further work would be the most beneficial. The first involves the application of the fault detection techniques of Chapter 4 on real engines. The second involves the extension of the NRC T400 model from steady state performance prediction to transient operation. A few smaller improvements to the NRC T400 model will then be discussed.

In Chapter 4, a list of potential faults such as a compressor or turbine blade tip clearance increase due to erosion were introduced as possible causes of the changes observed in the measured engine parameters. No definitive conclusions could be made about which type of engine damage was responsible for the change of performance of each engine. To do so would require more information about the relationship between the component characteristic flow, efficiency or PR and the presence of specific mechanical damage. Such information could be done by trending the changes in the measured engine parameters over time, and then tearing down the engine to verify what mechanical damage has occurred. The feedback from the engine inspection would enable the correlation of thermodynamic changes in engine performance to the various types of mechanical damage which may occur. Furthermore, it should be possible to correlate the mechanical engine damage which has occurred with life history of the engine. For example, we might expect blade tip clearance increases from sand being centrifuged in the compressor if the engine is operated in a dusty environment.

Also, a more detailed investigation of the installation effects on the engine performance would be useful. This could include measuring the compressor intake and engine exhaust temperatures and pressures more accurately. For the compressor, this could involve the usage of multiple wedge probes spaced evenly around the intake annulus which could obtain a better resolution of the intake flow. A similar thing could be done at the exhaust

flange of the engine where the exhaust nozzle is attached. The information from such testing would enable the engine installation conditions to be removed as a factor in the component scaling factors found in Chapter 5 or the engine fault signatures in Chapter 4. A more precise estimate of the power section condition could then be obtained.

To perform diagnostic work on the T400 control systems such as the air fuel control unit (AFCU), it is necessary to have a transient performance model of the engine. For steady state operation, things such as the fuel flow are fixed by the operating state of the various engine components. It is only when the engine is accelerating or decelerating that the control system inputs may be isolated. If data can be acquired relating to the nominal performance of the engine control systems, abnormalities in these systems will then be detectable during engine transients by comparison with the nominal control response. Transient performance modeling will also enable the user of NRC T400 to perform acceleration checks using the model instead of the actual power section in the same manner as the Topping test of Chapter 5. Finally, the inclusion of transient analysis will enable a more realistic analysis for the use of engine lifting studies.

A few “loose ends” which could be tied up include a more precise study on the relationship between the static and total compressor delivery pressure. The NRC T400 model at present can only estimate the static pressure from the total. Some steps may be taken to address the problem of convergence experienced by the performance matching algorithm as described in Chapter 5. This relates to the maximum convergence of the Newton-Raphson component matching routine described in Chapter 2. It may be possible to improve the final convergence of the performance matching routine by adding the component matching procedure described in Chapter 2 to it. Also, moving to a non linear interpolation of the compressor and turbine characteristics may improve the final convergence.

Further engine testing under a wider range of ambient temperatures would allow a more definitive verification of the temperature correction exponents which have been derived in

Chapter 3. Also, a closer study of the NRC T400 predicted maximum engine power at low altitudes and hot temperatures needs to be performed to determine why the model predictions are high. An investigation of how the Figure 42 was compiled in this flight regime would be also useful.

Finally, the technique of isolating instrumentation faults through the use of engine thermodynamics should be examined. Unfortunately, due to time limitations it was not possible to address this issue. The performance matching routine which has been developed is well suited for this purpose. The NRC T400 performance matching routine will have difficulty matching a temperature measured from a damaged thermocouple. Also, the usage of various engine parameter combinations in the performance matching process should yield varying degrees of success. If the convergence is poor if one particular parameter is used but fine using other parameters, the instrument measuring the former parameter is suspect.

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Figure 49 - Appearance and Installation of the P&WC T400
(Pratt & Whitney Canada Brochure)

Appendix: Block Diagrams for NRC T400/GASTURB Calculations:

The following block diagrams describe in a simplified manner what operations are performed by the NRC T400 variant of GASTURB for each of the operations specified in Figure 48 during component matching. They describe calculations performed for steady state off design performance only. In addition to this, the software also always calculates the design point state of the engine before handling off-design calculations, as some of the design point information will be needed. The on-design engine parameters are used in the calculations that follow, and for scaling component maps which are read from disk.. For the block diagrams below, some explanations are required. Gas properties such as the enthalpy (H) and the specific heat ratio (k) are calculated using a “half ideal gas” assumption which is described by Kurzke (1995). Polynomial equations are used to calculate values for H , k , C_p , and ϕ , which are assumed to vary with temperature only. The variable ϕ is an entropy function used for interpolation for H and PR , including the component efficiency. Pratt & Whitney Canada for their model specification engine (1973) assume a hydrocarbon fuel with a lower heating value of 18300 BTU/LB (43.124 kJ/kg). This model has done the same. The combustion products of this fuel are assumed to have the same molecular weight as dry air. It is assumed that no dissociation occurs in combustion products.

For the diagrams below, the arrows on the left hand side represent variables being input to the block, while those on the right hand side represent outputs from the block. Dotted arrows represent variables being passed on from the block but which are not changed by the block. There are several variables used in the calculations mentioned below which do not appear as inputs on the left hand side. These are considered as characteristic properties of the component being modeled for the purpose of these diagrams, and are not passed from block to block.

These variables are as follows:

Bleed Flows (HPC): $W_{nb}, W_{gdb}, W_{pdb}, W_{hb}, W_{obd}$

Blow off set points: $\left(\frac{W_{hb}}{W_2}\right)_{open}, \frac{N}{\sqrt{\Theta_{25}}}\bigg|_{open}, \frac{N}{\sqrt{\Theta_{25}}}\bigg|_{closed}$

In addition to these variables, there are others which are input into the various blocks below for this appendix only. A brief list of these is as below:

$\Delta\eta_{effects}$	-	Input values keyed in by the user to modify efficiency The LPC, HPC and PT each may have different values.
PW_{po}	-	HP spool power takeoff
$\Delta\eta_{wrtN}$	-	Used to account for some variation in the HPT efficiency due to changes in N_{HP} . This is a linear correction.
Q	-	Corrected air flow: $Q = \frac{W\sqrt{\Theta}}{\delta}$

In addition to the four errors as mentioned in Figure 48, If we choose to use maximum power limiters, there will be a fifth error to deal with. This error is the difference between the specified limiting variable, and the calculated variable as shown below.

$$Error = \frac{Value - Value_{maximum}}{Value_{maximum}}$$

Error values are calculated for each limiter variable selected, and the largest error amongst these is used as the fifth matching error. When limiters are being used, both T_4 and N_{HP} in the combustion chamber block below must be guessed.

Table 44 - GASTURB Capabilities

Task	Description
On Design Calculations	A standard cycle calculation with specified component efficiencies, mass flows and pressure ratios as mentioned above.
Compressor Design -Not Used	Calculates the compressor inlet area and design speed from the intake flow conditions and the inlet radius ratio and blade tip speed. The compressor efficiency can also be calculated.
Turbine Design -Not Used	Calculates roughly the turbine geometry and efficiency. It does this using a mean blade section and radius, and assumes symmetrical velocity triangles for each stage except the first, for which an axial inlet flow is assumed.
Steady State Off-Design	As described below and in Figure 48
Transient Calculations -Not Used	An extension of the steady state off design model which allows for power to be used to accelerate or decelerate the spool speeds, as well as incorporating a tunable proportional integral derivative (PID) control scheme. Other effects such as heat transfer are not accounted for.
Distortion Calculations -Not Used	Calculates the effect of a pressure or temperature distortion over a sector of a compressor inlet by handling the clean and distorted flow separately as if they flowed through two compressors in parallel with each other having the same static back pressure.
Effects Calculations	One can select variables to change and variables for which the effects of these changes are calculated. The results are presented in tabular form with the first column displaying the variable which is changed, the second and third showing the change in this variable, and the remaining columns showing the percent change in the dependent variables, or the change in temperature if a temperature has been selected.
Limiters	As mentioned above.

In addition to steady state modeling, GASTURB as provided is capable of dealing with transient modeling and inlet pressure and temperature distortion effects which have not been used for the purpose of the present work. A brief tabulation of the capabilities of GASTURB is as shown in Table 44.

A final mention is needed concerning the modeling of engine faults. In GASTURB as purchased the user has the option to input changes to the efficiencies of the LPC, HPC, HPT, and PT. Also, the flow capacity of the HPT and PT may be changed by the user to simulate turbine erosion. In addition, the software has been altered to allow the user to scale the LPC and HPC corrected flow to simulate faults such as blade fouling and tip clearance increases. The corrections are applied in the off design matching process only and are implemented by scaling the values read from the various component maps.

Figure 50 - PT6/T400 Matching Procedure in GASTURB

Figure 51 - Block Diagram of Intake Calculations

Figure 52 - Block Diagram of Axial (LPC) Compressor Calculations

Figure 53 - Block Diagram of Blow-off Valve Calculations

Figure 55 - Block Diagram of the Combustion Chamber Calculations

Figure 56 - Block Diagram of Gas Generator (HPT) Turbine Calculations

Figure 57 - Block Diagram of Power Turbine (PT) Calculations

Figure 58 - Block Diagram of Engine Exhaust Duct and Nozzle Calculations

Figure 59 - Block Diagram of Newton-Raphson Iteration Scheme

Performance Matching Routine Implemented with NRC T400

unit Matching;

{ \$O+,N+,E+ }

```
{ *****
*   PT6/T400 test data performance matching Procedure.  This procedure works to scale
*   the NRC T400 computer model to match the engine test data as closely as possible.
*   It receives from the nominal NRC T400 model and from a data file of engine test data
*   the following variables:
*
*   Pamb, Tamb, SHP, Wf, NG, T2, T3, P3s, ITT, EGT, W2, Nf.
*
*   Using these, a cost function is analyzed and the program attempts
*   to set the above variables equal for both the engine test and models.
*
*   This matching is done by manipulating the following variables in the
*   NRC T400 nominal performance model:
*
*   LPC, HPC, HPT, PT, Handling Bleed mass flows
*   LPC, HPC, HPT, PT efficiencies
*
*   The new calculated cycle parameters are accessed directly from
*   GASTURB, while the input data file and the "goodness of fit"
*   between the test and model results are accessed through an input file.
*   This is a new Turbo Pascal 7.0 unit which has been added to the basic GASTURB
*   package to perform the function described above.
***** }
```

interface

uses

Tprp_cyc, glob_cyc, simpprop, mathemat, util_1, util_2, disk_cyc,
 Crt, util_3, od_point;

const

NumZeroIts = 15;

type

data_point = array [1..12,1..30] of real;

Pdata_point = ^data_point;

data_o = array [1..30,1..30] of real;

Pdata_o = ^data_o;

Itry = Array [1..7] of real;

pctype = Array [1..8,1..7] of real;

ytype = Array [1..8] of real;

var

data_out : Pdata_o;

data_to_read : Array [1..12] of byte;

problem : boolean;

{ data : Pdata_point; <- defined globally in Pascal in another unit. This
 variable holds the data read in from the engine test data file }

{ pointnum : byte; <- Also defined globally. indicates the test data
 point number in use }

total : byte; {total number of dimensions in simplex routine }

chics_to_change : Array [1..7] of byte; {indicates which of the component
 characteristics are to be scaled. See function COST for details of
 which array index applies to which scaling factor }

chic_assign : Array [1..7] of byte; { An array indicating the index numbers of
 the component scaling factors in the simplex vertices which
 correspond to the chics_to_change indices above. }

x : byte; {used in setting iterate_hist }

finish	: boolean;	{ Stop if calculation is within GASTURB error!}
p	: ptype;	{ simplex vertices, each containing all relevant scaling factors}
y	: ytype;	{ cost function evaluated at each simplex vertex}
dummysp	: ptype;	{ Saves previous solution for restarts}
Restart	: boolean;	{ Indicates whether a restart is to be performed}
iterate_hist	: Array [1..NumZeroIts] of integer;	{ helps in convergence}
count2	: byte;	{ Number of restarts done on a given data point}
numberpoints	: byte;	{ Total number of data points in test input file}
Bleed_info	: ytype;	{ % Handling bleed in excess of the nominal bleed valve scheduling. i.e. amount of handling bleed leakage}

Procedure Match(last_file_name : string80); { Called from GASTURB to handle performance matching process}

Function cost(p_in : Itry; j : integer): real; { Performs the cost function using test and NRC T400 data. This is the function used in the simplex minimization}

Function ranl : real;

implementation

Function cost(p_in : Itry; j : integer): real;

{ This function calculates the overall function which this algorithm will seek to minimize. It consists of two parts. The first is the basic difference between the test data and the GASTURB output, the second is the calculation of penalty functions if the solution is getting out of a reasonable range}

{p_in above contains the coordinates of the vertex for which the cost function is being calculated. The variable j corresponds to the simplex vertex index number}

var

Error : real; {Individual errors calculated for each measured parameter}

Total Error : real; {The sum of the individual errors above}

Penalty : real; {Individual penalties applied to cost function if scaled component characteristics are out of a reasonable range}

Total Penalty : real; {The sum of the penalties above}

Gtout : Array [1..8] of real; {Array of results for NRC T400 predicted engine parameters}

Max Lim : Array [1..7] of real; {Max allowable component scaling factors}

Min Lim : Array [1..7] of real; {Min allowable component scaling factors}

```
k, l           : byte;           {Loop counting variables}
```

valid,

off map, {true if component operating point moves off of map}

converged : boolean; {True for sucessful convergence}

```
map_error      : integer;           { Given if a problem arises with component
                                     map }
```

begin

{ Set Gasturb input parameters from simplex vertices }

{If the test data input file indicates that this component characteristic is to be scaled, scale it. For details on the `chic_assign` variable, see the data input routine `Load_Test Data` below or the variable definition above}

if chics to change[1] = 1 then {Scaling compressor flow?}

begin

```
Basic data ptr^i value[35] := p in[chic assign[1]]; {Compressor Flow reduction}
```

```
Basic data ptr^i value[36] := p in[chic assign[1]]; {Both compressor sections}
```



```

end
else
begin
    Basic_data_ptr^.i_value[35] := 0.0;
    Basic_data_ptr^.i_value[36] := 0.0;
end;

if chics_to_change[2] = 1 then                {Scaling compressor efficiency?}
begin
    od_data_ptr^[2].i_value[17] := p_in[chic_assign[2]]; {Compressor Efficiency}
    od_data_ptr^[2].i_value[18] := p_in[chic_assign[2]]; {Reduction - both sections}
end
else
begin
    od_data_ptr^[2].i_value[17] := 0.0;
    od_data_ptr^[2].i_value[18] := 0.0;
end;

if chics_to_change[3] = 1 then                {Scaling HPT flow?}
    od_data_ptr^[2].i_value[14] := p_in[chic_assign[3]] {HPT Flow reduction}
else
    od_data_ptr^[2].i_value[14] := 0.0;

if chics_to_change[4] = 1 then                {Scaling HPT efficiency?}
    od_data_ptr^[2].i_value[19] := p_in[chic_assign[4]] {HPT Efficiency reduction}
else
    od_data_ptr^[2].i_value[19] := 0.0;

if chics_to_change[5] = 1 then                {Scaling PT flow?}
    od_data_ptr^[2].i_value[15] := p_in[chic_assign[5]] {PT flow reduction}

```

```

else
    od_data_ptr^[2].i_value[15] := 0.0;

    if chics_to_change[6] = 1 then                { Scaling PT efficiency?}
        od_data_ptr^[2].i_value[20] := p_in[chic_assign[6]] {PT efficiency reduction}
    else
        od_data_ptr^[2].i_value[20] := 0.0;

    if chics_to_change[7] = 1 then                { Scaling Handling bleed leakage?}
        Basic_data_ptr^.i_value[11] := p_in[chic_assign[7]]/100.0 {Handling bleed leakage}
    else
        Basic_data_ptr^.i_value[11] := 0.0;

    {Update output data pointer with these values to write to an output data file later}
    for k := 1 to 7 do
    begin
        if chics_to_change[k] = 1 then
            data_out^[k+5,pointnum] := p_in[chic_assign[k]]
        else
            data_out^[k+5,pointnum] := 0.0;
        end;

    problem := false;
    {Calculate the Gasturb Off-Design Point}
    calculate_off_design_point (0,valid,off_map,converged,map_error);
    {if we have a problem with the Gasturb convergence, deal with it now}
    if not converged then
        problem := true;

    if x > NumZeroIts then    {compile a history of # of loops required by component}

```

```

    x := 1;                {matching. If a string of one iteration matchings occur}
iterate_hist[x] := iteration_loops;    {we may conclude that the performance}
inc(x);                    {matching routine has converged}

{if all of loop history indicates single iteration component matching, stop calculating}
l := 0;
for k := 1 to NumZeroIts do
    if iterate_hist[k] > 1.5 then
        inc(l);
if l = 0 then
    finish := true;

if entrytemps then
    Bleed_info[j] := Bleed_flow; {calculated in NRC T400 model, as explained above}

if not problem then {if the above goes O.K., then let us proceed!}
begin
{Set Gasturb results from last iteration to SI units}          {Variable - units used:}
    GTout[1] := Basic_data_ptr^.o_value[55]*unit_con[8];      {P3s      -kPa}
    GTout[2] := Basic_data_ptr^.o_value[22]*unit_con[2];      {ITT      -deg K}
    GTout[3] := Basic_data_ptr^.o_value[1] *unit_con[4];      {PWSD     -kW}
    GTout[4] := Basic_data_ptr^.o_value[7] *unit_con[3]*3600; {Fuel Flow -kg/s}
    GTout[5] := Basic_data_ptr^.o_value[25]*unit_con[2];      {EGT      -deg K}
    GTout[6] := Basic_data_ptr^.o_value[30]*unit_con[3];      {Intake flow -Kg/s }
    GTout[7] := Basic_data_ptr^.o_value[17]*unit_con[2];      {T3       - deg K}
    GTout[8] := Tentry;    {Compressor Entry Temp (deg K) if entrytemps = true}

{NOTE: GTout[8] is handled separately before other errors & is only
    calculated if both the ambient and compressor entry temps are in the data file }

```

```

{ Again, let us save the gasturb outputs to our output file for
later viewing first}
for k := 1 to 7 do
begin
    if data_to_read[k+5] = 1 then
        data_out^[k+12,pointnum] := GTout[k]
    else
        data_out^[k+12,pointnum] := 0.0;
end;
if data_to_read[3] = 1 then {output calc T2}
    data_out^[20,pointnum] := GTout[8]
else
    data_out^[20,pointnum] := 0.0;

{convert P3s to Pa}
GTout[1] := GTout[1]*1000; {P3 static - Pa}

{sum up errors for each parameter (EGT for example)}
Total_Error := 0.0; {Set initial total error to zero}
Error := 0.0;

{We proceed to calculate the cost function here}
for k := 1 to 7 do
begin
    if data_to_read[k+5] = 1 then
    begin
        {Calculate out all of the errors - pointnum is the point # being worked on}
        Error := 2.0*abs(data^[k+5,pointnum]-
            GTout[k])/(abs(data^[k+5,pointnum])+abs(GTout[k]));
        if data^[k+5,pointnum] <> 0 then

```

```

        data_out^[k+23,pointnum] := 100*(Gtout[k]-
        data^[k+5,pointnum])/data^[k+5,pointnum]
    else
        data_out^[k+23,pointnum] := 0.0;
    {Calculate the Cost Function}
        Total_Error := Total_Error+Error;
    end
    else
    begin
        data_out^[k+23,pointnum] := 0.0;
        Error := 0.0;
    end;
end;

{Calculate out all of the penalties for parameter limit violations:}
{Parameters here are those component characteristics being modified}

{Set limiters so that component characteristics are out of a reasonable range
These limiters are expressed as percent changes from the unscaled component
characteristics}
Min_Lim[1]    := -15; {Min compressor flow % change}
Max_Lim[1]    := 10; {Max compressor flow % change}
Min_Lim[2]    := -10; {Min compressor efficiency " "}
Max_Lim[2]    := 10; {Max compressor efficiency " "}
Min_Lim[3]    := -10; {Min HPT flow " "}
Max_Lim[3]    := 10; {Max HPT flow " " - TEST SETTING}
Min_Lim[4]    := -10; {Min HPT efficiency " "}
Max_Lim[4]    := 10; {Max HPT efficiency " "}
Min_Lim[5]    := -10; {Min LPT flow " "}
Max_Lim[5]    := 10; {Max LPT flow " "}

```

```

Min_Lim[6]    := -15; {Min LPT efficiency " "}
Max_Lim[6]    := 20; {Max LPT efficiency " "}
Min_Lim[7]    := 0.; {Min Handling Bleed Wbld/W2}
Max_Lim[7]    := 10; {Max Handling Bleed Wbld/W2}

Total_Penalty := 0.0; {Initialize the Penalty function}
for k := 1 to 7 do
begin
  if chics_to_change[k] <> 1 then
  begin
    Penalty := 0.0;
    Total_Penalty := Total_Penalty+Penalty;
  end
  else
  begin {penalties for data available}
    Penalty := 0.0; {First, assume no penalties!}
    if P_in[chic_assign[k]] > Max_Lim[k] then
      Penalty := 1+ abs(1000*(P_in[chic_assign[k]]-Max_Lim[k])); {changed!}
    if P_in[chic_assign[k]] < Min_Lim[k] then
      Penalty := 1+ abs(1000*(Min_Lim[k]-P_in[chic_assign[k]])); {changed}
    {Calculate the penalty function}
    Total_Penalty := Total_Penalty+Penalty;
  end;
end;

{Add the penalty to the cost function for the total cost}
cost := Total_Error+Total_Penalty;
end; {calcs if problem = false}
end; {cost}

Function ran1 : real;

```

```

var
  ran      : real;
begin {generates random real #'s between 0 and 1}
  Randomize;
  ran      := random(65535)/65535.0;
  if (ran < (1/65535.0)) then {prevent ran1 = 0!}
    ran     := 1/65535.0;
  ran1     := ran;
end; {ran1}

procedure Match(last_file_name : string80);
{This is the procedure which does the performance matching and DND Topping test
routines}

```

```

var
  Not_finished      : boolean;
  Choice            : byte;
  next_choice       : byte;
  esc_pressed       : boolean;
  tolerance         : real;
  test_source       : string5;
  count            : byte;
  numfunc           : integer;
  jj               : byte;

```

```

procedure Select_option (Not_finished : boolean; var Choice : byte);

```

{This is a GASTURB procedure which has been used here for our purposes. It displays a menu on the screen and asks the user to select from the following choices:

Choice #1: Load Test Data File

Choice #2: Save Matched GASTURB File

Choice #3: Match Model to Data

Choice #4: Save Model Matching Results

Choice #5: Bell 212 Topping Test

The user selects the desired choice and this routine returns the variable Choice indicating the operation to be performed}

end; { Select_option }

procedure Save_GASTURB_data;

{This procedure simply calls a GASTURB routine which stores the present engine operating conditions and state to a standard GASTURB data file}

var

stored : boolean;

begin

repeat

Store_on_Disk (200,10,20,CycleFile,
EngineType,
stored);

until stored;

end; {Save_GASTURB_data}

procedure Load_test_data (last_file_name : string80;

var Not_finished : boolean);

{This procedure loads the engine test data from a data file and sets which engine parameters are to be used for the cost function and which component characteristics are to be scaled.}

var


```

i, j          : byte;          {Loop counting variables}
Error         : integer;
Filename      : string80;      {Holds test data input file name}
inputfile     : text;
title_read    : boolean;       {is input file title read?}
Trim          : real;          {for correcting trimmed ITT}

```

```
begin
```

```

    Error := 0;
    read_File_Name (900,10,30,true,last_file_name,FileName,Error);
    Reset_Screen;                {Reads the input file name}

```

```
if (FileName='no file') or (Error > 0) then
```

```

    begin
        Error:=1;
        exit;
    end;

```

```

last_file_name:= ' ';
open_file_for_read(FileName,inputfile,Error); {opens data file and returns handle}

```

```
If Error = 0 then                {Check to see if file found and opened OK}
```

```

begin
    Not_finished := false;
end;

```

```
if (Error=2) or (Error=3) then
```

```
    wait_for_action;
```

```
if (Error=0) then                {Procede if all is well}
```

```

begin
  for i:= 1 to 7 do
    begin
      chic_assign[i]:= 0;          {Initialize chic_assign array}
    end;

    {First, read the number of test data points to read in and use}
    readln(inputfile,numberpoints);

    {Now, read in the ITT trim used in the engine as explained in Chapter 5}
    readln(inputfile,Trim);

    {Next, indicate which of the available test data are to be used. Which engine
    parameters such as SHP, ITT ect are to be used in the cost function?}
    for i := 1 to 11 do
      begin
        read(inputfile,data_to_read[i]);
      end;
      readln(inputfile,data_to_read[12]);

      entrytemps := false;
      if (data_to_read[3] = 1) and (data_to_read[4] = 1) then
        entrytemps := true;          { Set true if both ambient and compressor intake
                                     temps available - special treatment given in this
                                     case}

      {Now, read in which component characteristics that you want to play with}
      total := 0;
      count := 1;
      for i := 1 to 6 do

```

```

begin
  read(inputfile,chics_to_change[i]);
  {If chics_to_change[i] "1", then component scaling factor "I" is scaled}
  if (chics_to_change[i] = 1) then
    begin
      total          := total+1;    {find # of dimensions}
      chic_assign[i]  := count;      {assign indices to each simplex vertex
                                     dimension}

      count          := count+1;
    end;
  end;

  {Repeat the above process for the last dimension}
  readln(inputfile,chics_to_change[7]);
  if entrytemps then
    chics_to_change[7] := 0;        {if Tamb and T2 avail - solve explicitly!}
  if chics_to_change[7] = 1 then {for handling bleed manipulation}
    begin
      total          := total+1;    {repeat above for last pt}
      chic_assign[7]  := count;
    end;

  {Now, read in the test data}
  for j := 1 to numberpoints do
    begin
      for i:= 1 to 12 do
        begin
          if i < 12 then
            begin
              read(inputfile,data^[i,j]);

```

```

        if i <= 5 then
            data_out^[i,j] := data^[i,j];
        end
    else
        begin
            readln(inputfile,data^[i,j]);
        end;
    end;
end;
close(inputfile);
end;

{ Sets some conversion factors to be used}
if SI then
begin
    for i:=1 to NumberofConversionFactors do
        unit_con[i]:=1;
    end
else
begin
    for i:=1 to NumberofConversionFactors do
        unit_con[i]:=conv[i];
    end;

    {Now, apply these conversion factors to the data just read from
    file}

{Unit Conversions for input from NRC T400 file with implanted faults}
if Trim <1 then
begin

```

```

for j := 1 to numberpoints do                                {Variables - Units}
begin {GASTURB Ouput Values:}
  data^[1,j]      := data^[1,j];                             {Mech Nhp}
  data^[2,j]      := data^[2,j];                             {Mech Npt}
  data^[3,j]      := data^[3,j] *unit_con[2];                {Tamb -K}
  data^[4,j]      := data^[4,j] *unit_con[2];                {Comp entry temp -K}
  data^[6,j]      := data^[6,j] *unit_con[8]*1000;           {P3s -Pa}
  data^[5,j]      := data^[5,j] *unit_con[8]*1000;           {P2 -Pa}
  data^[7,j]      := data^[7,j] *unit_con[2];                {ITT -K }
  data^[8,j]      := data^[8,j] *unit_con[4];                {PWSD-K}
  data^[9,j]      := data^[9,j] *unit_con[3]*3600;           {Wf -kg/hr }
  data^[10,j]     := data^[10,j] *unit_con[2];                {EGT -K }
  data^[11,j]     := data^[11,j] *unit_con[3];                {W2 -kg/s}
  data^[12,j]     := data^[12,j] *unit_con[2];                {T3 - comp del temp - k}
end;
end;

```

{Second copy is NRC Test Data Input}

```

if Trim >= 1 then
begin
  for j := 1 to numberpoints do
  begin {might want to change below!}                        {Measured Test Values:}
    data^[1,j]    := data^[1,j] /37800.0;                    {Mech Nhp}
    data^[2,j]    := data^[2,j] /33000.0;                    {Mech Npt}
    data^[3,j]    := data^[3,j] *unit_con[2];                {Tamb -K}
    data^[4,j]    := data^[4,j] *unit_con[2];                {Comp entry temp -K}
    data^[6,j]    := (data^[6,j] +data^[5,j])*unit_con[8]*1000; {P3s -Pa}
    data^[5,j]    := data^[5,j] *unit_con[8]*1000;           {P2 -Pa}
    data^[7,j]    := data^[7,j] +273.15+Trim/1.8;            {ITT -K }
    data^[8,j]    := data^[8,j] *unit_con[4];                {PWSD-K}

```

```

    data^[9,j]    := data^[9,j]  *unit_con[3];      {Wf -kg/hr }
    data^[10,j]   := data^[10,j] +273.15;          {EGT -K }
    data^[11,j]   := data^[11,j] *unit_con[3];      {W2 -kg/s}
    data^[12,j]   := data^[12,j] *unit_con[2];      {T3 - comp del temp - k}
  end;
end;

end; {Load_test_data}

procedure Save_Matched_Data;

var
  i,j              : byte;
  Filename         : string80;
  foutput          : text;
  fileopen         : boolean;
  oldoutname       : string80;

begin
  { Open output file using GASTURB routine}
  FileName := '';
  open_File_for_write(900,10,30,oldoutname,FileName,foutput,fileopen);
  oldoutname := FileName;

  if fileopen then
    begin
      {Each of the output parameters listed below corresponds to the indices of the
      data_out pointer which follows. The output is written to file in a tabular format
      with the lines directly below as the header and the data_out pointer filling in the
      data below.}

```

```

writeln(foutput,'GASTURB Model to Test Data Matching Results');
writeln(foutput);
write(foutput,'Nhp          Nlp          Tamb          T2          P2
          Delta Wc      ');
write(foutput,'DeltaEffc      Delta Whpt      Delta Effhpt      Delta Wlpt      Delta
          Efflpt          Delta HBld      ');
write(foutput,'P3s          ITT          PWSD          Wf          EGT
          W2          ');
write(foutput,'CDT          Calc T2          # func evals      cost func      T2
          error(%)      P3s error(%)      ');
writeln(foutput,'ITT error(%)          PWSD error(%)          Wf error(%)      EGT
          error(%)      W2 error(%)      CDT error(%)      ');

{ The output data are now written to file}
for i := 1 to numberpoints do
  for j:= 1 to 30 do
    begin
      if j < 30 then
        write(foutput,data_out^[j,i]:14:4)
      else
        writeln(foutput,data_out^[j,i]:14:4);
    end;
  close(foutput);
end;

end; { Save_Matched_Data}

procedure Restart_Minimization(count2 : byte);
{ This procedure will restart the simplex routine to follow to ensure that the performance

```

matching run has not snagged itself at a point which is not the global minimum which is being searched for}

type

Pitry = ^Itry;

var

j, k : byte;

sign : real; {Sets a number as being positive or negative}

summ : integer; {Used to see if the restart has converged to same solution as previous run}

guessp : Pitry; {Used to reset new simplex vertex coordinates around convergence point of previous run}

rand1 : real; {Random numbers}

rand2 : real;

begin

x := 1;

finish := false; {for iteration of next point or restart }

summ := 0; {check to see if new soln same as one before}

if count2 >= 2 then

for j := 1 to (total+1) do

for k := 1 to total do

begin

if (p[j,k] < (dummpyp[j,k]+0.1)) and (p[j,k] > (dummpyp[j,k]-0.1)) then

summ := summ + 0

else

summ := summ + 1;

end;

if (summ < 0) or (count2 < 2) then {if soln has changed or count2 < 2, restart}


```

Restart := true
else
  Restart := false;

if count2 > 10 then {If more then 10 restarts, the situation is hopeless - give up!}
  Restart := false;

if Restart = true then
begin
  {Save previous solution into dummyp}
  new(guessp);
  for j := 1 to (total+1) do
    for k := 1 to total do
      dummyp[j,k] := p[j,k];

  {reset vertices of simplex randomly for restart run}
  for j := 1 to (total+1) do
    for k := 1 to total do
      begin
        if j > 1 then          {leave first dimension alone!}
          begin
            if ran1 < 0.5 then  {set sign of change randomly}
              sign := -1
            else
              sign := 1;

            p[j,k] := p[1,k] + sign*ran1;  {reset all but one vertex}
            if k = 7 then              {max change 0.5%}
              begin
                if p[j,k] < 0.0 then  {keep handling bleed in reasonable range}

```

```

        p[j,k] := 0.0;
        if p[j,k] > 10.0 then
            p[j,k] := 10.0;
        end;
    end;
end;
end;

{Now, must solve for a new cost function soln for each vertex!}
for j := 1 to NumZeroIts do {reset iteration history - convergence}
    iterate_hist[j] := 2;

    for k := 1 to 7 do
        guessp^[k] := 0.0;

        for j := 1 to (total+1) do
            begin
                for k := 1 to total do
                    guessp^[k] := p[j,k]; {Copy one vertex at a time into guessp for cost function}
                    y[j] := cost(guessp^j);
                end;

                dispose(guessp);
            end; {if restart = true }
        end; {Restart_Minimization}
    end;
end;

```

procedure Match_model_to_test_data(Var nfunc : integer, Var rtol : real);
 {This routine is a Nelder Mead Simplex multidimensional minimization as described in
 Chapter 5. This algorithm is as detailed in Press et al (1989). It minimizes the cost
 function described in Chapter 5 by scaling the various component efficiencies and

flows}

label 99;

const

ftol	= 0.00008;	{If average of largest & smallest cost function less than this value, performance matching stops - not generally the active stopping criteria}
nfuncmax	= 2000;	{Defines max # of function evaluations before stopping}
alpha	= 1.0;	{Parameters used in simplex expansions and}
beta	= 0.5;	{contractions. }
gamma	= 2.0;	

type

Pitry	= ^Itry;
-------	----------

var

mpts,	{Number of vertices in Simplex}
inhi,	
ilo,	{Index of vertex with smallest cost function}
ihi,	{Index of vertex with largest cost function}
i, n, j	: integer; {loop counting variables}
ndim	: byte; {Number of dimensions of problem}
ytry, ysave, sum, swapp	: real;
psum	: PItry;

function amotry(var p	: ptype; {N dimensional vertex coordinates}
var y	: ytype; {Array of cost functions for all vertices}
var sum	: Itry;
ndim, ihi	: integer;
var nfunc	: integer;

```

        fac          : real); real;

```

change below!

{Moves a vertex with the highest cost function across the face of the simplex using a scaling factor fac. The moved vertex replaces the original if the cost function is reduced}

```

var

```

```

    j          : integer;

```

```

    fac1, fac2, ytry : real;

```

```

    ptry        : PIttry;

```

```

begin

```

```

    new(ptry);

```

```

    fac1 := (1.0-fac)/ndim;

```

```

    fac2 := fac1-fac;

```

```

    for j := 1 to ndim do

```

```

        ptry^[j] := sum[j]*fac1-p[ihi,j]*fac2;

```

```

    ytry := cost(ptry^,ihi);           {Find a new cost function}

```

```

    if problem then                    {Exit now if NRC T400 execution fails}

```

```

        exit;

```

```

    nfunc := nfunc+1;

```

```

    if ytry < y[ihi] then

```

```

        begin                               {if the new point has lower cost function than the }

```

```

            y[ihi] := ytry;                 {worst vertex, replace the worst vertex with it}

```

```

            for j := 1 to ndim do

```

```

                begin

```

```

                    sum[j] := sum[j]+ptry^[j]-p[ihi,j];

```

```

                    p[ihi,j] := ptry^[j]

```

```

        end
    end;
    amotry := ytry;
    dispose(ptry);
end; {amotry}

```

Procedure Initialize;

var

```

    k, d                : byte;
    altitude, deltaT, dummy : real;
    Pinit               : PItry;

```

begin

```

    New(Pinit); {initialize cost function pointer}
    {fix the operating state to that of the engine tested:}
    od_data_ptr^[2].i_value[2] := data^[1,pointnum]; {Nhp set}
    od_data_ptr^[2].i_value[9] := data^[2,pointnum]; {Nlpt set}
    dummy                     := (data^[5,pointnum]/101325);
    altitude                  := (1000/0.0225577)*(1-Raise(dummy,(1/5.25588)));
    Basic_data_ptr^.i_value[1] := altitude/unit_con[1]; {altitude set}

    if (data_to_read[3] = 1) and not entrytemps then {Ambient temperature available}
    begin
        deltaT := data^[3,pointnum]-(288.15-6.5*altitude/1000);
        Basic_data_ptr^.i_value[32] := 1; {mix bleed with intake}
    end;

    if (data_to_read[4] = 1) then {Compressor intake temperature only is available}
    begin

```

```

deltaT                := data^[4,pointnum]-(288.15-6.5*altitude/1000);
Basic_data_ptr^.i_value[32] := 0; {do NOT mix bleed with intake}
end;

Basic_data_ptr^.i_value[2]    := deltaT/unit_con[2]; {Delta T from ISA set}

for k:= 1 to 8 do    {Initialize simplex vertices with zero}
  for d := 1 to 7 do
    p[k,d] := 0.0;

{Initialize the remaining vertices of the simplex around our initial guess solution
above}
for k := 2 to mpts do
  for d := 1 to 7 do
    begin
      if chics_to_change[d] = 1 then
        begin
          if (k-1) = chic_assign[d] then
            begin
              if (d=3) or (d=5) or (d=7) then
                p[k,chic_assign[d]] := 4.0      {set turb & bleed flows +ve}
              else
                p[k,chic_assign[d]] := -4.0;    {set rest -ve}
            end
          else
            p[k,chic_assign[d]] := 0.0;
          end;
        end;
      end;
    end;

{initialize procedure for halting calculation}

```

$x := 1$; {Used in setting `iterate_hist` array. When many successive solutions of the NRC T400 model are completed with only one iteration, we may conclude that we are not going to get any further. Therefore we stop at such a time.}

`finish:=false`; {used as above}

for $k := 1$ to `NumZeroIts` do

`iterate_hist[k] := 2`;

{Now, call the cost function below for each of the above vertices to determine values for them}

for $k := 1$ to `mpts` do

begin

for $d := 1$ to 7 do

begin

$Pinit^d := p[k,d]$;

end;

$y[k] := \text{cost}(Pinit^k,k)$;

if problem then

`exit`;

end;

{initialize bleed flow variable - keeps track of handling bleed leakage for each vertex of the simplex}

for $k := 1$ to 8 do

`Bleed_info[k] := 0`;

`Dispose(Pinit)`;

end; {Initialize}

begin {Match_Model_to_Test_Data}

```

ndim := total;           {Set number of dimensions}
new(psum);
mpts := ndim+1;          {Set number of simplex vertices}
nfunc := 0;              {We begin the first function evaluation}
if not Restart then
    Initialize;           {Initialize p and y arrays as above}
if problem then          {exit if NRC T400 fails to converge}
    exit;

for j := 1 to ndim do
begin
    sum := 0.0;
    for i := 1 to mpts do
        sum := sum+p[i,j];
    psum^[j] := sum;
end;

while true do
begin
    ilo := 1;             {Sort out the vertices of the initial guessed simplex}
    if y[1] > y[2] then    {in the order of the worst cost function to the best.}
    begin
        ihi := 1;
        inhi := 2
    end
    else begin
        ihi := 2;
        inhi := 1
    end
end;

```



```

for i := 1 to mpts do
begin
  if y[i] < y[ilo] then
    ilo := i;
  if y[i] > y[ihi] then
begin
  inhi := ihi;
  ihi := i
end
else if y[i] > y[inhi] then
  if i <> ihi then
    inhi := i
end;

{compute the average of the cost function of the best & worst points}
rtol := (abs(y[ihi])+abs(y[ilo]))/2.0;

{Decide whether to continue or stop. If we are within the tolerance above, or
we have exceeded the maximum number of iterations allowed, or if our step
sizes are now within the calculation errors of the NRC T400 model, we stop.}
if (rtol < ftol) or finish or (nfunc >= nfuncmax) then
begin
  {We are finished, so put the best vertex in slot #1,.}
  swapp := y[1];
  y[1] := y[ilo];
  y[ilo] := swapp;
  for n := 1 to ndim do
begin
  swapp := p[1,n];
  p[1,n] := p[ilo,n];

```

```

    p[ilo,n] := swapp;
end;

{move this best pt into the output array}
for n := 1 to 7 do
begin
    if chics_to_change[n] = 1 then
        data_out^[n+5,pointnum] := p[1,chic_assign[n]]
    else
        data_out^[n+5,pointnum] := 0.0;
    end;

    if entrytemps then      {Fill in found bleed leakage of best point}
        data_out^[12,pointnum] := 100*Bleed_info[ilo];

    goto 99; {Exit the Simplex routine}
end;

{For a new iteration, the worst point on the simplex is reflected through it is
search of lower cost functions.}

ytry := amotry(p,y,psum^,ndim,ihf,nfunc,-alpha);
if problem then {exit minimization if NRC T400 doesn't converge}
    exit;

if ytry <= y[ilo] then
begin
    ytry := amotry(p,y,psum^,ndim,ihf,nfunc,gamma);
    if problem then
        exit;

```

```

end
else if ytry >= y[ihi] then
begin

{If the reflected point above is worse than the second highest point, then a one
dimensional contraction is done to try and find an intermediate point with a
lower cost function}
    ysave := y[ihi];
    ytry := amotry(p,y,psum^,ndim,ihi,nfunc,beta);
{If all of the above has failed, the simplex is contracted around the vertex with
the lowest cost function}
    if ytry >= ysave then
    begin
        for i := 1 to mpts do
            if i < ilo then
            begin
                for j := 1 to ndim do
                begin
                    psum^[j] := 0.5*(p[i,j]+p[ilo,j]);
                    p[i,j] := psum^[j]
                end;
                y[i] := cost(psum^,i);
                if problem then {exit if NRC T400 fails to converge}
                    exit;
            end;
            nfunc := nfunc+ndim;
            for j := 1 to ndim do
            begin
                sum := 0.0;
                for i := 1 to mpts do

```

```

        sum := sum+p[i,j];
        psum^[j] := sum;
    end;
end;
end;
end;
99:
    dispose(psum)
end; {Match_model_to_test_data}

```

Procedure Bell_212_Topping_Test;

type

```

    Temp_in      = Array [1..9] of real;
    Temp_out     = Array [1..10] of real;
    PTemp_in     = ^Temp_in;
    PTemp_out    = ^Temp_out;

```

var

```

    Temporary    : PTemp_in;    { A temporary pointer }
    OP_State     : PTemp_out;    { Holds the engine operating state }
    OK           : boolean;      { Tells if max power limiters are set up o.k. }
    valid,
    off_map,     { true if a component operating point in GASTURB moves off of
                  the map }
    converged    : boolean;      { true for sucessful convergence }
    map_error    : integer;
    Pass_Fail,   { Topping test outcome }
    Active_Limiter : string[15]; { Active max power limiter (SHP, ITT for example) }
    Difference    : real;
    j             : byte;

```

```

Filename      : string80;      {Topping test output filename}
foutput       : text;
fileopen      : boolean;
oldoutname    : string80;

begin

    {check to see if maximum power limiters set up and running}
    OK := false;
    if max_power and not transient then
        OK := true;

    if OK then                                {Limiters are set up and all is O.K.}
        begin

            {Read in the Topping test output file name}
            Reset_Screen;
            FileName      := '';
            oldoutName    := '';
            open_File_for_write(900,10,30,oldoutname,FileName,foutput,fileopen);
            oldoutname    := FileName;

            new(Temporary);
            new(OP_State);

            {Store initial engine state}
            Temporary^[1] := Basic_data_ptr^.i_value[35]; {Axial flow}
            Temporary^[2] := Basic_data_ptr^.i_value[36]; {Centrifugal flow}
            Temporary^[3] := od_data_ptr^[2].i_value[17]; {Axial Efficiency}
            Temporary^[4] := od_data_ptr^[2].i_value[18]; {Centrifugal Efficiency}

```

```

Temporary^[5] := od_data_ptr^[2].i_value[14]; {HPT Flow }
Temporary^[6] := od_data_ptr^[2].i_value[19]; {HPT Efficiency}
Temporary^[7] := od_data_ptr^[2].i_value[15]; {lpt flow}
Temporary^[8] := od_data_ptr^[2].i_value[20]; {lpt efficiency}
Temporary^[9] := Basic_data_ptr^.i_value[11]; {handling bleed valve leakage}

```

```

{Run GASTURB and get actual engine power results}

```

```

calculate_off_design_point (0,valid,off_map,converged,map_error);

```

```

{Set the operating state of the performance matched engine under test}

```

```

OP_State^[1] := Basic_data_ptr^.i_value[1];      {altitude (ft)}
OP_State^[2] := Basic_data_ptr^.i_value[2];      {delta T from ISA - Deg R}
OP_State^[3] := od_data_ptr^[2].i_value[2];      {Mech Nhpt}
OP_State^[4] := od_data_ptr^[2].i_value[9];      {Mech Npt}
OP_State^[7] := Basic_data_ptr^.o_value[1];      {PWSD -SHP}
OP_State^[8] := Basic_data_ptr^.o_value[63];     {Trimmed ITT -deg R}
OP_State^[9] := Basic_data_ptr^.o_value[22];     {Thermodynamic ITT}
OP_State^[10] := Basic_data_ptr^.o_value[7]*3600; {Fuel Flow -lb/hr}
OP_State^[6] := OP_State^[7]*550*60/(6600*1028*2*Pi*XN_LPT)*100;
{Actual Bell 212 TRQ (%)}

```

```

{Find out which limiter is active for the actual engine}

```

```

case limiter_code of

```

```

1 : Active_Limiter := ' Mech Nhpt      ';
2 : Active_Limiter := ' Relative Nhpt  ';
3 : Active_Limiter := ' Comp Del Temp  ';
4 : Active_Limiter := ' Comp Del Pres  ';
5 : Active_Limiter := ' TIT             ';

```

```

6 : Active_Limiter := ' Trimmed ITT      ';
7 : Active_Limiter := ' EGT              ';
11 : Active_Limiter := ' TRQ              ';

else
    Active_Limiter := ' Beats Me!        ';
end;

{Reset the engine variables with values of 0 - the undamaged engine}
Basic_data_ptr^.i_value[35] := 0; {Axial flow}
Basic_data_ptr^.i_value[36] := 0; {Centrifugal flow}
od_data_ptr^[2].i_value[17] := 0; {Axial Efficiency}
od_data_ptr^[2].i_value[18] := 0; {Centrifugal Efficiency}
od_data_ptr^[2].i_value[14] := 0; {HPT flow}
od_data_ptr^[2].i_value[19] := 0; {HPT efficiency}
od_data_ptr^[2].i_value[15] := 0; {PT flow}
od_data_ptr^[2].i_value[20] := 0; {PT efficiency}
Basic_data_ptr^.i_value[11] := 0; {handling bleed valve leakage}

{Run unfaulted engine scenario as the baseline}
calculate_off_design_point (0,valid,off_map,converged,map_error);
{Find Bell 212 TRQ under given ambient conditions with no implanted faults}
OP_State^[5] := (Basic_data_ptr^.o_value[62]-0.02)*100;

{Now, determine if we passed or failed the topping test!}
Pass_Fail := ' Failed!      ';
Difference := OP_State^[6] - OP_State^[5];
if Difference >= 0 then
    Pass_Fail := ' Passed!    ';

```

```

{ output the results to a file}
if fileopen then
begin
  writeln(foutput,'The Topping Test Results are as Follows');
  writeln(foutput);
  writeln(foutput,'The engine operating state is:');
  writeln(foutput,'Altitude      Delta Tamb      Nhpt      Npt      ');
  for j := 1 to 4 do
    write(foutput,OP_State^[j]:15:5);
  writeln(foutput);
  writeln(foutput);
  writeln(foutput,'The Topping Test Results are as follows:');
  writeln(foutput,'PASS/FAIL      Active Lim      Pass TRQ(%)      Our TRQ(%)      ');
  writeln(foutput,Pass_Fail:15,Active_Limiter:15,OP_State^[5]:15:5,OP_State^[6]
    :15:5);
  writeln(foutput);
  writeln(foutput,'Other global variables of interest:');
  writeln(foutput,'SHP      Trim ITT      Untrim ITT      Fuel Flow      ');
  for j := 7 to 10 do
    write(foutput,OP_State^[j]:15:5);
  writeln(foutput);
end;
close(foutput); {close output file}

{Final Stage of Routine has arrived - reset global variables to
their original values}
Basic_data_ptr^.i_value[35] := Temporary^[1]; {Axial flow}
Basic_data_ptr^.i_value[36] := Temporary^[2]; {Centrifugal flow}
od_data_ptr^[2].i_value[17] := Temporary^[3]; {Axial Efficiency}
od_data_ptr^[2].i_value[18] := Temporary^[4]; {Centrifugal Efficiency}

```



```

od_data_ptr^[2].i_value[14] := Temporary^[5]; {HPT flow}
od_data_ptr^[2].i_value[19] := Temporary^[6]; {HPT efficiency}
od_data_ptr^[2].i_value[15] := Temporary^[7]; {PT flow}
od_data_ptr^[2].i_value[20] := Temporary^[8]; {PT efficiency}
Basic_data_ptr^.i_value[11] := Temporary^[9]; {handling bleed valve leakage}

```

```

{Get rid of remaining pointers, and wrap things up}

```

```

dispose(Temporary);

```

```

dispose(OP_State);

```

```

end;

```

```

end; {Bell_212_Topping_Test}

```

```

begin {Match - everything is controlled from here }

```

```

Reset_Screen;

```

```

Not_finished      := true;

```

```

next_choice       := 1;

```

```

{initialize pointers needed}

```

```

New(data);

```

```

New(data_out);

```

```

repeat

```

```

    choice := next_choice;

```

```

    Select_option (Not_finished, Choice);

```

```

    esc_pressed := false;

```

```

    case Choice of

```

```

1 : begin
    {Run procedure Load_test_data}
    Load_test_data (last_file_name,Not_finished);
end;

2 : begin
    {Save a standard gasturb data file}
    Save_GASTURB_data;
    Reset_Screen;
end;

3 : begin
    {Run the performance matching routine}
    for jj := 1 to (numberpoints) do
    begin
        Restart := false;
        count2 := 1;
        repeat
        begin
            pointnum := jj;      {Set test data point number being used}
            Match_model_to_test_data(numfunc,tolerance);
            data_out^[21,pointnum] := numfunc; {# of function iterations needed}
            data_out^[22,pointnum] := tolerance; {Tolerance rtol in simplex routine}
            Restart_Minimization(count2);
            inc(count2);
        end;
        until not Restart;
    end;
    entrytemps := false;

```

end;

4 : begin

{Run procedure Save_Matched_Data}

Save_Matched_Data;

Reset_Screen;

end;

5 : begin

{Run the DND Topping test}

Bell_212_Topping_Test;

end;

else

esc_pressed := true;

end;

if esc_pressed then

begin

Dispose(data);

Dispose(data_out);

end;

until esc_pressed;

end;

end.

Component Map Generation Programs for GASTURB: COMPMAP.C

```
/******
```

```
* PROGRAM EXPLANATION:
```

```
* File Name: COMPMAP.C
```

```
* This program creates input compressor maps useable in GasTURB 6.0
```

```
* from a data file which you input and the design point which is keyed
```

```
* in. It is written in ANSI C.
```

```
*
```

```
* The input data file is in the following form:
```

```
*
```

```
* Line 1:    # Speed Lines
```

```
* Line 2:    # Pts. in First Speed Line
```

```
* Line 3:    # Pts. in Second Speed Line
```

```
* Line 4:    # Pts. in Third " " ect
```

```
* Line 3:    1st Speed Value
```

```
* Line 4:    PR , Q, Efficiency for point 1 (in three columns)
```

```
* Line 5+:   continuing pions on succeding lines until all points for 1st Speed Value
```

```
*
```

```
are covered.
```

```
* Next Line: 2nd Speed Value - and onwards until all speed lines covered.
```

```
*
```

```
* It fits linear Beta lines to the data and returns the design pt Beta.
```

```
*
```

```
* NOTE! - The speed lines MUST be in ascending order from lowest to
```

```
* highest and the data MUST be in ascending order from the lowest
```

```
* pressure ratio to the highest. If they are not, this program
```

```
* will not work! One speed line MUST have a non-D speed of 1.
```

```
*****/
```

```
#include <stdio.h>
```

```

#include <stdlib.h>
#include <math.h>

/* Used later for determining if speed line segment is vertical */
#define error 0.0001

int
main(void)
{
char    Reynolds[31], InputFile[41], OutputFile[41], Out2[41], Title[41];
int     NumSpdLines, *NumbPts, count1, count2, count3;
int     NumbBetaLines, TF;
double  DesignBeta, NonDSpeed[10], Design_PR, PR[10][20], Q[10][20];
double  *b, *m, *SLm, *SLb, mincrement, X, Y, dummyx, dummyy, Eff_dum1;
double  RawDatain[10][10][3], Eff[10][20], Surge[2][10], *Beta, DeltaTo;
double  BetaX, BetaY, Eff_dum2, W;
FILE    *inp, *outp, *outp2;

/*****
* Details on Variables Used:
*
* InputFile[41]      -The name of the data file mentioned above which is to be
*                    loaded for processing (the compressor characteristic).
*                    (max 40 characters)
*
* OutputFile[41]     -The name of the output data file which is to be used in the
*                    GasTURB software package (max 40 characters).
*
* Title[41]          -The title name which appears on the header of the output
*                    file (max 40 characters).

```

*
 * NumSpdLines -The number of speed lines to be read from the input data
 * file. This is the first number on the data file and may
 * vary from 3 to 10.
 *
 * *NumbPts -A pointer storing the number of data points in the data file
 * for each speed line.
 *
 * count 1-3 -Counting integers used in loops and some dummy variables.
 *
 * NumbBetaLines -The number of Beta Lines to be fitted (4-20). The user keys
 * this number in when requested.
 *
 * Design_PR -Specifies the compressor design pressure ratio.
 *
 * NonDSpeed -This variable receives the non dimensional speed for each
 * compressor speed line.
 *
 * RawDatain -This is a 3X3 matrix which receives the bulk of the input data.
 * the first dimension refers to speed line, the second to rows, and
 * the third to columns. The first column contains PR, the second
 * non dimensional mass flow, the third isentropic efficiencies.
 *
 * *b, *m, *SLm, *SLb, mincrement - Describe linear equations for the Beta lines
 * (*b and *m) and the non dimensional speed lines (*SLm, *SLb).
 *
 * X, Y, dummyx, dummyy - dummy variables used in obtaining line equations.
 *
 * *inp, *outp -File pointers for data input and output.
 * *outp2

```

*
* Q[10][20]          -Output non dimensional mass flow rates (m*sqrt(theta)/delta)
*
* PR[10][20]         -Output non compressor PR.
*
* Eff[10][20]        -Output compressor efficiency
*
* Surge[2][10]       -Surge Line data output.
*****/

/* Algorithm for data input (both manual and file) */

printf("Enter the input File name (Path Included) - 40 Char. Max:\n");
scanf("%s", InputFile);

printf("Enter Map Output File Title - 40 Char. Max:\n");
scanf("%s", Title);

printf("Enter Design Pt. File Name - 40 Char. Max:\n");
scanf("%s", Out2);

printf("Enter Output File Name - 40 Char. Max:\n");
scanf("%s", OutputFile);

do
{
    printf("Enter the # of Beta Lines to Use (4 to 20!)\n");
    scanf("%d", &NumbBetaLines);
}
while (NumbBetaLines<3 && NumbBetaLines>21);

```

```

printf("Design Pt. Non Dimensional Mass Flow>");
scanf("%lf", &W);

printf("Design Pt. PR>");
scanf("%lf", &Design_PR);

/* Allocating pointers */
inp=fopen(InputFile,"r");
fscanf(inp,"%d", &NumSpdLines);
NumbPts=(int*)calloc(NumSpdLines,sizeof(int));
/* Y-intercepts of Beta lines */
b=(double*)calloc(NumbBetaLines,sizeof(double));
/* Slopes of Beta lines */
m=(double*)calloc(NumbBetaLines,sizeof(double));
Beta=(double*)calloc(NumbBetaLines,sizeof(double));

/* Read the number of data points in each speedline */
count3=0;
for (count1=0; count1<NumSpdLines; count1++)
{
    fscanf(inp,"%d", &NumbPts[count1]);
    if (NumbPts[count1]>count3)
        count3=NumbPts[count1];
}

/* Slope and Y-intercept of speed line segments */
SLm=(double*)calloc(count3,sizeof(double));
SLb=(double*)calloc(count3,sizeof(double));

```



```

/* Read in main body of data file */
for (count1=0; count1<NumSpdLines; count1++)
{
    fscanf(inp, "%lf", &NonDSpeed[count1]);

    for (count2=0; count2<10; count2++)
    {
        for (count3=0; count3<3; count3++)
        {
            if(count2<NumbPts[count1])
                fscanf(inp, "%lf", &RawDatain[count1][count2][count3]);
            else
                RawDatain[count1][count2][count3]=0.0;
        }
    }
}
fclose(inp);

/* Algorithm to get Beta line slopes */
/* Equation for bottom Beta Line ( Beta = 0) algorithm, found by looping over the
   minimum PR points in each speed line to find a Beta line which touches two speedlines
   at their minimum values and is below the rest of the compressor map */
X=RawDatain[0][0][1];
Y=RawDatain[0][0][0];
m[0]=100.0;

for(count1=1; count1<NumSpdLines; count1++)
{
    dummyx=RawDatain[count1][0][1];
    dummyy=RawDatain[count1][0][0];

```

```

        if(((dummyy-Y)/(dummyx-X))<m[0])
        {
            m[0]=(dummyy-Y)/(dummyx-X);
            b[0]=Y-m[0]*X;
        }
    }

    /* Equation for Top Beta Line Algorithm */
    /* Repeats the above operation except keeping the map below this Beta line */

    count2=NumbPts[0];
    X=RawDatain[0][count2-1][1];
    Y=RawDatain[0][count2-1][0];
    m[NumbBetaLines-1]=-100.0;

    for(count1=1; count1<NumSpdLines; count1++)
    {
        count3=NumbPts[count1]-1;
        dummyx=RawDatain[count1][count3][1];
        dummyy=RawDatain[count1][count3][0];
        if(((dummyy-Y)/(dummyx-X))>m[NumbBetaLines-1])
        {
            m[NumbBetaLines-1]=(dummyy-Y)/(dummyx-X);
            b[NumbBetaLines-1]=Y-m[NumbBetaLines-1]*X;
        }
    }

    /* Solve for the meeting pt. for Beta=0 & Beta=1 Lines */

    X=(b[NumbBetaLines-1]-b[0])/(m[0]-m[NumbBetaLines-1]);

```

```
Y=m[0]*X+b[0];
```

```
BetaX=X;
```

```
BetaY=Y;
```

```
/* Get Rest of Beta Equations - achieved by taking the above meeting point as a point on
   all of the Beta lines. The other lines go through this point, but have intermediate
   slopes between the minimum and maximum Beta lines */
```

```
mincrement=(m[NumbBetaLines-1]-m[0])/(NumbBetaLines-1);
```

```
for(count1=1; count1<(NumbBetaLines-1); count1++)
```

```
{
    m[count1]=m[count1-1]+mincrement;
    b[count1]=Y-m[count1]*X;
}
```

```
/* Doing the actual work of the program - fitting B Lines! */
```

```
/* Do speedline by speedline - Each speed line is split into multiple line segments. For
   instance, a speed line with 5 points is split into 4 line segments. For each speedline, an
   intersection point is found between each speed line segment and each Beta line. A
   process of eliminatio then follows in which the correct intersection point is identified */
```

```
for(count1=0; count1<NumSpdLines; count1++) /* Outer loop is by speed line # */
```

```
{
    /* Get Slopes of all non vertical sections of each speed line */
```

```
    for(count2=1; count2<NumbPts[count1]; count2++)
```

```
    {
        dummyx=(RawDatain[count1][count2][1]-RawDatain[count1][count2-
            1][1]);
```

```

dummyy=(RawDatain[count1][count2][0]-RawDatain[count1][count2-
1][0]);
if(fabs(dummyx)>error) /* procede only if not a singularity */
{
SLm[count2-1]=dummyy/dummyx;
SLb[count2-1]=RawDatain[count1][count2][0]-SLm[count2-
1]*RawDatain[count1][count2][1];
}
}

/* Do the solving between the Beta and Speed Lines Here - find intersections between the
Beta line and each speed line segment in turn */

for(count2=0; count2<NumbBetaLines; count2++) /* Beta Line Number */
{
count3=0; /* Speed Line segment number */
TF=0; /* Loop Repeat Criterion (Stop when TF=1) */
do
{
dummyx=RawDatain[count1][count3+1][1]-
RawDatain[count1][count3][1];
dummyy=RawDatain[count1][count3+1][0]-
RawDatain[count1][count3][0];
if((fabs(dummyx) == 0) && (fabs(dummyy) == 0))
{ } /* If the speed line segment is a point, skip it! */
else
{
if(fabs(dummyx)<error) /* Dealing with vertical speed lines */
{
/* X = Constant Q at Speed Line Value */
X=RawDatain[count1][count3][1];

```

```

/* Y = Value of Beta Line at X (which is PR) */
Y=m[count2]*X+b[count2];
}
else
{
/* Solve the equations for speed line and Beta - for all other lines
than the two cases above*/
X=(SLb[count3]-b[count2])/(m[count2]-SLm[count3]);
Y=m[count2]*X+b[count2];
if(Y<RawDatain[count1][0][0])
{
X=RawDatain[count1][0][1];
Y=m[count2]*X+b[count2];
}
}
}

/* Here is the elimination process, the Beta line only actually
crosses one speed line segment. We find the correct solution
here using the IF statements to follow for the various cases. The
PR and Efficiency of the correct solution are interpolated out in
the body of each IF statement*/

if((fabs(dummyx) == 0) && (fabs(dummyy) == 0))
{ } /* Ignore points ! */
else
{

/* Case 1 - a vertical speed line (i.e. choked) */

```

```

if(((fabs(dummyx)<error) &&
      (Y<RawDatain[count1][count3+1][0])) ||
      (Y<RawDatain[count1][0][0]))
{
Q[count1][count2]=X;
PR[count1][count2]=Y;
TF=1;

/* Interpolate Efficiencies - new lines of code */
Eff_dum1=(Y-
RawDatain[count1][count3][0])/(RawDatain[count1][count3+
      1][0]-RawDatain[count1][count3][0]);
Eff_dum2=Eff_dum1*(RawDatain[count1][count3+1][2]-
      RawDatain[count1][count3][2]);
Eff[count1][count2]=Eff_dum2+RawDatain[count1][count3][2];
}

/* Case 2 - neither PR nor Q constant - most of the points */

if((Y<=RawDatain[count1][count3+1][0]) &&
      (Y>=RawDatain[count1][count3][0]) && (dummyx!=0))
{
Q[count1][count2]=X;
PR[count1][count2]=Y;
TF=1;

/* Solve for efficiency, dealing with the fact that at some pts Q may
be constant while at others PR may be constant - still part of case 2
*/

```

```

if(dummyy>=dummyx) /* If true, use PR to find Efficiency */
{
X=(RawDatain[count1][count3+1][2]-
    RawDatain[count1][count3][2]);
Y=(PR[count1][count2]-
    RawDatain[count1][count3][0])/(RawDatain[count1][count3
    +1][0]-RawDatain[count1][count3][0]);
Eff[count1][count2]=X*Y+RawDatain[count1][count3][2];
}
else /* Else, Use Q to find Efficiency */
{
X=(RawDatain[count1][count3+1][2]-
    RawDatain[count1][count3][2]);
Y=(Q[count1][count2]-
    RawDatain[count1][count3][1])/(RawDatain[count1][
    count3+1][1]-RawDatain[count1][count3][1]);
Eff[count1][count2]=X*Y+RawDatain[count1][count3][2];
}
}

/* Case 3 - Beyond Surge line - just filling in numbers for Gasturb -
of no physical significance! */
if((Y>RawDatain[count1][NumbPts[count1]-1][0]) && (count3 ==
    (NumbPts[count1]-2)))
{
Q[count1][count2]=X;
PR[count1][count2]=Y;
TF=1;

/* Just assign efficiency as the same value as that at stall */

```

```

        Eff[count1][count2]=RawDatain[count1][NumbPts[count1]-1][2];
    }
}
count3++;
}
while((count3<(NumbPts[count1]-1)) && (TF == 0));
}
}

```

/* The surge line is now obtained by assuming the max PR point of each speed line is at surge */

```
for (count1=0; count1<NumSpdLines; count1++)
```

```
{
    Surge[1][count1]=RawDatain[count1][NumbPts[count1]-1][1]; /* Mass Flows */
    Surge[0][count1]=RawDatain[count1][NumbPts[count1]-1][0]; /* Surge PR's */
}

```

/* Calculate out all of the Beta Values corresponding to each of the lines above */

```
Beta[0]=0.0;
```

```
for (count1=1; count1<NumbBetaLines; count1++)
```

```
    Beta[count1]=Beta[count1-1]+1.0/((double)NumbBetaLines-1.0);
```

/* Find the Design Point Beta Value to key into GASTURB to fix the design point in the map */

/* Start by finding the speed line (if any) where Corr Nhp = 1 */

```
count1=0;
```

```
count2=0;
```

```
TF=0;
```

```
do
```



```

{
    if(NonDSpeed[count1] == 1)
    {
        count2=count1;
        TF=1; /* Rel Corr NG =1 line found */
    }

    if((NonDSpeed[count1] < 1) && (NonDSpeed[count1+1] > 1))
        TF=2; /* no Relative Corrected Nhp =1 line present in map */

    count1++;
}
while ((NonDSpeed[count1-1] != 1) && (count1<NumSpdLines));

/* No design point could be found in the map - check your map */
if(TF == 0)
{
    printf("Check your input file - Corr Nhp speed lines less than and greater than 1
        required!");
    DesignBeta=2;
}

if(TF == 1)
{
    /* Now, Extract the Design Point Beta Value if Corr Nhp = 1 line exists in map */
    count1=0;
    count3=0;
    do
    {
        if(Design_PR<=PR[count2][count1])

```

```

        count3=count1-1;
        count1++;
    }
    while ((Design_PR>PR[count2][count1-1]) && (count1<NumbBetaLines));

    X=(double)count3/((double)NumbBetaLines-1.0);
    Y=(double)(count3+1)/((double)NumbBetaLines-1.0);
    DesignBeta=(Design_PR-PR[count2][count3])/(PR[count2][count3+1]-
        PR[count2][count3])*(Y-X)+X;
    }

    if(TF ==2)
    {
        /* if we don't have a line in the input file with Rel Corr NG =1, we will
        have to interpolate here for the design point. Start by fitting a Beta line
        to the design Pt.: */

        X=(Design_PR-BetaY)/(W-BetaX); /* slope */

        /* Now, Find the two Beta Lines Surrounding our Design Pt. Line */
        count1=0;
        count2=NumbBetaLines;
        do
        {
            if((X >= m[count1]) && (X <= m[count1+1]))
                count2=count1;
            count1++;
        }
        while ((count2 != count1) || (count1 < NumbBetaLines));
    }

```

```

/* Finally, interpolate the Beta Number */
Y=(X-m[count2])/(m[count2+1]-m[count2])+(double)count2;
DesignBeta=Y/(NumbBetaLines-1);
}

/* Final Output (Map File) - The rest of COMPMAP.C exists to write the output to the
standard GASTURB 6.0 component map format */

outp=fopen(OutputFile,"w");
fprintf(outp,"99 %s\n",Title);
fprintf(outp,"Reynolds: RNI=0.1 f=0.95 RNI=1 f=1\n");
fprintf(outp,"Mass Flow\n");

X=NumSpdLines+1.0+(NumbBetaLines+1.0)/1000.0;
Y=2.0+(NumSpdLines+1.0)/1000.0;

/* Print the Non-D Mass Flow Table */
fprintf(outp,"%10.5f",X);

for (count1=0; count1<4; count1++)
    fprintf(outp,"%10.5f",Beta[count1]);

fprintf(outp,"\n");
for (count1=4; count1<NumbBetaLines; count1++)
{
    fprintf(outp,"%10.5f",Beta[count1]);
    if((count1+2)%5 == 0)
        fprintf(outp,"\n");
}

```

```

if((NumbBetaLines+1)%5 != 0 )
    fprintf(outp, "\n");

for (count1=0; count1<NumSpdLines; count1++)
{
    fprintf(outp, "%10.5f", NonDSpeed[count1]);

    for (count2=0; count2<4; count2++)
        fprintf(outp, "%10.5f", Q[count1][count2]);

    fprintf(outp, "\n");

    for (count2=4; count2<NumbBetaLines; count2++)
    {
        fprintf(outp, "%10.5f", Q[count1][count2]);
        if((count2+2)%5 == 0)
            fprintf(outp, "\n");
    }

    if((NumbBetaLines+1)%5 != 0 )
        fprintf(outp, "\n");
}

/* Print the Efficiency Table */
fprintf(outp, "\n");
fprintf(outp, "Efficiency\n");
fprintf(outp, "%10.5f", X);

for (count1=0; count1<4; count1++)
    fprintf(outp, "%10.5f", Beta[count1]);

```

```

fprintf(outp, "\n");
for (count1=4; count1<NumbBetaLines; count1++)
{
    fprintf(outp, "%10.5f", Beta[count1]);
    if((count1+2)%5 == 0)
        fprintf(outp, "\n");
}

if((NumbBetaLines+1)%5 != 0 )
    fprintf(outp, "\n");

for (count1=0; count1<NumSpdLines; count1++)
{
    fprintf(outp, "%10.5f", NonDSpeed[count1]);

    for (count2=0; count2<4; count2++)
        fprintf(outp, "%10.5f", Eff[count1][count2]);

    fprintf(outp, "\n");

    for (count2=4; count2<NumbBetaLines; count2++)
    {
        fprintf(outp, "%10.5f", Eff[count1][count2]);
        if((count2+2)%5 == 0)
            fprintf(outp, "\n");
    }

    if((NumbBetaLines+1)%5 != 0 )

```

```

        fprintf(outp, "\n");
    }

    /* Print the PR Table */
    fprintf(outp, "\n");
    fprintf(outp, "Pressure Ratio\n");
    fprintf(outp, "%10.5f", X);

    for (count1=0; count1<4; count1++)
        fprintf(outp, "%10.5f", Beta[count1]);

    fprintf(outp, "\n");
    for (count1=4; count1<NumbBetaLines; count1++)
    {
        fprintf(outp, "%10.5f", Beta[count1]);
        if((count1+2)%5 == 0)
            fprintf(outp, "\n");
    }

    if((NumbBetaLines+1)%5 != 0 )
        fprintf(outp, "\n");

    for (count1=0; count1<NumSpdLines; count1++)
    {
        fprintf(outp, "%10.5f", NonDSpeed[count1]);

        for (count2=0; count2<4; count2++)
            fprintf(outp, "%10.5f", PR[count1][count2]);
    }

```

```

    fprintf(outp, "\n");

    for (count2=4; count2<NumbBetaLines; count2++)
    {
        fprintf(outp, "%10.5f", PR[count1][count2]);
        if((count2+2)%5 == 0)
            fprintf(outp, "\n");
    }

    if((NumbBetaLines+1)%5 != 0 )
        fprintf(outp, "\n");
}

/* Print the Surge Line Data */
fprintf(outp, "\nSurge Line\n");
fprintf(outp, "%10.5f", Y);

count1=0;
do
{
    fprintf(outp, "%10.5f", Surge[1][count1]);
    count1++;
}
while ((count1<4) && (count1<NumSpdLines));
fprintf(outp, "\n");

if(NumSpdLines>4)
{
    for (count1=4; count1<NumSpdLines; count1++)
    {

```

```

        fprintf(outp,"%10.5f",Surge[1][count1]);
        if((count1+2)%5 == 0)
            fprintf(outp,"\n");
    }
}

if((NumSpdLines+1)%5 != 0 )
    fprintf(outp,"\n");

fprintf(outp," 1.000 ");

count1=0;
do
{
    fprintf(outp,"%10.5f",Surge[0][count1]);
    count1++;
}
while ((count1<4) && (count1<NumSpdLines));
fprintf(outp,"\n");

if (NumSpdLines>4)
{
    for (count1=4; count1<NumSpdLines; count1++)
    {
        fprintf(outp,"%10.5f",Surge[0][count1]);
        if((count1+2)%5 == 0)
            fprintf(outp,"\n");
    }
}

```



```

if((NumSpdLines+1)%5 != 0 )
    fprintf(outp, "\n");

fclose(outp);          /* Finished writing component map */

/* Print out Design pt. position in the compressor map to screen & file */
outp2=fopen(Out2, "w");

fprintf(outp2, "Here is the brief design pt. data for the map file %s.", OutputFile);
fprintf(outp2, "\n\nThe map input file was %s.", InputFile);
fprintf(outp2, "\nYour input design PR was %f,", Design_PR);
fprintf(outp2, "\nand your calculated design Beta is %f for a Non-D Speed of
1.", DesignBeta);

fclose(outp2);

printf("\n\n\nHere is the brief design pt. data for the map file %s.", OutputFile);
printf("\n\nThe map input file was %s.", InputFile);
printf("\nYour input design PR was %f,", Design_PR);
printf("\nand your calculated design Beta is %f for a Non-D Speed of 1.", DesignBeta);
printf("\nYou may find this information also in the file %s.", Out2);

return(0);
}

```

TURBMAP.C

```

/*****
* PROGRAM EXPLANATION:
* File Name: TURBMAP.C
* This program creates input compressor maps useable in GasTURB 6.0
* from a data file which you input and the design point which is keyed
* in.
*
* The data file is in the following form:
*
* Line 1: # Speed Lines
* Line 2: # Pts. in First Speed Line
* Line 3: # Pts. in Second Speed Line
* Line 4: # Pts. in Third " " ect
* Line 3: 1st Speed Value
* Line 4: PR Q Efficiency }for pt 1 (in three columns)
* Line 5: Second point etc. until all points of 1st speed value covered
* Line 6: 2nd Speed Value - repeat lines 1-5 until all speed lines covered.
*
* This program fits linear Beta lines to the turbine map and returns the design pt Beta
* value.
*
* NOTE! -The speed lines MUST be in ascending order from lowest to
* highest and the data MUST be in ascending order from the lowest
* pressure ratio to the highest. If they are not, this program
* will not work! One speed line MUST have a non-D speed of 1 as
* presently implemented.
*****/
#include <stdio.h>

```

```

#include <stdlib.h>
#include <math.h>

int
main(void)
{
char    Reynolds[31], InputFile[41], OutputFile[41], Out2[41], Title[41];
int     NumSpdLines, *NumbPts, count1, count2, count3;
int     NumbBetaLines, TF;
double   DesignBeta, NonDSpeed[10], Design_PR, PR[10][20], Q[10][20];
double   PRincrement, betaincrement, X, Y, Z;
double   RawDatain[10][15][3], Eff[10][20], *Beta;
FILE     *inp, *outp, *outp2;

/*****
* Details on Variables Used (Significant ones as of this time):
*
* InputFile[41]      -The name of the data file mentioned above which is to be
*                    loaded for processing (the turbine characteristic).
*                    (max 40 characters)
*
* OutputFile[41]     -The name of the output data file which is to be used in the
*                    GasTURB software package (max 40 characters).
*
* Title[41]          -The title name which appears on the header of the output
*                    file (max 40 characters).
*
* NumSpdLines        -The number of speed lines to be read from the input data
*                    file. This is the first number on the data file and may
*                    vary from 3 to 10.

```

```

*
* *NumbPts          -A pointer storing the number of data points in the data file
*                   for each speed line.
*
*
* count 1-3         -Counting integers used in loops and some dummy variables.
*
* NumbBetaLines     -The number of Beta Lines to be fitted (4-20). The user keys
*                   this number in when requested.
*
*
* Design_PR         -Specifies the turbine design pressure ratio.
*
*
* NonDSpeed         -This variable recieves the non dimensional speed for each
*                   turbine speed line.
*
*
* RawDatain         -This is a 3X3 matrix which receives the bulk of the input data.
*                   the first dimension refers to speed line, the second to rows, and
*                   the third to columns. The first column contains PR, the second
*                   non dimensional mass flow, the third isentropic efficiencies.
*
*
* X, Y, Z           -Dummy variables used in obtaining line equations.
*
*
* *inp, *outp       -File pointers for data input and output.
*
* *outp2
*
* Q[10][20]         -Output non dimensional mass flow rates ( $m \cdot \sqrt{\theta} / \Delta$ )
*
*
* PR[10][20]        -Output non dimensional turbine PR.
*
*
* Eff[10][20]       -Output turbine efficiency.
*****/

```

```

/* Algorithm for data input (both from keyboard and file) */

printf("Enter the input File name (Path Included) - 40 Char. Max:\n");
scanf("%s", InputFile);

printf("Enter Map Output File Title - 40 Char. Max:\n");
scanf("%s", Title);

printf("Enter Design Pt. File Name - 40 Char. Max:\n");
scanf("%s", Out2);

printf("Enter Output File Name - 40 Char. Max:\n");
scanf("%s", OutputFile);

do
{
    printf("Enter the # of Beta Lines to Use (4 to 20!)\n");
    scanf("%d", &NumbBetaLines);
}
while (NumbBetaLines<3 && NumbBetaLines>21);

printf("Design Pt. PR>");
scanf("%lf", &Design_PR);
inp=fopen(InputFile,"r");

fscanf(inp,"%d", &NumSpdLines);
/* Initialize pointers */
NumbPts=(int*)calloc(NumSpdLines,sizeof(int));
Beta=(double*)calloc(NumbBetaLines,sizeof(double));

```

```

/* Read from the input file the number data points for each speed line */
for (count1=0; count1<NumSpdLines; count1++)
    fscanf(inp,"%d", &NumbPts[count1]);

/* Read in the data - Corrected flow, PR and efficiency for each speed line */
for (count1=0; count1<NumSpdLines; count1++)
{
    fscanf(inp,"%lf",&NonDSpeed[count1]);

    for (count2=0; count2<15; count2++)
    {
        for (count3=0; count3<3; count3++)
        {
            if(count2<NumbPts[count1])
                fscanf(inp,"%lf",&RawDatain[count1][count2][count3]);
            else
                RawDatain[count1][count2][count3]=0.0;
        }
    }
}
fclose(inp);

/* Doing the actual work of the program - fitting B Lines! */
/* Do speedline by speedline - A much simpler process here than for COMPMAP.C.
Here, the Beta lines are fit on the basis of the minimum and maximum PR of each speed
line. The minimum PR point gets Beta = 0, the maximum PR point gets Beta = 1, and
the remaining Beta values are fitted by interpolating in each speed line by equal
increments of PR */

for(count1=0; count1<NumSpdLines; count1++)

```

```

{
    /* Get the peak and lowest PR for each speed line */
    PR[count1][0]=RawDatain[count1][0][0]; /* Min. PR */
    /* Line below finds the maximum PR for each speed line */
    PR[count1][NumbBetaLines-1]=RawDatain[count1][NumbPts[count1]-1][0];
    PRincrement=(PR[count1][NumbBetaLines-1]-
        PR[count1][0])/((double)NumbBetaLines-1);

    /* Match Beta values to speed line PR as described in Chapter 2. Interpolate the
       component efficiency at these points. */
    for(count2=1; count2<NumbBetaLines; count2++)
        PR[count1][count2]=PR[count1][count2-1]+PRincrement;

    for(count2=0; count2<NumbBetaLines; count2++)
    {
        for(count3=1; count3<NumbPts[count1]; count3++)
        {
            if((PR[count1][count2]>=RawDatain[count1][count3-1][0]) &&
                (PR[count1][count2]<=RawDatain[count1][count3][0]))
            {
                X=(PR[count1][count2]-RawDatain[count1][count3-1][0])/(RawDatain[count1][count3][0]-
                    RawDatain[count1][count3-1][0]);
                Y=RawDatain[count1][count3][1]-RawDatain[count1][
                    count3-1][1];
                Z=RawDatain[count1][count3][2]-RawDatain[count1][
                    count3-1][2];
                Q[count1][count2]=X*Y+RawDatain[count1][count3-1][1];
                Eff[count1][count2]=X*Z+RawDatain[count1][count3-1][2];
            }
        }
    }
}

```

```

        }
    }
}

/* Calculate out all of the Beta Values corresponding to the points above */
Beta[0]=0.0;
betaincrement=1.0/((double)NumbBetaLines-1.0);
for (count1=1; count1<NumbBetaLines; count1++)
    Beta[count1]=Beta[count1-1]+betaincrement;

/* Find the Design Point (Beta Value) */
/* Start by finding the speed line where Non-D Speed = 1 */
count1=0;
count2=0;
do
{
    if(NonDSpeed[count1] == 1)
        count2=count1;
    count1++;
}
while ((NonDSpeed[count1-1] != 1) && (count1<NumSpdLines));

/* Now, Extract the Design Point Beta Value */
count1=0;
count3=0;
do
{
    if(Design_PR<=PR[count2][count1])
        count3=count1-1;

```



```

        count1++;
    }
    while ((Design_PR>PR[count2][count1-1]) && (count1<NumbBetaLines));

    X=(double)count3*betaincrement;
    Y=((double)count3+1.0)*betaincrement;
    DesignBeta=(Design_PR-PR[count2][count3])/(PR[count2][count3+1]-
        PR[count2][count3])*(Y-X)+X;

    /* Print the new turbine map to a file in standard GASTURB 6.0 map format */
    outp=fopen(OutputFile,"w");
    fprintf(outp,"99 %s\n",Title);
    fprintf(outp,"Reynolds: RNI=0.1 f=0.95 RNI=1 f=1\n");
    /* Print the PR Data */
    fprintf(outp,"Min Pressure Ratio = f(N/sqrt(T))\n");
    Y=2+(NumSpdLines+1)/1000.0;
    fprintf(outp,"%10.5f",Y);

    count1=0;
    do
    {
        fprintf(outp,"%10.5f",NonDSpeed[count1]);
        count1++;
    }
    while((count1<4) && (count1<NumSpdLines));
    fprintf(outp,"\n");

    if(NumSpdLines>4)
    {
        for(count1=4; count1<NumSpdLines; count1++)

```

```

        {
            fprintf(outp,"%10.5f",NonDSpeed[count1]);
            if((count1+2)%5 == 0)
                fprintf(outp,"\n");
        }
    if((NumSpdLines+1)%5 != 0)
        fprintf(outp,"\n");
}

fprintf(outp," 0.00000");

count1=0;
do
{
    fprintf(outp,"%10.5f",RawDatain[count1][0][0]);
    count1++;
}
while((count1<4) && (count1<NumSpdLines));
fprintf(outp,"\n");

if(NumSpdLines>4)
{
    for (count1=4; count1<NumSpdLines; count1++)
    {
        fprintf(outp,"%10.5f",RawDatain[count1][0][0]);
        if((count1+2)%5 == 0)
            fprintf(outp,"\n");
    }
}
if((NumSpdLines+1)%5 != 0)
    fprintf(outp,"\n");

```

```

}

fprintf(outp, "\nMax Pressure Ratio = f(N/sqrt(T))\n");
Y=2+(NumSpdLines+1)/1000.0;
fprintf(outp, "%10.5f", Y);

count1=0;
do
{
    fprintf(outp, "%10.5f", NonDSpeed[count1]);
    count1++;
}
while ((count1<4) && (count1<NumSpdLines));
/* fprintf(outp, "\n"); */

if(NumSpdLines>4)
{
    for (count1=4; count1<NumSpdLines; count1++)
    {
        fprintf(outp, "%10.5f", NonDSpeed[count1]);
        if((count1+2)%5 == 0)
            fprintf(outp, "\n");
    }
}

if((NumSpdLines+1)%5 != 0 )
    fprintf(outp, "\n");

fprintf(outp, " 0.00000");

```

```

count1=0;
do
{
    fprintf(outp,"%10.5f",RawDatain[count1][NumbPts[count1]-1][0]);
    count1++;
}
while ((count1<4) && (count1<NumSpdLines));
fprintf(outp,"\n");

if(NumSpdLines>4)
{
    for (count1=4; count1<NumSpdLines; count1++)
    {
        fprintf(outp,"%10.5f",RawDatain[count1][NumbPts[count1]-1][0]);
        if((count1+2)%5 == 0)
            fprintf(outp,"\n");
    }
}

if((NumSpdLines+1)%5 != 0 )
    fprintf(outp,"\n");

X=NumSpdLines+1.0+(NumbBetaLines+1.0)/1000.0;
Y=2.0+(NumSpdLines+1.0)/1000.0;

/* Print the Non-D Mass Flow Table */
fprintf(outp,"Mass Flow = f(N/sqrt(T),relative Pressure Ratio)\n");
fprintf(outp,"%10.5f",X);

for (count1=0; count1<4; count1++)

```

```

    fprintf(outp, "%10.5f", Beta[count1]);

fprintf(outp, "\n");
for (count1=4; count1<NumbBetaLines; count1++)
{
    fprintf(outp, "%10.5f", Beta[count1]);
    if((count1+2)%5 == 0)
        fprintf(outp, "\n");
}

if((NumbBetaLines+1)%5 != 0 )
    fprintf(outp, "\n");

for (count1=0; count1<NumSpdLines; count1++)
{
    fprintf(outp, "%10.5f", NonDSpeed[count1]);

    for (count2=0; count2<4; count2++)
        fprintf(outp, "%10.5f", Q[count1][count2]);

    fprintf(outp, "\n");

    for (count2=4; count2<NumbBetaLines; count2++)
    {
        fprintf(outp, "%10.5f", Q[count1][count2]);
        if((count2+2)%5 == 0)
            fprintf(outp, "\n");
    }

    if((NumbBetaLines+1)%5 != 0 )

```

```

        fprintf(outp, "\n");
    }

    /* Print the Efficiency Table */
    fprintf(outp, "\n");
    fprintf(outp, "Efficiency = f(N/sqrt(T), relative Pressure Ratio)\n");
    fprintf(outp, "%10.5f", X);

    for (count1=0; count1<4; count1++)
        fprintf(outp, "%10.5f", Beta[count1]);

    fprintf(outp, "\n");
    for (count1=4; count1<NumbBetaLines; count1++)
    {
        fprintf(outp, "%10.5f", Beta[count1]);
        if((count1+2)%5 == 0)
            fprintf(outp, "\n");
    }

    if((NumbBetaLines+1)%5 != 0 )
        fprintf(outp, "\n");

    for (count1=0; count1<NumSpdLines; count1++)
    {
        fprintf(outp, "%10.5f", NonDSpeed[count1]);

        for (count2=0; count2<4; count2++)
            fprintf(outp, "%10.5f", Eff[count1][count2]);

        fprintf(outp, "\n");
    }

```

```

    for (count2=4; count2<NumbBetaLines; count2++)
    {
        fprintf(outp,"%10.5f",Eff[count1][count2]);
        if((count2+2)%5 == 0)
            fprintf(outp,"\n");
    }
    if((NumbBetaLines+1)%5 != 0 )
        fprintf(outp,"\n");
}

fclose(outp);

/* Print out Design pt. data to screen & file */
outp2=fopen(Out2,"w");

fprintf(outp2,"Here is the brief design pt. data for the map file %s.",OutputFile);
fprintf(outp2,"\n\nThe map input file was %s.",InputFile);
fprintf(outp2,"\nYour input design PR was %f",Design_PR);
fprintf(outp2,"\nand your calculated design Beta is %f for a Non-D Speed of
1.",DesignBeta);

fclose(outp2);

printf("\n\n\nHere is the brief design pt. data for the map file %s.",OutputFile);
printf("\n\nThe map input file was %s.",InputFile);
printf("\nYour input design PR was %f",Design_PR);
printf("\nand your calculated design Beta is %f for a Non-D Speed of 1.",DesignBeta);
printf("\nYou may find this information also in the file %s.",Out2);

return(0);
}

```

Input File Formats Used

GASTURB 6.0

The GASTURB input files are arranged in a consistent manner. The first lines begin with the number “99” which tells GASTURB that these are component characteristics. The second line provides information on the Reynolds number effects upon the component characteristics. In the NRC T400 model, this information has been coded directly into the executable files, and these numbers have no effect. The remainder of the files are broken up into tables describing corrected mass flows, pressure ratios and efficiencies as functions of the β values described in Chapter 2 and corrected rotational speeds. A more detailed description of these tables follows.

To clarify the organization of these files, each of the numbers have been identified with a different font depending upon its nature. The numbers which appear in **bold** indicate the number of rows and columns in each table. They are determined by the following formula:

$$\text{Number} = \text{Number of Rows} + \text{Number of Columns} / 1000$$

The numbers in *italic* are the β values. These values are most closely correlated to the PR of the compressor or turbine. The underlined numbers are the corrected rotational speed ($N/\sqrt{\Theta_{in}}$) of the turbomachinery. The numbers with lines through them are merely place holders. They must be present, but have no effect. Text within braces { } are comments only, and are not part of the data file as read by GASTURB. Finally, the remaining numbers in the table are either the corrected mass flow, pressure ratio or efficiency as indicated by the label at the top of each table.

Reynolds: RNI=0.100 f=1 RNI=1.000 f=1.000

Mass Flow

4.00600	0.0	0.25	0.50	0.75
1.00				
<u>0.50000</u>	100.00000	90.00000	75.00000	60.00000
50.00000				
<u>0.80000</u>	130.00000	120.00000	110.00000	90.00000
70.00000				
<u>1.00000</u>	150.00000	140.00000	130.00000	100.00000
80.00000				

Efficiency

4.00600	0.0	0.25	0.50	0.75
1.00				
<u>0.50000</u>	0.40000	0.50000	0.60000	0.70000
0.65000				
<u>0.80000</u>	0.60000	0.70000	0.80000	0.85000
0.80000				
<u>1.00000</u>	0.65000	0.75000	0.85000	0.88000
0.80000				

Pressure Ratio

4.00600	0.0	0.25	0.50	0.75
1.00				
<u>0.50000</u>	2.00000	3.00000	3.50000	5.00000
7.00000				
<u>0.80000</u>	3.00000	4.00000	5.50000	6.50000
8.00000				
<u>1.00000</u>	4.00000	5.00000	6.00000	7.00000
9.00000				

Surge Line {first line is mass flow, second is PR}

1.00300	50.00000	70.00000	80.00000
1.00000	7.00000	8.00000	9.00000

99 demo GASTURB turbine map input

Reynolds: RNI=0.1 f=1 RNI=1 f=1

Min Pressure Ratio = $f(N/\sqrt{T})$

<u>2.00500</u>	<u>0.50000</u>	<u>0.60000</u>	<u>0.80000</u>	<u>1.00000</u>
0.00000	1.20000	1.30000	1.35000	1.40000

Max Pressure Ratio = $f(N/\sqrt{T})$

<u>2.00500</u>	<u>0.50000</u>	<u>0.60000</u>	<u>0.80000</u>	<u>1.00000</u>
0.00000	3.00000	3.20000	3.50000	4.00000

Mass Flow = $f(N/\sqrt{T}, \text{relative Pressure Ratio})$

<u>6.00500</u>	<i>0.00000</i>	<i>0.25000</i>	<i>0.50000</i>	<i>1.00000</i>
<u>0.50000</u>	20.00000	40.00000	50.00000	60.00000
<u>0.60000</u>	25.00000	45.00000	55.00000	65.00000
<u>0.80000</u>	27.00000	47.00000	57.00000	65.00000
<u>1.00000</u>	27.00000	47.00000	57.00000	65.00000
<u>1.20000</u>	25.00000	45.00000	55.00000	65.00000

Efficiency = $f(N/\sqrt{T}, \text{relative Pressure Ratio})$

<u>6.00500</u>	<i>0.00000</i>	<i>0.25000</i>	<i>0.50000</i>	<i>1.00000</i>
<u>0.50000</u>	0.80000	0.85000	0.90000	0.88000
<u>0.60000</u>	0.81000	0.86000	0.91000	0.90000
<u>0.80000</u>	0.82000	0.88000	0.92000	0.91000
<u>1.00000</u>	0.84000	0.90000	0.93000	0.92000
<u>1.20000</u>	0.82000	0.88000	0.92000	0.91000

Performance Matching Routine File Formats

The first step of the performance matching routine implemented in NRC T400 is to read the tested engine performance data from disk. The file format of this data file is as described below. It is an ASCII text file like the other file formats already mentioned.

- Line 1: Number of engine data points in the file
- Line 2: ITT trim of the engine as listed on the engine name plate. This value is zero for NRC T400 data.
- Line 3: A string of 12 ones or zeroes separated by tabs. This line indicates which of the engine parameters are to be used in the cost function and which are to be ignored. The ones indicate that the parameter is to be used, while a zero indicates that it is to be ignored. The engine parameter designations which correspond to each of these numbers are as follows:
 N_{hp} , N_{PT} , T_{amb} , T_2 , P_2 , P_{3s} , ITT, SHP, W_f , EGT, W_2 , T_3
- Line 4: A string of 7 ones and zeros separated by tabs. This line indicates which of the component characteristics such as compressor flow or HPT efficiency is to be scaled as part of the simplex algorithm, and which are to be ignored. As above, ones indicate that the component characteristic is to be scaled, and zero indicates that it is to be ignored. The component characteristics which correspond to each of these numbers are as follows:
 Corr W_c , η_c , Corr W_{HPT} , η_{HPT} , Corr W_{PT} , η_{PT} , % Handling Bleed Leak
- Line 5: This is the first data point. The measured parameters designated in line 3 are listed here in the same order. Each line after this lists the measured data for each succeeding data point until all of the data points have been listed. Note that all 12 columns must be filled in. Those columns designated to hold engine

parameters which are not being used must be filled with place holders for the unused parameter.

A sample data file is shown below to illustrate the format described above.

Sample input File

```

1      {One data point}
50      {A 500F ITT trim is used as described in Chapter 5}
1  1  0  1  1  1  1  1  1  0  1  0  {Tamb, EGT, and T3 not used}
1  1  1  1  0  1  0                  {Corr WPT and % Handling Bleed
                                     not scaled}
Nhp NPT 0  T2  P2  P3s  ITT SHP Wf 0  W2, 0  {Data point 1 with place holders
                                                for unused parameters}

```

The units associated with each of the engine parameters in the input file depend on whether the data has come from the NRC test stand or from the NRC T400 model. Table 45 below lists them.

Finally, a brief mention should be made to the output file format. Not much explanation is necessary as it is simply of a tabular format which is quite easy to follow. The variables written out to file for each engine test point examined are as below.

N_{hp}, N_{PT}, T_{amb}, T₂, and P₂, 8 component scaling factors as described in Line 4 above, P_{3s}, ITT, SHP, W_f, EGT, W₂, Compressor delivery temperature (CDT), Calc T₂, # func evals, cost func, T₂ error(%), P_{3s} error(%), ITT error(%), SHP error(%), W_f error(%), EGT error(%), W₂ error(%), CDT error(%)

The first five parameters written to file specify the engine operating condition. Next, the 8 component characteristic scaling factors as found by the simplex algorithm are written, each in a column reserved for it. Columns representing unscaled component

characteristics are filled in with zeroes. Next, the values of some engine parameters of interest as predicted by NRC T400 are listed for the scaled model engine. The “Calc T2” variable refers to the compressor inlet temperature calculated assuming a uniform mixing of the ambient air and the handling bleed air as discussed in Chapter 5. Finally, the percent errors between the predicted engine parameters and the measured values are listed to provide the user with an indication of how well the performance matching has succeeded on a parameter by parameter basis.

Table 45 - Units Used for Engine Parameter Input to Performance Matching Routine

Engine Parameter	NRC Test Stand Units	NRC T400 Units
N_{hp}	RPM	Normalized (Range from 0-1)
N_{PT}	RPM	Normalized (Range from 0-1)
T_{amb}	$^{\circ}R$	$^{\circ}R$
T_2	$^{\circ}R$	$^{\circ}R$
P_2	psia	psia
P_{3s}	psig	psia
ITT	$^{\circ}C$ (Trimmed as measured)	$^{\circ}R$
SHP	HP	HP
W_f	lbm/hour	lbm/s
EGT	$^{\circ}C$	$^{\circ}R$
W_2	lbm/second	lbm/s
T_3	not measured	$^{\circ}R$

Bell 212 Topping Test File Formats

The Bell 212 DND Topping test as implemented in the NRC T400 model does not read data from a file. Instead, the data as shown in the GASTURB 6.0 data input screen is used directly. The operation of this routine is described in Chapter 5.

For the output, the Bell 212 Topping test routine writes an output file which indicates whether the power section in question has passed or failed the topping test. Also indicated are the % TRQ values required of the engine if it is to pass the test under the ambient conditions in question. The % TRQ actually produced by the performance matched NRC T400 model is also shown, along with the maximum power limiter which is in effect. Finally, a few critical engine parameters which specify the engine operating state are listed. A sample Topping test output file is as shown below.

Sample Topping Test Output Written to File

The Topping Test Results are as Follows:

The engine operating state is:

Altitude	Delta Tamb (Deg R)	Nhp	Npt
5000.00000	26.83080	1.00000	0.97000

The Topping Test Results are as follows:

PASS/FAIL	Active Lim	Pass TRQ(%)	Our TRQ(%)
Passed!	Mech Nhp	49.30023	53.13595

Other global variables of interest:

SHP	Trim ITT	Untrim ITT	Fuel Flow
665.82971	1831.39148	1892.43262	385.38668

File Formats for COMPMAP.C and INTERP.C

These pages show the input file format for COMPMAP.C and TURBMAP.C. The two programs utilize the same input file text file formatting, so only one example has been shown. It should be noted that for these files the corrected speeds and PR's MUST be arranged in ascending order. Also, COMPMAP.C or TURBMAP.C cannot smooth the data before fitting β lines. The user should plot the component characteristic curves in a separate plotting package to ensure the data is smooth before proceeding. The programs COMPMAP.C and TURBMAP.C provide as output text files with the input formats required by GASTURB. The numbers in these sample files have no physical meaning, and have been placed there to illustrate the formatting of the file only. The input file format for INTERP.C is similar with the exception that the corrected rotational speeds form a first column in a four column format. This provides a "carpet" of points from which INTERP.C will interpolate lines of constant corrected speed. The program INTERP.C operates in the same manner as COMPMAP.C except that it uses the β lines that it has fit to perform a second interpolation for constant spool speeds. For more information about these programs, see Chapter 2 and the program flowcharts and printouts to follow.

Compressor Map input to COMPMAP.C

```

3  {Number of constant corrected speed lines}
5  {Number of points in first speed line}
5  {" " " " " " " "}
5
0.60000  {<--Corrected speed - Speed line #1}
2.20000      15.00000      0.65000
2.80000      15.00000      0.75000
3.50000      14.00000      0.78000
4.80000      12.00000      0.80000
6.20000      10.00000      0.85000

```

<u>0.80000</u>		
2.50000	20.00000	0.70000
3.00000	20.00000	0.78000
3.80000	17.00000	0.80000
5.00000	15.00000	0.82000
6.50000	13.00000	0.86000
<u>1.00000</u>		
3.00000	25.00000	0.70000
3.50000	25.00000	0.78000
4.30000	22.00000	0.80000
5.50000	20.00000	0.82000
7.20000	17.00000	0.86000
{ PR	Corr. Mass Flow	Efficiency }

IMAGE EVALUATION TEST TARGET (QA-3)

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