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UNIVERSITÉ DE MONTRÉAL

CONCEPTUAL STUDY OF ALTERNATE INDUSTRIAL GAS TURBINE CYCLES

par

Benoit TRUDEL

DÉPARTEMENT DE GÉNIE MÉCANIQUE

ÉCOLE POLYTECHNIQUE

RAPPORT DE PROJET PRÉSENTÉ EN VUE DE L'OBTENTION

DU GRADE DE MAÎTRE EN INGÉNIERIE (M.Ing.)

(GÉNIE AÉRONAUTIQUE)

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UNIVERSITÉ DE MONTRÉAL

ÉCOLE POLYTECHNIQUE

Ce rapport de projet intitulé:

CONCEPTUAL STUDY OF ALTERNATE INDUSTRIAL GAS TURBINE CYCLES

présenté par: Benoit TRUDEL

en vue de l'obtention du grade de: Maître en Ingénierie (M.Ing.)

a été dûment accepté par le jury d'examen constitué de:

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ABSTRACT

This is a study of the thermodynamic potential of a few complex cycles for industrial gas turbines. The main additions to the basic gas turbine cycle are:

- water or steam injection
- intercooling
- recuperation

The performance of each cycle is evaluated in terms of efficiency and power for a three- and two-shaft engine configuration. A description and an illustration of each cycle is provided with the assumptions used in the simulation. The assumptions relate to the pressure loss, effectiveness or efficiency, and bleed fraction of the new components added to the simple cycle. Due to Rolls-Royce confidentiality rules, the results are shown in non-dimensional form. The conclusion of the work is that the simultaneous use of intercoolers and recuperators is the best combination to enhance the performance of an engine.

RÉSUMÉ

Ce projet consiste en une étude préliminaire du potentiel thermodynamique et une simulation de differents cycles de turbines à gaz industrielles. Le but de cette étude est de déterminer la meilleure façon de développer le Trent Industriel dans le futur. L'évaluation relative de la performance des cycles étudiés permettra d'effectuer un choix.

L'étude a débuté par une analyse de la littérature sur le sujet des cycles de turbines à gaz industrielles. Ensuite, le travail a consisté principalement à modéliser ces cycles, les programmer, simuler et enfin analyser les résultats. Tout ce travail a été accompli en milieu industriel.

L'entreprise, Turbines à Gaz Rolls-Royce (Canada) Inc. (TAGRR) est une filliale du groupe britannique Rolls-Royce plc. et a vu le jour à la fin de l'année 1992.

Rolls-Royce plc. est un groupe international oeuvrant dans le génie. Grâce à son expérience internationale et les habiletés technologiques, Rolls-Royce est un leader dans les marchés suivants: les turbines à gaz aéronautiques, marines et industrielles, la génération d'électricité, le génie nucléaire et les matériaux.

Rolls-Royce est constitué de deux groupes principaux: le groupe aérospatial, spécialisé dans les turbines à gaz pour les avions civils et militaires; et le groupe

industriel, qui conçoit, construit et installe les sytèmes de génération, transmission et distribution d'électricité ainsi que les équipements miniers, de propulsion marine, de pompage de pétrole et de gaz, et de défense.

Turbines à gaz Rolls-Royce a été formée pour accomplir le développement de la version industrielle du Trent. Le Trent industriel sera conçu pour produire plus de 50 MW d'électricité avec grande efficacité et de faibles émissions de polluants. A cet effet, un accord statégique a été signé entr Rolls-Royce et Westinghouse Electric Corporation. Cette alliance améliore la position de Rolls-Royce dans les marchés mondiaux des turbines à gas industrielles. Bien sûr, le Trent industriel est un des objets de cette alliance.

La compagnie Turbines à Gaz Rolls-Royce est divisée en plusieurs services, aussi dits départements. Le poste de l'auteur, ingénieur de performance, se trouve au sein du département de Performance et Contrôle.

Le département de Performance et Contrôle maintient des liens avec la plupart des autres départements. Bien sûr, les contacts sont plus fréquents avec le département d'Aérothermique. Ce dernier fournit, par exemple, les cartes des compresseurs et des turbines afin de les inclure dans le modèle du moteur. La tâche principale des ingénieurs de performance est de définir le point d'opération optimum et les autres conditions d'opérations de la machine. Ceci permet aux autres départements de concevoir les composantes et systèmes du moteur.

L'entreprise entretien aussi des relations avec les autres membres de Rolls-Royce: Rolls-Royce Inc. (Atlanta) a contribué à la définition aérodynamique du compresseur.

Le Trent industriel est un moteur dérivé du Trent aéronautique. Le Trent possède trois arbres concentriques portant chacun un compresseur et une turbine. Des aubes à angle variables et des soupapes d'extraction permettent d'élargir l'enveloppe d'opération du moteur. Dans sa version industrielle, la soufflante (fan) du moteur aéro fait place à un nouveau compresseur basse pression. Ce compresseur est lié directement à la turbine basse pression ainsi qu'à la génératrice électrique. Celle-ci est situé du côté des gaz chauds et la puissance lui est transmise sans boîte de réduction. De plus, pour assurer un courant de fréquence stable, l'abre moteur tourne à vitesse constante. Le nouveau système de combustion est constitué de huit chambres cylindriques. La combustion atteindra des niveaux très bas d'émissions de Nox et de CO pour satisfaires les normes environnementales. L'ensemble turbine et générateur, appelé commercialement Econopac, sera lancé sur les marchés électriques de 50 et 60 Hz. La première turbine industrielle Trent sera en opération en 1996.

Le moteur a été modélisé par les ingénieurs de performance de RRGTE et de RRIMGT. Ce modéle thermodynamique uni-dimensionnel prend la forme d'un programme RRAP modulaire écrit en FORTRAN.

Le cycle thermodynamique de base d'une turbine à gaz est le cycle de Brayton. L'objectif de l'étude est de trouver un cycle d'une performance supérieure en terme de puissance et de rendement thermique. Dans l'étude de croissance d'une turbine, les options suivantes sont considérées:

1. L'augmentation de la température à l'entrée de la turbine (HP)
2. L'amélioration de la performance des composantes
3. L'augmentation du débit massique
4. Les cycles complexes

Les deux premières options sont rejetées puisque la température est limitée par les matériaux est les émissions; et la qualité des composantes, par le niveau de la technologie actuelle. Pour sa part, l'augmentation du débit implqie des modifications majeures au moteur et a donc des conséquences trop coûteuses. Une des contrainte du développement du Trent industrielle est de conserver le maximum de pièces commumes avec son équivalent aéronautique. Donc l'option 3 est aussi mise de côté. Le terme cycle complex est utilisé ici pour décrire un cycle de Brayton où sont ajoutés d'autres éléments. Parmi les cycles complexes, le cycle combiné où une turbine à vapeur récupère l'énergie des gaz d'échappement fait déjà partie des plans de l'alliance WEC-Rolls-Royce. Pour cette raison, ce cycle est exclu se cette étude.

Par contre, les cycles avec injection d'eau ou de vapeur, avec refroidisseur intermédiaire et avec regénération font l'objet de cette étude. Ce rapport présente une description de ces cycles, les hypothèses ayant servi à la simulation ainsi que les résultats. Les hypothèses concernent les pertes de pression, l'efficacité et les fractions de débit d'extraction des nouvelles composantes ajoutées au cycle Brayton de base. La performance des cycles est évaluée en fonction de la puissance et du rendement thermique. Pour des raisons de confidentialité, ceux-ci ont été normalisés. Pour effectuer une comparaison équitable, les cycles ont un rapport de pression et une température à l'entrée de la turbine communs.

Le cycle avec injection d'eau démontre une puissance supérieure due principalement à l'augmentation du débit massique. Par contre, le rendement thermique diminue puisque l'évaporation de l'eau "coûte" beaucoup d'énergie au cycle. Si de la vapeur était disponible, l'injection de vapeur offirait la même augmentation de puissance mais avec une rendement supérieur. Le cycle de Brayton avec un seul refroidisseur intermédiaire (LP) présent le même rendement que l'injection de vapeur mais donne plus de puissance. Un cycle avec un refroidisseur (IP) et un regénérateur accroît encore plus la puissance que le cycle précédent, avec un rendement semblable. Enfin, l'aujout d'un second refroidisseur (LP) au même cycle augmente cette fois le rendement tout en conservant la puissance du cycle.

En conclusion, l'ajout de refroidisseurs intermédiaires et de regénérateurs représente la meilleure façon d'accroître la performance des cycles thermodynamiques de turbines à gaz.

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- Mary Fletcher and Bob Watson (RRIMGT Ansty) who are responsible for some of the complex cycles additions to an Industrial Trent engine model

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LIST OF SYMBOLS

AC	Alternating Current
CC	Combined Cycle
DICR	Dual Intercooled Recuperated
FH	Fuel Heater
HAT	Humid Air Turbine
HP	High Pressure
IC	Intercooler
ICR	Intercooled Recuperated
ICRR	Intercooled Recuperated Reheated
IP	Intermediate Pressure
ISO	International Standard Organization
LP	Low Pressure
NRC	National Research Council
ppmv	part per million volume
REC	Recuperator
RR	Rolls-Royce
RRAP	Rolls-Royce Aerothermal Program
RRGTE	Rolls-Royce Gas Turbine Engines Canada Ltd.
RRIMGT	Rolls-Royce Industrial & Marine Gas Turbines Ltd.

SC	Simple Cycle
VIGV	Variable Inlet Guide Vanes
WEC	Westinghouse Electric Corporation

Variables

ρ	Density
Δ	Difference
ε	Effectiveness
η	Efficiency
Θ	Enthalpy function
β	Interpolation variable in compressor maps
A	Area
C	Constant
CH	Constant
Cp	Specific heat
D	Constant
f	Fuel Air Ratio
FAR	Fuel Air Ratio
h	Specific enthalpy
H	Enthalpy

LHV	Lower Heating Value
LMTD	Log Mean Temperature Difference
MW	Molecular Weight
N	Speed
P	Pressure
Pr	Pressure ratio
P_W	Power
R	Gas constant
q	Heat
T	Temperature
T41	Turbine Inlet Temperature (TIT)
UA	Heat transfer coefficient x area
V	Velocity
W	Mass flow
W	Work
WFR	Water/Fuel Ratio
Z	Comparison Parameter

Subscripts

A	Air (side)
cool	Cooling fluid
Cp	Specific heat
f	Fuel flow
FH	Fuel Heater
G	Gas (side)
h	Enthalpy
HPC	High Pressure Compressor
i	In
IC	Intercooler
IPC	Intermediate Pressure Compressor
is	Isentropic
max	Maximum
o	Out
p	Polytropic
rad	Radiation
rec	Recuperator
SC	Simple Cycle
t	Turbine
U	Universal

CHAPTER 1. INTRODUCTION

This project is in fact a course (*Projet de maîtrise en ingénierie MEC6901*) part of the Aerospace Master program offered at the École Polytechnique de Montréal. The Master's project has been carried out at Rolls-Royce Gas Turbine Engines.

This document is the Master's project report[1]. In the introduction, the goal of the project is identified and the project work schedule is illustrated. In the following section, the reader is introduced to the company RRGTE. The international and local hierarchy of Rolls-Royce is shown and a description of the company, product and market is given. Then the section 3 focuses on the project work. An abstract is provided in section 1.3. Finally, in the conclusion, the personal contribution of the author to the project is stated. The author also issues recommendations for future work and assesses the skills and knowledge earned during the project.

1.1 Project Description

This is a preliminary engine growth study for the Industrial Trent gas turbine. In other words, it is not a new engine design but the evolution of an existing one. A complete study would include the economical, technological and environmental aspects

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[1]The format of the report follows the guidelines given in "*Guide de publication d'une thèse de doctorat d'un mémoire de maîtrise ou d'un rapport de projet de maîtrise, Normes et procédures*".

of the development of the engine. This preliminary study will only scratch the surface of the technological side, as seen from the performance (department) point of view.

The objective is to study the thermodynamic performance of different gas turbine cycles to find one with higher output shaft power and better efficiency. As an engine growth study, one of the assumptions is to keep the engine core unchanged.

1.2 Project Schedule

The schedule below lists the activities of the project and the time spent on each task.

	93	93	93	93	93	93	93	93	94
	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.
Training	———	———							
Literature Analysis		———	———						
Programming & simulation		———	———				———	———	———
Analysis of results				———	———	———	———	———	———
Documentation					———	———	———	———	———

Figure 1 Schedule

During the required training, the author was introduced to the computer environment and taught the Rolls-Royce Aerothermal Program and utilities. The project started with quite an exhaustive literature analysis. In fact, a lot of effort is in the research for new gas turbine cycles. The author has read a number of papers on the matter (some of which are listed in reference) and issued a summary of those for internal needs.

The programming and simulation of the different gas turbine cycles has been carried out with different tools. Two different Rolls-Royce Aerothermal FORTRAN Programs and other softwares were used in this project. The analysis of the results from the previous step followed and it is presented in this document.

CHAPTER 2. THE COMPANY: RRGTE

Rolls-Royce plc is a high integrity engineering group bringing advanced cost-effective technology to aerospace and industrial power systems markets worldwide. Extensive international experience and technological skills make Rolls-Royce a world market leader in its chosen product fields: aero, marine and industrial gas turbines, power generation, nuclear engineering and materials handling.

The company has two main operating groups: Aerospace and Industrial Power.

The Aerospace Group serves both civil and military aircraft markets, providing engines for most types of aircraft in service today. In the civil sector Rolls-Royce is one of only three full capability engine design and manufacturing companies. Rolls-Royce engines power the world's largest airliners through small business and corporate jets. The company is continuing to expand its product range and is developing engines for new large civil airliners.

In the military aerospace market, Rolls-Royce designs and manufacture the latest in fast combat aircraft power plants and is also highly successful in providing engines for jet trainer aircraft and helicopters.

Today's Rolls-Royce is a significant supplier wherever cost-effective engineering solutions are required. A hierarchy diagram illustrates the relationships between all members of Rolls-Royce plc. (Figure 2 in Appendix I).

Rolls-Royce Gas Turbine Engines (Canada) Limited (RRGTE), located in Dorval, was established in late 1992 to undertake the required engineering research and design work to develop the Industrial Trent. Rolls-Royce Inc (Atlanta, Georgia) has assisted RRGTE in Industrial Trent engine design. These two companies are members of the Rolls-Royce plc group.

RRGTE and Westinghouse Electric Corporation (WEC) are working together to develop the 50-MW Trent based power generation plant. The packaged generating system is marketed under the name of Trent EconoPac. A 15-year alliance between the WEC and Rolls-Royce plc was signed in 1992. Westinghouse, a leader in the global power generation market, is headquartered in Pittsburgh, Pensylvania. This new alliance increases Rolls-Royce's competitive position in power generation markets.

2.1 Internal organization

RRGTE hierarchy is illustrated by the Figure 3 in Appendix I. All departments are listed on the diagram.

RRGTE is led by a President and assisted by a vice-president. Although, each department belongs to a Manager, departments are grouped by application under a Director. The author, a Performance engineer, is in the Performance and Controls Department, under the Director of Technology.

2.2 Relationships among the company

The Performance and Controls Department uses mathematical models of the engine to simulate the engine performance under different operating conditions. Therefore, the performance engineers provide the required information i.e. performance data to the other departments such as Aerothermal, Design, ... to design the engine components.

One of the performance engineers' tasks is to investigate advanced technologies for future engine development. This study of complex cycles is part of the future engine research program.

2.3 The product: the Industrial Trent

RRGTE has been formed to carry out the development of the industrial version of the Trent. This engine represents the Group's most significant investment in the industrial field to date.

At the heart of the Trent EconoPac is the Rolls-Royce Industrial Trent gas turbine. Based on the Aero Trent, the industrial engine is benefiting from a rigorous development and testing work that has been accomplished on the Aero engine. The Trent, in common with all members of the Rolls-Royce RB211 family, is a three-shaft design (low-pressure compressor and turbine, intermediate-pressure compressor and turbine, and high-pressure compressor and turbine). The engine has variable inlet guide vanes and blow-off valves to provide best performance over its operating envelope.

The Industrial Trent shares significant commonality with its Aero parent (figure 4 in Appendix I). The Aero engine uses a large diameter single stage low-pressure fan to provide a high bypass ratio. The Industrial Trent will replace the fan with a new two-stage low-pressure compressor. This new compressor is smaller in diameter and will be driven by the five-stage, direct-drive, low-pressure turbine. The generator is also driven by the LP turbine from the hot end of the engine. The first two stages of the turbine will be identical to those in the Aero Trent, but the last three will be slightly increased in diameter to help improve exhaust efficiency.

The Industrial Trent will feature a Dry Low Emissions (DLE) combustion system. This design is already being tested in the Industrial RB211 engine and will enter service with the RB211 in 1994.

The new combustion system incorporates a series of staged pre-mix, lean-burn combustion cans which allow the engine to achieve low NO_X and CO simultaneously. Eight of these combustors are incorporated in a single module of the Industrial Trent design. Initial engines will be guaranteed to achieve 25 ppmv NO_X with programs in place to reduce this below 10 ppmv.

The entire Trent gas turbine will feature modular construction so that individual modules can easily be removed and replaced. The benefit to operators is that they can reduce the number of spares they hold. Also, refurbishment can be carried out on individual modules rather than having to take the engine out of service.

The Industrial Trent is the latest member of a new, powerful, gas turbine family currently under development at Rolls-Royce. In September, the Trent 700 Aero engine was delivered to *Airbus Industrie* in preparation for flight testing on an Airbus A330 in early 1994. Joint Air worthiness Authority certification of this engine variant will be achieved before the end of 1993. The Trent 700, rated at 72000 pounds of thrust, is the market-leading engine on the A330 with 39% of the customers having selected the Rolls-Royce power plant.

In October, Trent 800 testing began at the Rolls-Royce Derby, England, facility. This engine, initially rated at 84000 lb. of thrust, is scheduled to enter service on the Boeing 777 aircraft in 1996. The variant has already achieved 93500 lb. of thrust in its first series of test. Major international airlines have already selected the Trent 800, which is due to be certificated in 1995.

2.4 Customers and market

The purpose of the development program is to provide the marketplace with the largest packaged power system available with an aeroderivative combustion turbine and at an efficiency that is unmatched. It is to be used for peaking, combined cycle, and cogeneration applications in both 50- and 60-Hz markets. To satisfy increasingly stringent emissions laws worldwide, dry low emissions (DLE) combustors are provided with dual fuel capability.

In 1996, the first Trent EconoPac will generate electricity at a commercial installation. It is expected that, in 1996 and the following years, an important need for industrial engines will arise.

A member of Rolls-Royce Industrial Power Group, Rolls-Royce Industrial & Marine Gas Turbines Ltd. (RRIMGT Ansty) will handle the marketing of the engine with Westinghouse (Orlando).

CHAPTER 3. PROJECT

3.1 Description

RRGTE Performance department has developed a model of the Industrial Trent engine with the help of RRIMGT. This one dimensional thermodynamic model has been built into a software known as Rolls-Royce Aerothermal Program (RRAP). It allows the performance engineers to do non real-time simulation of the engine and to predict steady state and transient behavior. The engine performance program is shortly (and symbolically) described by the diagram of figure 5 in Appendix I. The first line indicates flow path station numbers for the program internal use. The program calculates the cycle by going through each component which name is given at the third line. The arrows illustrate the direction of the computation. The bottom line shows engine station numbers that follow the standard numbering convention given by ARP 755 (reference 1).

The engine model is currently in a configuration called Simple Cycle (SC). It is the basic (open) Brayton cycle using a compressor, a combustor and a turbine. The goal of this study is to investigate alternate cycles to produce more output power and to achieve better efficiency/heat rate with minimum engine modification. By adding new elements or components to the simple gas turbine cycle, it becomes a so called "complex" cycle. One of them is the combined cycle where a steam boiler and steam turbine are added to the gas turbine. Since WEC has already agreed to build a combined cycle, it is not included in this project. The complex cycles of interest feature:

- Water/steam injection
- Intercooling
- Recuperation

All engine configurations assume a three- or two-shaft gas turbine with output power extracted from the LP shaft. The three-shaft engine is of prime interest because it is the current Industrial Trent configuration and is given more attention in the project.

3.2 The options considered

Usually, one considers the following steps in engine growth:

1. Higher T41
2. Better components
3. Higher mass flow
4. Complex cycles (water/steam injection, intercooling, recuperation)

3.2.1. Higher T41

Raising the turbine inlet temperature also known as "Throttle Push" increases the work output of a gas turbine cycle. A higher turbine inlet temperature increases the enthalpy difference across the turbines and hence the output power for constant compressor work. For a turbine, the power is given by:

$$P_{W_t} = W_t \cdot \left[h_t(T_i) - h_t(T_o) \right] \tag{1}$$

The turbine inlet temperature (T_i) is ultimately limited by the material maximum temperature. The surfaces of the components exposed to the hot gas must be maintained below a certain safe working temperature, consistent with mechanical strength and corrosion resistance. As the turbine inlet temperature is raised, the temperature difference between the hot gas and the metal surfaces will increase. The cooling requirements will then increase both with respect to the amount of coolant for a given stage and to the proportion of the expansion path which has to be cooled. Cooling of stages in the expansion path counteracts the effect of increased inlet temperature. When, for a given level of cooling technology, the turbine inlet temperature is raised beyond a certain value, the cooling penalties are such that the cycle efficiency falls.

Turbine temperature are further limited by emissions considerations. In fact, in the case of an industrial engine, this is a major concern. The relation between NO_X and CO and temperature (T41) is shown by the next figure. The nitrous oxides (NO_X)

emissions increase with turbine entry temperature whereas the carbon monoxide decrease. For given maximum allowable quantities of emissions, the turbine entry temperature is limited on the high side by the NO_x curve and on the low side by the CO curve.

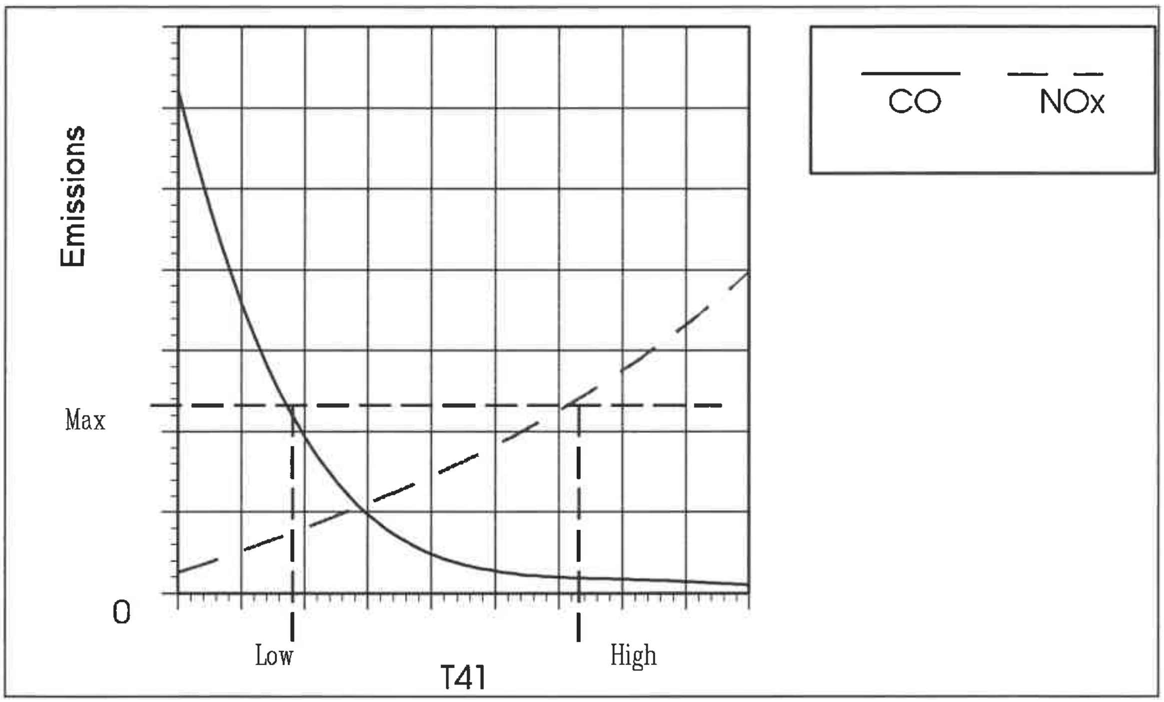

Figure 6 Emissions

3.2.2. Better components

The efficiency of the components is mainly limited by the state of the technology. The quality of a component is stated by its efficiency. The efficiency of the turbine, for example, is buried in the term $h_t(T_0)$ of equation (1). Indeed the efficiency of a turbine is:

$$\eta_t = \frac{h_t(T_i) - h_t(T_o)}{h_t(T_i) - h_t(T_{ois})} \tag{2}$$

3.2.3. Higher air mass flow

The air mass flow (W_t) given in equation (1) is effectively a big driver of turbine power. Its value is calculated as:

$$W_t = \rho \cdot V \cdot A \tag{3}$$

To increase the air mass flow of the simple cycle requires significant modifications. Examples are to increase the diameter (and intake cross section area) of the engine, restagger turbine blades or add stages to the LP compressor. The last one of those ideas also known as "Supercharging" has the lowest cost but is still more expensive than the options considered here. Engine modifications are expensive and increase the variety of spare parts. For this reason, a great deal of effort has been put in to keep the Industrial Trent core common with the Aero Trent. For this reason, the potential of the increased air flow option will not be investigated further in this project.

An element called a "chiller" which decreases compressor inlet temperature increases in fact the air density and hence the mass flow. Although it is promising, it is left out of the present work because it is equivalent to a lower ambient temperature and therefore easily simulated.

3.2.4. Complex cycles

Complex cycles provide solutions for engine growth when cycle temperatures are limited, component efficiencies are state-of-the-art and minimal changes to the existing turbomachinery are desired. In the following, a few complex gas turbine cycles are studied and compared. For all of them, the turbine inlet temperature and the overall pressure ratio are held constant. It is assumed that the modifications required by the complex cycles are possible and affordable.

RRAP Description

Before the cycles are described and because a major part of the project has been carried out with Rolls-Royce Aerothermal programs (BA48, BA51), some description of them is required. However, because it is private data, only limited information is made public.

The programs are modular and call basic Rolls-Royce subroutines known as "Bricks" for each component: compressor, turbine,... The matching of an engine model is an iterative process that involves the adjustment of a set number of independent parameters (the variables) such as rotational speed, β or fuel flow, until the set differences between pairs of predetermined values of an equal number of dependent parameters (the matching quantities) have been reduced to zero within a given set of tolerance. The process of finding the zeros of a function or set of functions, possibly also subject to a set of constraints, is accomplished by successive evaluation of the functions and constraints. Due to the iterative nature of the calculations, a multi-dimensional convergence method is used to solve the equations. At the heart of the method is the evaluation of the matrix of the partial derivatives of the matching quantities with respect to each variable and the resolution of the system of equation.

The program BA48 allows the user to simulate a three shaft gas turbine with output power from the LP shaft with options for water injection and intercooling. The program BA51 was developed from the Industrial Trent model BA48 and incorporates option to model water or steam injection, intercooling, recuperation and other complex cycles. The two programs use the current Industrial Trent core (IP and HP) compressors and turbine maps because it is intended to keep the core hardware.

3.2.4.1. Water/steam injection

Description:

Water injection is a well known method to increase power of an engine. It is achieved by raising the mass flow trough the turbines. It is used on Aero engines as well as industrial engines. Water at ambient temperature is injected in the air flow. The water temperature selected (ambient) is the most realistic and a different one would have very little effect on the cycle.

Water injection not only increases power but reduces the emissions. The concern about emission levels comes from the fact that the laws are more strict for ground operating engines than aircraft engines. The reduction of emissions with water has been achieved in actual tests. The emission levels may be evaluated in different operating conditions for a simple cycle (that is, without injection) with empirical relationships (shown in Figure 6). For the time being, no quantitative prediction of emissions can be made for other cycles.

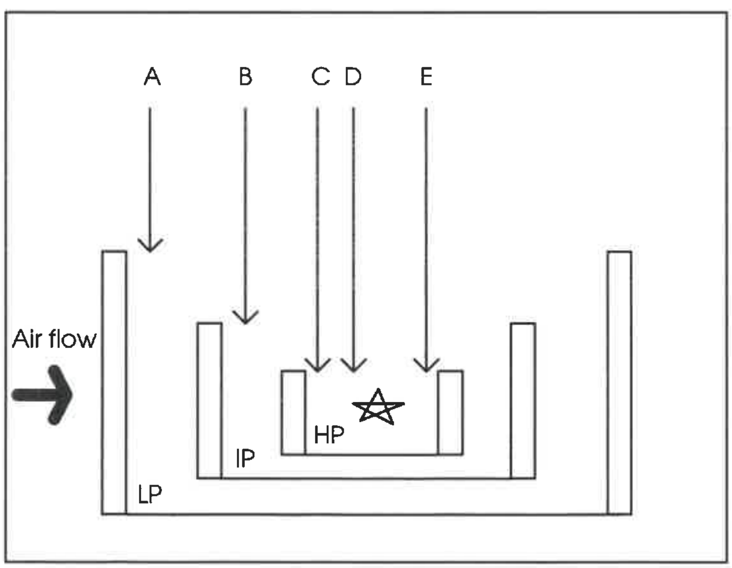

Figure 7 Water/steam injection

In the figure above, the Trent is schematically shown by 3 shafts with the corresponding LP, IP and HP compressors and turbines. The combustor is simply represented by a star. The arrows illustrate the water/steam flow at all the possible injection locations.

The possible theoretical locations for water/steam injection as shown above are:

- LP-IP Duct (A)
- IP-HP Duct (B)
- HPC Exit Duct (C)
- Combustor (D)
- Turbine Entry Duct (E)

It has been demonstrated in reference 2 that a higher mass flow increases output power especially if this extra flow (due to injection) needs not to be pressurized by the gas turbine compressors. So water injection is most efficient when injected downstream of the compressors. Considering those facts, one would inject in the HP compressor exit duct, combustor or turbine entry duct. Furthermore, because of the benefits of water in the combustion process with respect to the NO_X, the ideal injection locations are the HP compressor exit duct or combustor.

Assumptions:

If the gas temperatures are low, the amount of evaporation will be limited by the water ratio consistent with a relative humidity of 1. In other words, the amount of water injected is limited by the saturation of the air. The water injection cycle assumes saturated air.

Furthermore, an enthalpy balance is performed for the evaporation process allowing for the latent heat of evaporation. Here, it is assumed that all the water is evaporated and so gives temperatures lower than those that can really be achieved.

A pressure drop is modeled separately.

Results:

Power increased by the additional flow injected in the combustor as shown by the equation (1) above. The drop in efficiency is due to the latent heat of water that requires more fuel for the same turbine inlet temperature. As a matter of fact, all cases (and configurations) were tested with a constant and identical turbine inlet temperature (T_{41}). The relation between the output power and efficiency versus WFR is quite linear and plotted below. The WFR value of 1 was selected to meet the emissions requirements.

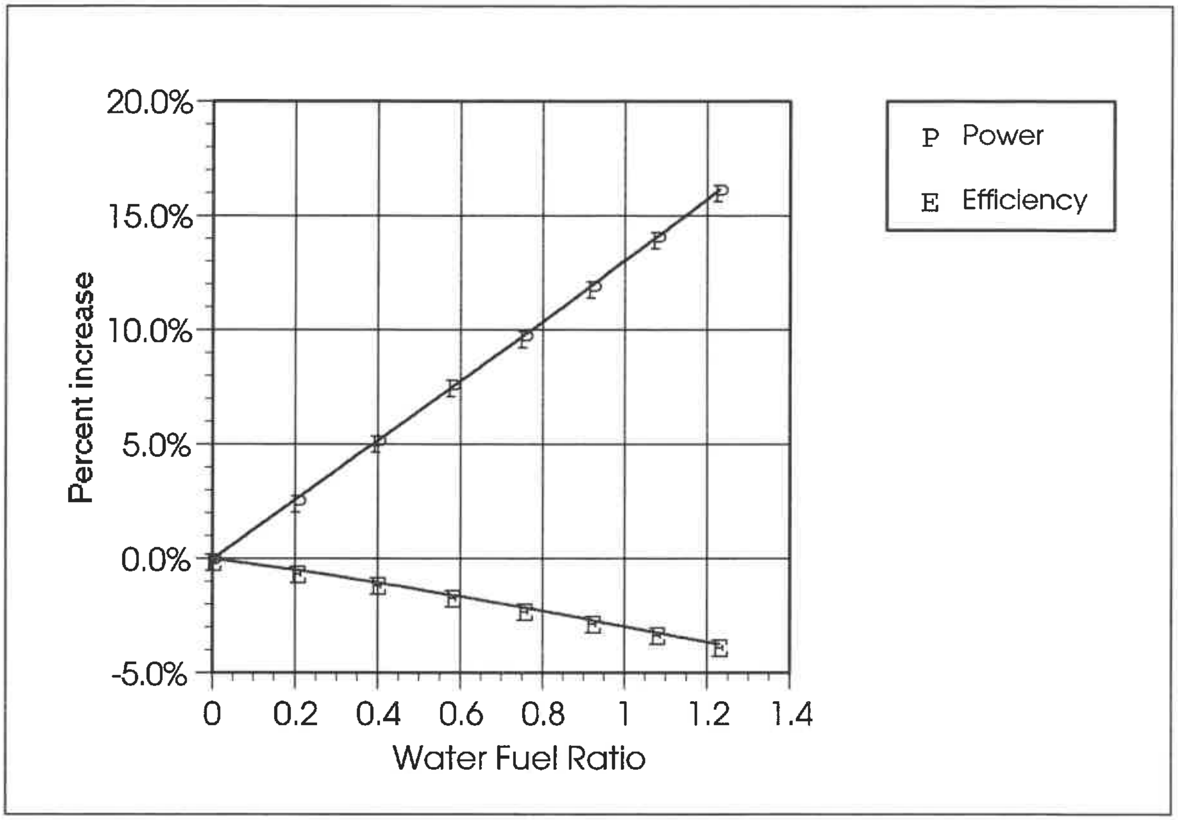

Figure 8 Water Injection

For a water fuel ratio (WFR) of 1, the results show:

- 13% relative increase of output shaft power
- 10% relative increase of specific power
- 3% relative increase of inlet air mass flow
- 16% relative increase of fuel flow
- 3% relative <u>decrease</u> of thermodynamic efficiency $\left(\frac{\Delta\eta}{\eta}\right)$

Steam:

Description:

Steam injection also has potential for engine growth. It may be injected at the same locations mentioned above. Steam has a clear advantage over water: it does not have efficiency penalty because its injection does not require extra energy (i.e. engine fuel) for vaporization in the combustor. Steam could be produced using the exhaust gases, as in the case of combined cycle operation.

Assumptions:

The pertinent assumptions used for water injection are also valid for steam. The amount of steam injected is also limited by the saturation of air. It is assumed that steam is "free", i.e. available at no energy "cost". In other words, the heat used to generate the steam is not included in the efficiency calculation.

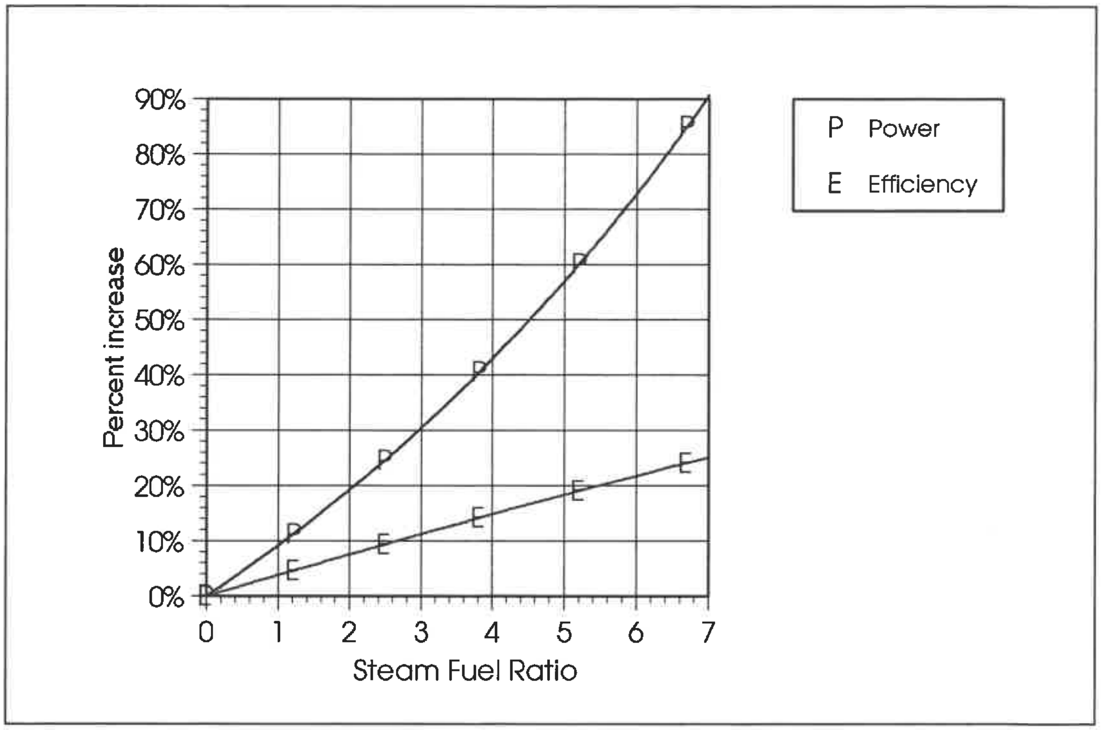

Figure 9 Steam injection

Results:

It results in an increase in both power and efficiency. The figure above illustrates the increase in power and efficiency due to steam injection.

Since no Steam Fuel Ratio (SFR) value has been recommended yet, the same value of one is used as in the case of water injection. With those assumptions, the power and efficiency increases are about 10% and 4% respectively.

The following illutrates the same RRAP results but plotted against the ones from references 2, 4 and 5. New X axis units (from the references) are used here.

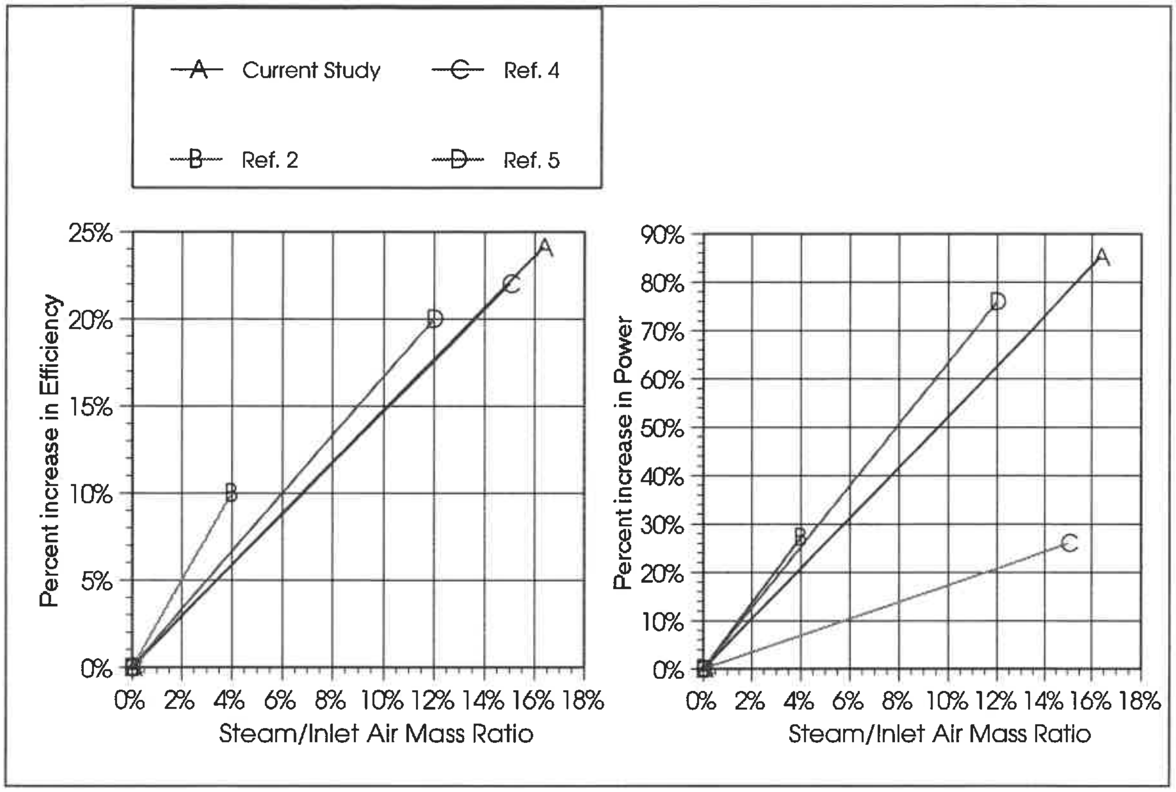

Figure 10 Steam injection results comparison

The performance of a steam injected cycle varies with the overall pressure ratio and with the turbine inlet temperature. However, the comparison of the results shows that Rolls-Royce model (points A) is very realistic and more conservative than others. Around the value of 1.6% Steam to Inlet Air ratio which is equivalent to a Steam Fuel ratio of 1.0, the increases in both power and efficiency agree and validates the results.

3.2.4.2. Intercooling

At high pressure ratios, the negative effect of adiabatic compression limits the ability to get substantial increases in cycle efficiency. By intercooling a compressor, a closer approach to isothermal compression is achieved. Furthermore, specific power is increased by intercooling.

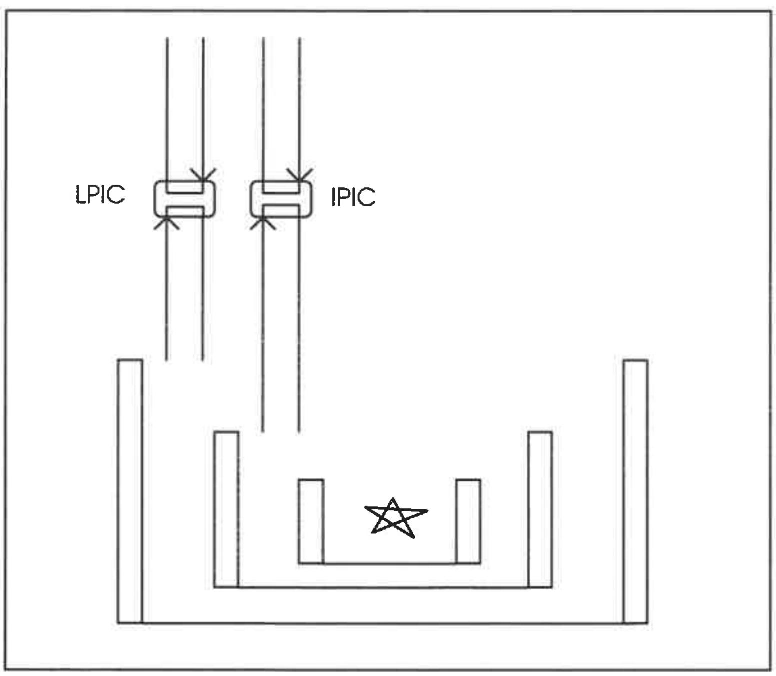

Figure 11 Intercoolers

Description:

The above schematic illustrates the location of the LP and IP intercoolers (LPIC, IPIC). The compressed air flow is directed into a non-mixing heat exchanger where it is cooled by heat transfer to a cooling fluid. The basic equation of heat transfer is given below:

$$Q = UA \cdot LMTD \tag{4}$$

where:

Q	Heat transferred
UA	Heat transfer coefficient x Area
$LMTD$	Log Mean Temperature Difference

This UA method is mostly used in off-design mode. An alternative way to define the design point operation of an intercooler is to use the effectiveness relation:

$$\varepsilon_{IC} = \frac{q}{q_{\max}} = \frac{T_{A_i} - T_{A_o}}{T_{A_i} - T_{cool_i}} \tag{5}$$

Therefore, once the intercooler effectiveness (ε_{IC}) and cooling fluid temperature (T_{cool_i}) are assumed, the output air temperature (T_{A_o}) is known.

Assumptions:

The coolant is assumed to be water at ISO temperature (288.15 K) and is not mixed with the engine air flow. The LP and IP intercoolers effectiveness levels (ε_{IC}) are

85% and 90% respectively. Furthermore, the heat extracted from the compressed air by the intercoolers is not used anywhere in the cycle except when a fuel heater is added.

The compressors operate at their design point in all cycles. In other words, they have always the same efficiency (η), speed (N) and β values whether intercoolers are in use or not. This is also true when recuperator is added later. However the air mass flow (W_A) and the corrected air mass flow $\left(\frac{W_A\sqrt{T}}{P}\right)$ through the LP and IP compressors vary significantly and implies some hardware modifications to them. A more realistic assumption is to use the same compressors but that would have forced an engine rematch.

The pressure drop across the intercoolers is 5%. This compares to 2.5% used in reference 3.

Results:

Intercoolers reduce the compressor work for a constant pressure ratio or temperature difference. The most efficient way of using a single intercooler is between the LP and IP compressors because it reduces the temperature of the two downstream compressors. For this reason, the IP intercooler alone will not be considered. At constant T41 and constant compressor efficiency, the results with the addition of the LP intercooler are the following:

LPIC

- 24% relative increase of output shaft power
- 21% relative increase of specific power
- 2% relative increase of inlet air mass flow
- 19% relative increase of fuel flow
- 4% relative increase of thermodynamic efficiency
- 46 K IPC entry temperature reduction

Although the results above are for one constant value of the turbine inlet temperature, similar results were found for a wide range of T_{41} values (30 K).

Moreover, it is possible to extract heat from the intercoolers for fuel heating. The default fuel temperature is 288.15 K but it may be increased with such a heat exchanger also known as fuel heater to a value $\left(T_{f_o}\right)$ calculated as:

$$T_{f_o} = \varepsilon_{FH} \cdot \left(T_{A_i} - T_{f_i}\right) + T_{f_i} \tag{6}$$

with $T_{f_i} = 288.15K$

3.2.4.3. Recuperation

Description:

The single improvement that gives the greatest increase in the thermal efficiency is the addition of a device for transferring energy (a heat exchanger) from the hot turbine exhaust gas to the air leaving the compressor. The next figure illustrates the flow diagram of a (dual) recuperated gas turbine cycle. Here, the high temperature of the exhaust gases is used to heat the compressed air and save on fuel. Two counter-flow recuperators (R1, R2) are modeled in the Rolls-Royce Aerothermal Program.

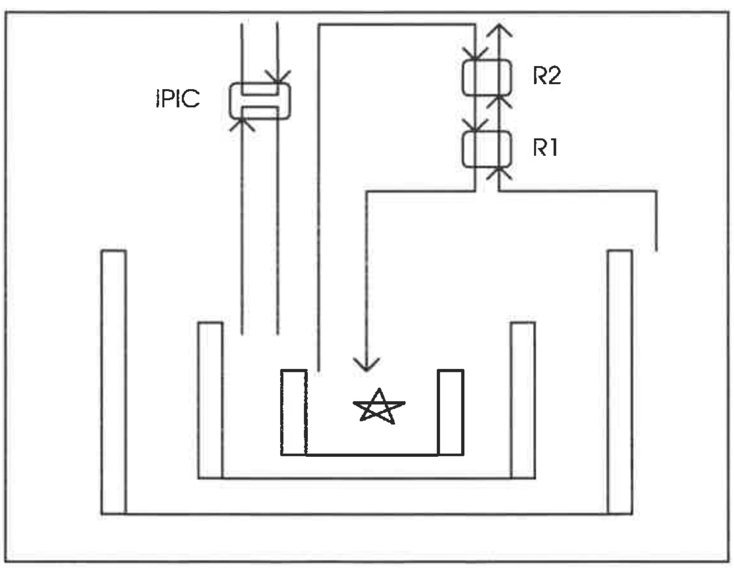

Figure 12 Recuperators

Assumptions:

The recuperator effectiveness is assumed to be 85%, as in reference 4. The definition of effectiveness is:

$$\varepsilon_{rec} = \frac{\min\left[\left(T_{A_o} - T_{A_i}\right), \left(T_{G_i} - T_{G_o}\right)\right]}{\left(T_{A_i} - T_{G_i}\right)} \tag{7}$$

Due to the size of recuperators and the gas residence time in the recuperator, radiation heat losses are included. Rolls-Royce engine model allows constant radiation losses (ΔH_{rad}) from the recuperators and decreases the recuperator exhaust gas temperature to a value (T'_{G_o}) given by:

$$T'_{G_o} = T_{G_i} - \left(1 + \frac{\Delta H_{rad}}{\Delta H_{rec}}\right) \cdot \left(T_{G_i} - T_{G_o}\right) \tag{8}$$

The pressure losses ($\frac{\Delta P}{P_i}$) are set to 5% on the air side and 7.6% on the gas side.

Results

Two intercooled recuperated (ICR) cycles above has been simulated: one with both intercoolers (DICR) and one with only the IP intercooler. The LP intercooler could not be used with the recuperator because in this cycle the exhaust temperature was lower than the combustor entry temperature. That defeats the whole purpose of a recuperator. The same is true for a complex cycle made of one recuperator without intercooler.

The results of the cycles are:

IPIC + REC

- 64% relative increase of output shaft power
- 31% relative increase of specific power
- 26% relative increase of inlet air mass flow
- 57% relative increase of fuel flow
- 5% relative increase of thermodynamic efficiency
- 244 K HPC entry temperature reduction

LPIC + IPIC + REC

- 63% relative increase of output shaft power
- 36 % relative increase of specific power
- 20% relative increase of inlet air mass flow
- 49% relative increase of fuel flow
- 10% relative increase of thermodynamic efficiency
- 246 K HPC entry temperature reduction

3.2.4.4 Two-shaft engine cycles

Description

One significantly different Trent engine configuration is investigated here. The simple cycle engine is made of 3 compressors (LPC, IPC, HPC) and only 2 turbines (LPT, HPT) linked through 2 shafts. In the complex cycle, the following features are added: 2 intercoolers (LPIC, IPIC), reheat, fuel heaters (FH) and recuperator (REC). Bleeds are modeled with extraction positions from the IP and HP compressors and with return positions after LP and HP turbines respectively. This interesting cycle is illustrated below:

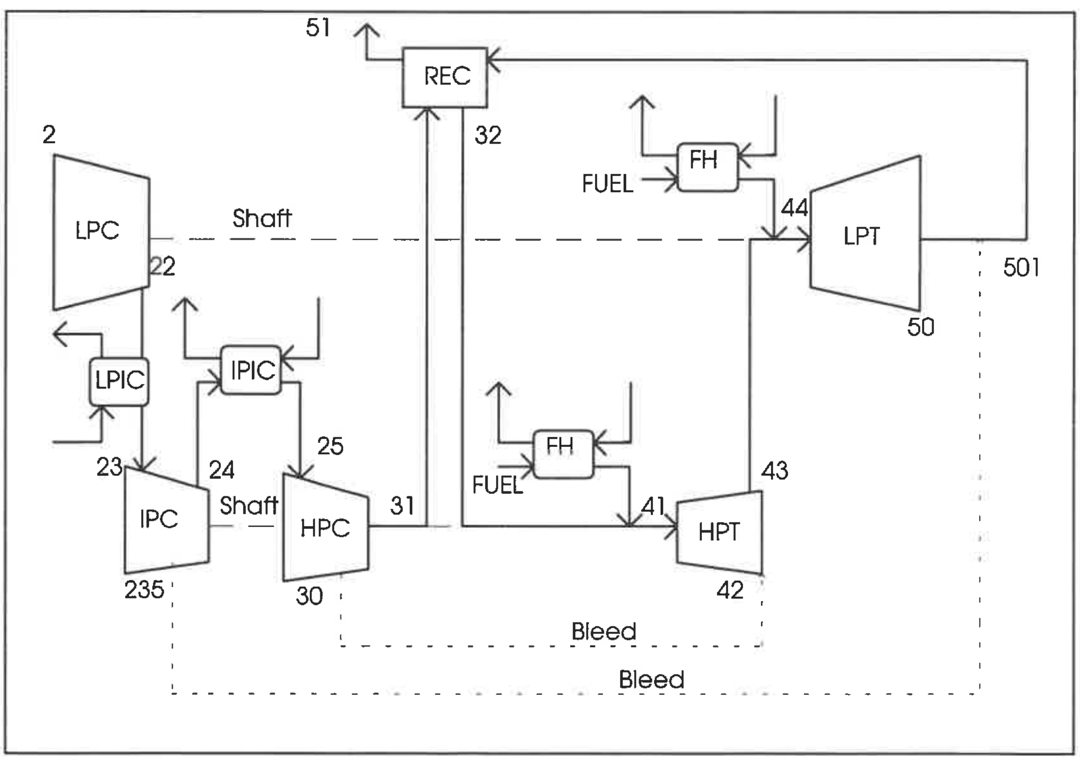

Figure 13 Two-shaft engine configuration

Assumptions and equations

This engine configuration model was built into a different program and relies on a different set of assumptions. Because this program is not a Rolls-Royce Aerothermal Program and has been written by the author, the basic equations of the model are supplied in the text. The assumptions for thermodynamic variables for both two- and three-shaft engine are tabulated below against data from other references:

Table 1 Assumptions

	Current Study 2-shaft	Current Study 3-shaft	Reference 3	Reference 4
Component	Polytropic efficiency			Polytropic efficiency
LPC	88%	Private Data		87%
IPC	88%	Private Data		
HPC	89%	Private Data		
	Isentropic efficiency			**Polytropic** efficiency
HPT	85%	Private Data		87%
IPT		Private Data		
LPT	93%	Private Data		
	Effectiveness	Effectiveness		Effectiveness
LPIC	85%	85%		
IPIC	90%	90%		
Recuperator	85%	85%		85%
Fuel Heaters	85%	Not Used		
	Pressure Loss	Pressure Loss	Pressure Loss	Pressure Loss
Intercoolers	2.5%	5%	2.5%	
Combustor	5%	3.5%	4%	4%
Reheat	5%	Not Used		
Recuperator				
air side	2.5%	5%	0.6%	2%
exhaust side	4%	7.6%	0.6%	4%
	Bleed fraction			
HP bleed	5%	(Complicated bleed network)		
IP bleed	5%			

This table demonstrates that the current assumptions are realistic and more conservative than others. Indeed, the losses assumed are slightly higher than what was found in the literature. Furthermore, bleeds are included and contribute to more conservative performance.

The temperature rise due to the compression process is modeled using the equation with the polytropic efficiency and with known (fixed) pressure ratio. For the LP compressor and using the station numbers as illustrated in the figure 13:

$$T_{23} = T_2 \cdot \left(\mathrm{Pr}_{LPC}\right)^{\left(\frac{\gamma-1}{\gamma \cdot \eta_p}\right)} \tag{9}$$

The enthalpy and specific heat are computed using the polynomial coefficients given by Chappell and Cockshutt (NRC). Also included is the fuel/air ratio (FAR) correction for the products of combustion. The equations used are:

$$\left.\begin{aligned}
Cp_A(T) &= C_{0_A} + C_{1_A} \cdot T + C_{2_A} \cdot T^2 + C_{3_A} \cdot T^3 + \ldots \\
h_A(T) &= C_{0_A} \cdot T + \frac{C_{1_A}}{2} \cdot T^2 + \frac{C_{2_A}}{3} \cdot T^3 + \ldots + CH \\
Cp_G(T) &= Cp_A(T) + \frac{f}{1+f} \cdot \Theta_{Cp}(T) \\
h_G(T) &= h_A(T) + \frac{f}{1+f} \cdot \Theta_h(T) \\
\Theta_{Cp}(T) &= C_{0_G} + C_{1_G} \cdot T + C_{2_G} \cdot T^2 + \ldots \\
\Theta_h(T) &= D_{0_G} + D_{1_G} \cdot T + D_{2_A} \cdot T^2 + \ldots
\end{aligned}\right\} \tag{10}$$

Two sets of constants (*C, CH, D*) are involved in the above equations for temperature ranges 200 to 800 Kelvin and for 800 to 2200 K. Furthermore, because all the equations are functions of the temperature, an iterative process is necessary to find the temperature corresponding to a known function (enthalpy, for example) value.

Furthermore, the gas constant (*R*) and the specific heats ratio (γ) for a thermodynamic process is computed as a function of the fuel/air ratio and the average temperature for the process. For example:

$$\left.\begin{aligned} R_A &= \frac{R_U}{MW_A} \\ R_A &= \frac{R_U \cdot (1+f)}{(R_A + f \cdot MW_A)} \\ \gamma &= \frac{1}{\left(1 - \dfrac{R}{Cp\left(\dfrac{T_i + T_o}{2}\right)}\right)} \end{aligned}\right\} \quad (11)$$

For the LP intercooler as for all other components with a given pressure loss $\left(\frac{\Delta P}{P}\right)$, the pressure drop is modeled as:

$$P_{23} = P_{22} \cdot \left(1 - \frac{\Delta P}{P}\right) \quad (12)$$

The air side of the recuperator goes through an increase of temperature and enthalpy. This is computed with the equation below using the average temperature of the process between stations 31 and 32:

$$H_{32} = H_{31} + \varepsilon_{rec} \cdot W_A \cdot (T_{501} - T_{31}) \cdot Cp_A\left(\frac{T_{31} + T_{32}}{2}\right) \tag{13}$$

Moreover, heat is extracted from the two intercoolers for fuel heating. The heat transferred from the LP intercooler, for example, to the fuel by the fuel heater is calculated as:

$$\left.\begin{aligned} Q_{FH} &= \varepsilon_{FH} \cdot \Delta H_{LPIC} \\ \Delta H_{LPIC} &= H_{22} - H_{23} \end{aligned}\right\} \tag{14}$$

This is a correction to the cycle calculation which is given in terms of heat units and subtracted from the total energy supplied to the engine in the form of fuel. The effectiveness of both fuel heaters (ε_{FH}) is assumed to be 85%. The fuel is assumed to remain in the same state. Even if it is likely to happen, the evaporation of liquid fuel is not currently handled by the model. Although the engine is designed for both gas and liquid fuel operation, gas fuel is likely to be the most used.

The fuel flow required for the combustion is found from an enthalpy balance involving the known T_{41} temperature and the fuel Lower Heating Value (*LHV*):

$$W_f = \frac{H(T_{41}) - H(T_{32})}{LHV} \tag{15}$$

In the previous equation, the combustion efficiency of 100% is implied.

The HP turbine exit enthalpy and temperature are found from the work balance. Because the HP turbine drives the HP and IP compressors, the enthalpy at station 42 is:

$$H(T_{42}) = H(T_{41}) - W_{HPC} - W_{IPC} \tag{16}$$

The previous equation implicitly assumes a mechanical efficiency of 100%.

Using the isentropic efficiency definition, the HP exit isentropic temperature is given by:

$$T_{42_{is}} = T_{41} - \frac{(T_{41} - T_{42})}{\eta_{HPT_{is}}} \tag{17}$$

Therefore, knowing the temperature ratio, the pressure is computed as:

$$P_{42} = P_{41} \cdot \left(\frac{T_{42_{is}}}{T_{41}} \right)^{\frac{\gamma}{\gamma - 1}} \tag{18}$$

The IP and HP bleed flows are assumed to be cooled back to ambient temperature. This supposition is accepted for an industrial engine where there is no limitation on the weight and size. An enthalpy balance is performed when the bleeds mix back into the main stream. The pressure loss between station 43 and 44 is associated with the mixing, duct, stator and other effects.

After the second combustor, the reheat temperature (T_{44}) is equal to the turbine inlet temperature (T_{41}). For both combustors, pressure losses are included in the model.

For the LP turbine, the calculation is different because the final pressure must be atmospheric pressure. The pressure calculation is carried out in the upstream direction as follows:

$$\left.\begin{aligned} P_{501} &= \frac{P_{51}}{\left(1-\frac{\Delta P}{P}\right)} \\ P_{50} &= \frac{P_{501}}{\left(1-\frac{\Delta P}{P}\right)} \\ T_{50_{is}} &= T_{44}\cdot\left(\frac{P_{50}}{P_{44}}\right)^{\frac{\gamma-1}{\gamma}} \\ T_{50} &= T_{44}-\eta_{LPT_{is}}\cdot\left(T_{44}-T_{50_{is}}\right) \end{aligned}\right\} \qquad (19)$$

The power resulting from the simulation is for a constant unit intake air mass flow. This is equivalent to computing specific power. At last, the cycle power and efficiency are given by:

$$\left.\begin{aligned} P_W &= \mathbf{W}_{LPT} - \mathbf{W}_{LPC} \\ P_W &= (H_{44} - H_{50}) - (H_{22} - H_2) \\ \eta &= \frac{Q_{f1} + Q_{f2} - Q_{FH}}{P_W} \\ Q_{f1} &= H_{41} - H_{32} \\ Q_{f1} &= H_{44} - H_{43} \end{aligned}\right\} \quad (20)$$

Results

The efficiency of the cycle has increased very much with the use of fuel heaters. The efficiency ratio is so high that one can believe that the assumptions underlying the fuel heater model may be incorrect. Furthermore, the reheat drove the power higher and also had positive effect on the efficiency. In this cycle, the reheat does not have the usual efficiency penalty because the exhaust heat is recuperated.

The performance of the different complex cycles resulting of the appropriate combinations of the components are shown below. However, with the two-shaft engine model, no water nor steam injection was tested.

LPIC

- 40% relative increase of specific power
- 31% relative increase of fuel flow
- 10% relative increase of thermodynamic efficiency
- 105 K IPC entry temperature reduction

IPIC + REC

- 39% relative increase of specific power
- 25% relative increase of fuel flow
- 14% relative increase of thermodynamic efficiency
- 265 K HPC entry temperature reduction

LPIC + IPIC + REC

- 55 % relative increase of specific power
- 25% relative increase of fuel flow
- 27% relative increase of thermodynamic efficiency
- 280 K HPC entry temperature reduction

LPIC + IPIC + REC+FH

- 55 % relative increase of specific power
- 25% relative increase of fuel flow
- 60% relative increase of thermodynamic efficiency
- 280 K HPC entry temperature reduction

LPIC + IPIC + REC+FH+REHEAT

- 104 % relative increase of specific power
- 56% relative increase of fuel flow
- 65% relative increase of thermodynamic efficiency
- 280 K HPC entry temperature reduction

3.3 Results for all cycles

The specific work $\left(\frac{P_W}{W}\right)$ is a good indication of an engine's quality and usually a parameter for comparison of machines of different size and type. However the total shaft output power is the variable of most interest to compare different complex cycles involving the industrial Trent because the engine and its intake area are likely to remain fixed. So both power and specific power increase will be shown in the next pages.

Finally, the results for the three-shaft and two-shaft engine are displayed in the following tables and illustrated by figures. The parameters used are ratios of the complex cycles output power, specific power and efficiency to the simple cycle output power, specific power and efficiency, i.e. $\left(\frac{P_W}{P_{W_{SC}}}\right)$, $\left(\frac{P_W/W}{\left(P_W/W\right)_{SC}}\right)$, $\left(\frac{\eta}{\eta_{SC}}\right)$ respectively.

Table 2 Three-shaft engine complex cycles performance

Cycle	Power ratio	Specific Power ratio	Efficiency Ratio
SC	100%	100%	100%
Water Injection	113%	113%	97%
Steam Injection	110%	110%	104%
LPIC	124%	121%	104%
IPIC+ REC	164%	131%	104%
LPIC+ IPIC+ REC	163%	136%	110%

For table 3 and figure 16, due to the assumptions the power ratios are in fact specific power ratios and are not tabulated because they have the same values.

Table 3 Two-shaft engine complex cycles performance

Cycle	Specific Power ratio	Efficiency Ratio
SC	100%	100%
LPIC	140%	110%
IPIC+ REC	139%	114%
LPIC+ IPIC+ REC	155%	127%
LPIC+ IPIC+ REC+ FH	155%	160%
LPIC+ IPIC+ REC+ FH+ REHEAT	204%	163%

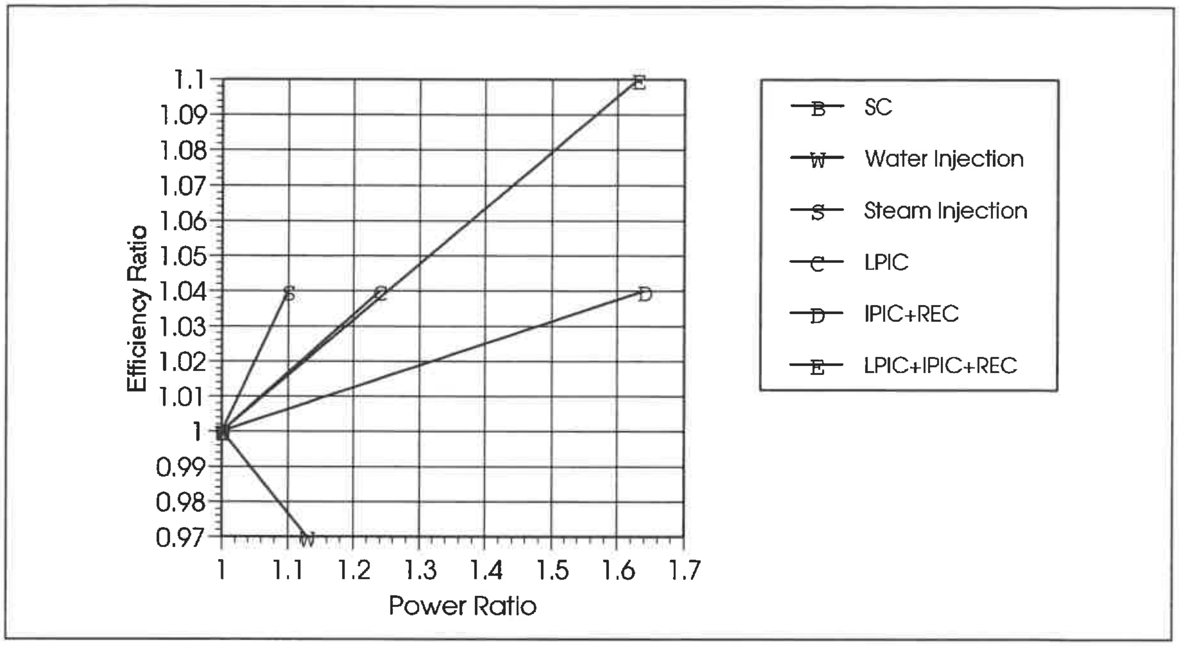

Figure 14 Three-shaft engine complex cycles performance (a)

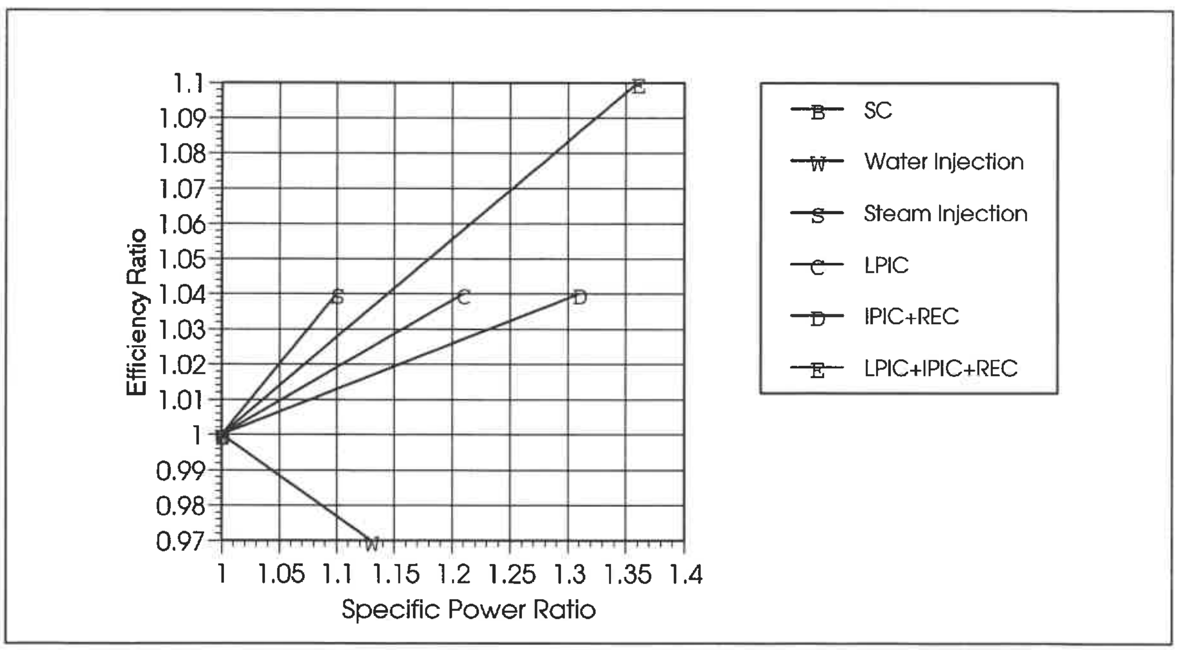

Figure 15 Three-shaft engine complex cycles performance (b)

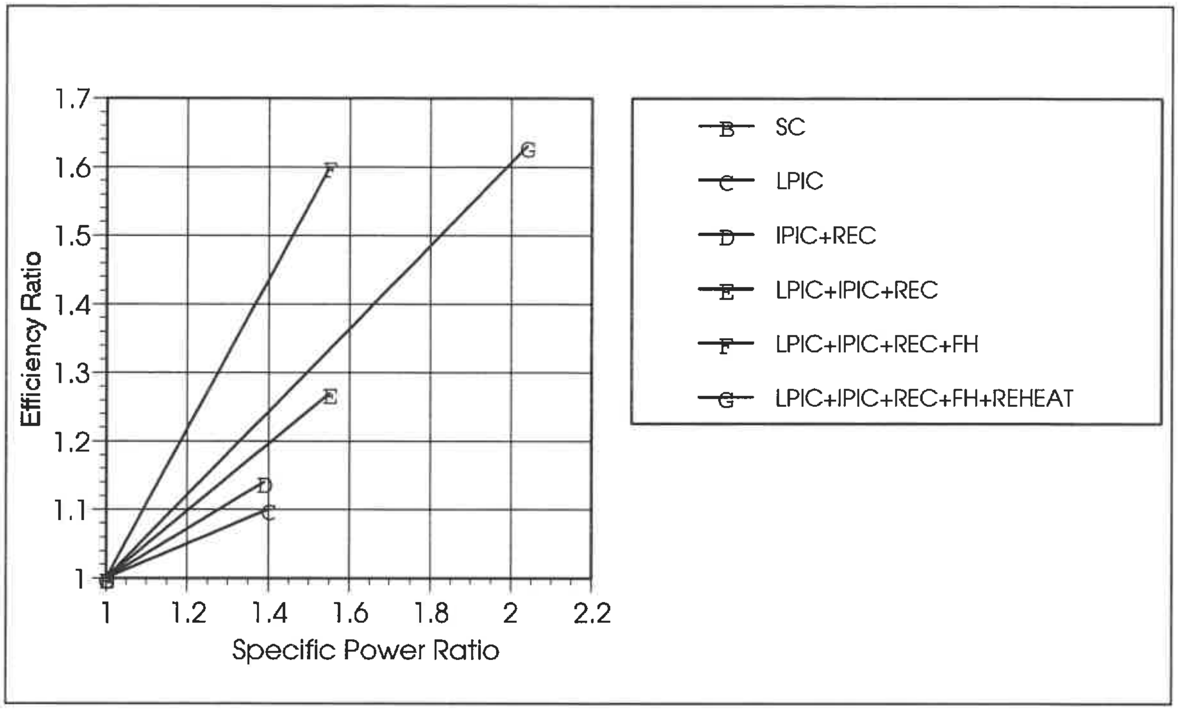

Figure 16 Two-shaft engine complex cycles performance

The figures 14 to 16 illustrates the efficiency ratio versus (specific) power ratio. The performance of each complex cycle is shown by a point which is joined by a line to the simple cycle point. Since it is used as the reference for comparison, the simple cycle point coordinates are (1.0, 1.0) and is shown by a "B".

In figures 14 and 15, point "E" clearly shows a better efficiency when two intercoolers and a recuperator are used. In figure 16, point "F" (versus "E") demontrates the dramatic efficiency improvement of a fuel heater for a constant power ratio. Then the addition of reheat pushes the power ratio higher (to point "G") with a small increase in efficiency.

The above results should be used with caution because the three- and two-spool engine models rely on a different set of assumptions. Moreover, the efficiency ratio is much higher for a complex cycle that has a low simple cycle efficiency. This is actually the case of the two-spool engine and is the reason for the very high efficiency ratios displayed. This is explained by the fact that 1% efficiency is easier to gain from a poor cycle than from a good cycle.

3.4 The option retained

Before a final decision can be made, some economical study should be completed. However, from the results presented above, one may conclude that advanced gas turbine cycles are very interesting. Because the objective is to find a cycle that increases both power and efficiency, one could ask for weighting fractions to represent the importance of each one. With the fractions, a new parameter (Z) may be created to allow easy comparison using this single parameter. For example,

$$Z = 0.5 \cdot \left(\frac{P_W}{P_{W_{SC}}} \right) + 0.5 \cdot \left(\frac{\eta}{\eta_{SC}} \right)$$

where the power increase has as much importance as the efficiency increase. Such an equation is ultimately given by the cost of electricity.

However, in most of the cycles shown, the power increase go hand in hand with the efficiency increase. In fact, the water injected cycle in the only one where the efficiency worsens. Finally, the three-shaft engine has best performance with an ICR cycle using two intercoolers and recuperator. The two-shaft engine displays excellent performance in the same cycle but has even better results when fuel heater and reheat is added. But prior to selecting the ICRR cycle with fuel heater, extra validation of the model is suggested. Therefore the best option recommended is an ICRR cycle.

CHAPTER 4. CONCLUSION

4.1 Conclusion with respect to the results

From the results presented, several statements can be made on the cycles. One notices that the water injection increases power but has a penalty in terms of efficiency. The steam injection has the same gain in power and shows no drop in efficiency. The use of intercoolers mainly increases the output power. On the other hand, the recuperator has a major effect on efficiency. For this reason, combinations of intercoolers and recuperator were among the cycles of interest and demonstrated excellent performance. In fact, the ICR and ICRR cycles offers the highest output power and efficiency combination among the complex cycles studied.

4.2 The author's contribution to the project

Most of this project was handled by the author on his own since the other RRGTE's performance engineers postponed the detailed Industrial Trent engine growth study. In fact, RRGTE has only evaluated the water injection as an engine growth cycle. Those results prepared by Greg Chapman were presented in the document.

The Rolls-Royce Aerothermal Programs (BA48, BA51) used in this study are developed by the engineers at RRIMGT, RR Bristol as well as RRGTE. RRIMGT contributed to this project by providing results of the performance of a few advanced Industrial Trent cycles.

In summary, the contributions of the author are the complex cycles literature analysis, RRAP development and use to simulate complex cycles, development of other softwares, analysis of results and documentation.

4.3 Recommendations

The first recommendation is of course to verify all assumptions. The assumptions for pressure loss, effectiveness,... were given by past experiences and lines up with data found in the literature. The recommendation that should be of great interest is to see if the engine modifications implied in the cycles are possible and affordable. This requires an evaluation of the cost of the engine modifications and a complete economical study.

Time was not sufficient to carry the analysis of many other complex cycles of interest, namely the humid air turbine (HAT) cycle. This cycle is in development and very promising but has not been built yet. Furthermore, two excellent cycles (LPIC+IPIC+REC+FH, +REHEAT) were simulated for the two-shaft engine only and need to be modeled on the three-spool engine.

To date the design point performance has been the main concern, however the off-design performance of the cycles needs to be investigated. Since it involves more work, a preliminary selection of cycles is suggested.

4.4 Engineering skills and knowledge earned from the project

First of all, the author has gone through a very useful training on the new computer environment and softwares. The knowledge he has earned there is more related to the operation of the computers and programs. However as a result the Industrial Trent is understood much better. Furthermore the literature on advanced cycles increased his knowledge of thermodynamics and of gas turbines.

The new skill the author has to acquire is to manage the development of Rolls-Royce program (BA48) done by more than two engineer programmers. The author carries the responsibility of the Industrial Trent engine performance program development.

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APPENDIX I: Figures

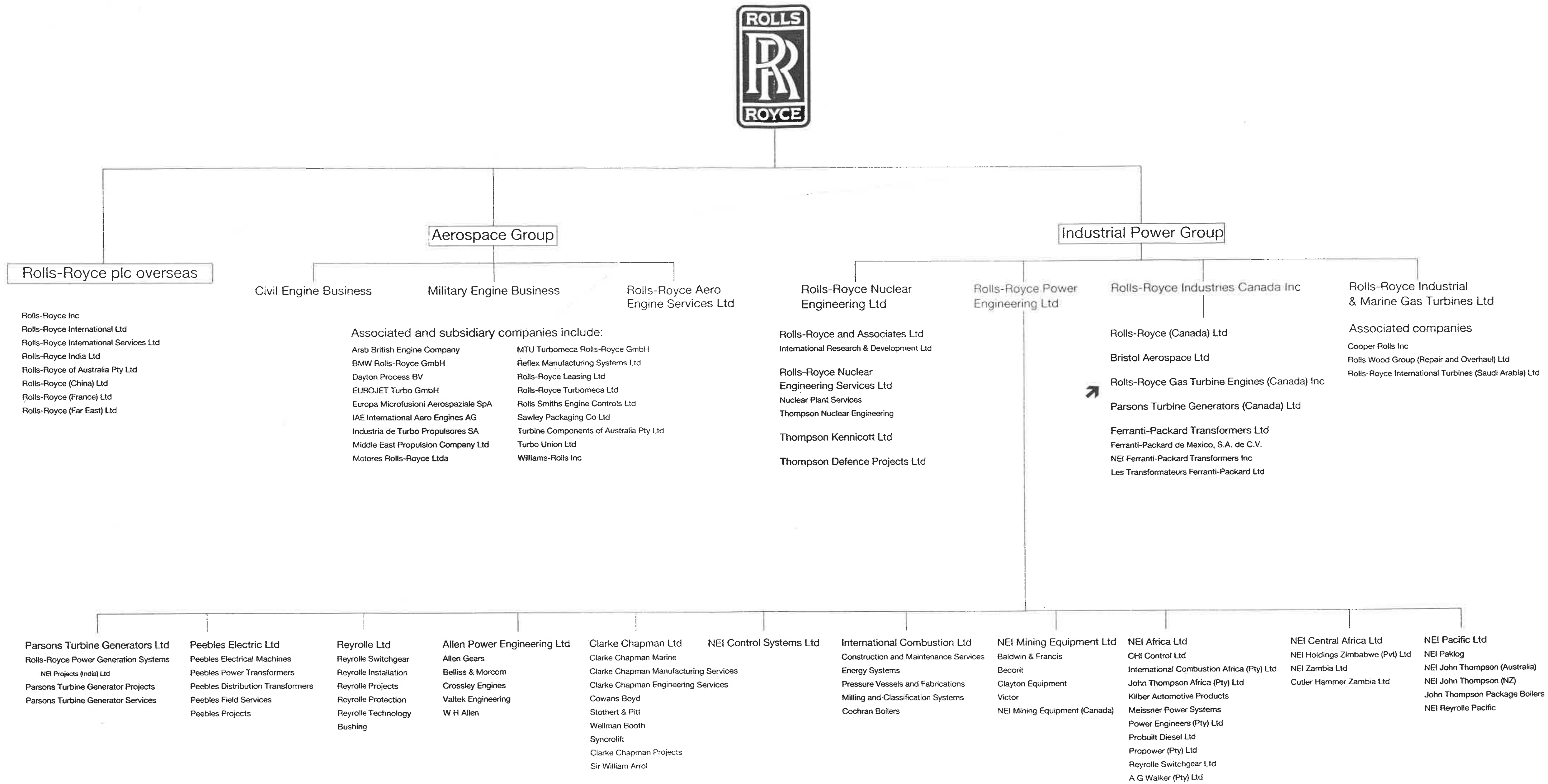

Figure 2 Rolls-Royce plc hierarchy diagram

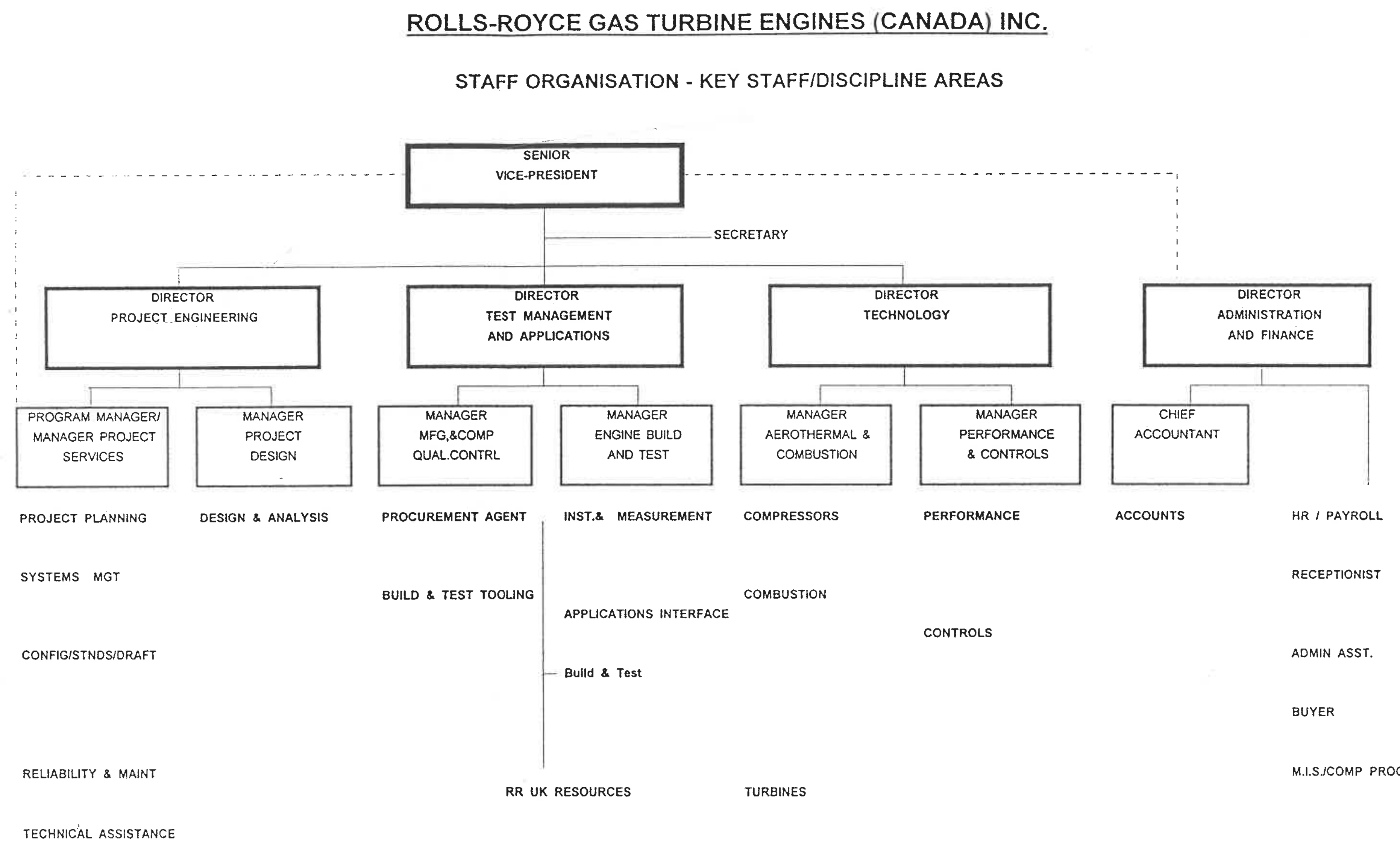

Figure 3 Rolls-Royce Gas Turbine Engines hierarchy diagram

ROLLS-ROYCE INDUSTRIAL & MARINE GAS TURBINES LIMITED

Industrial Trent derivation

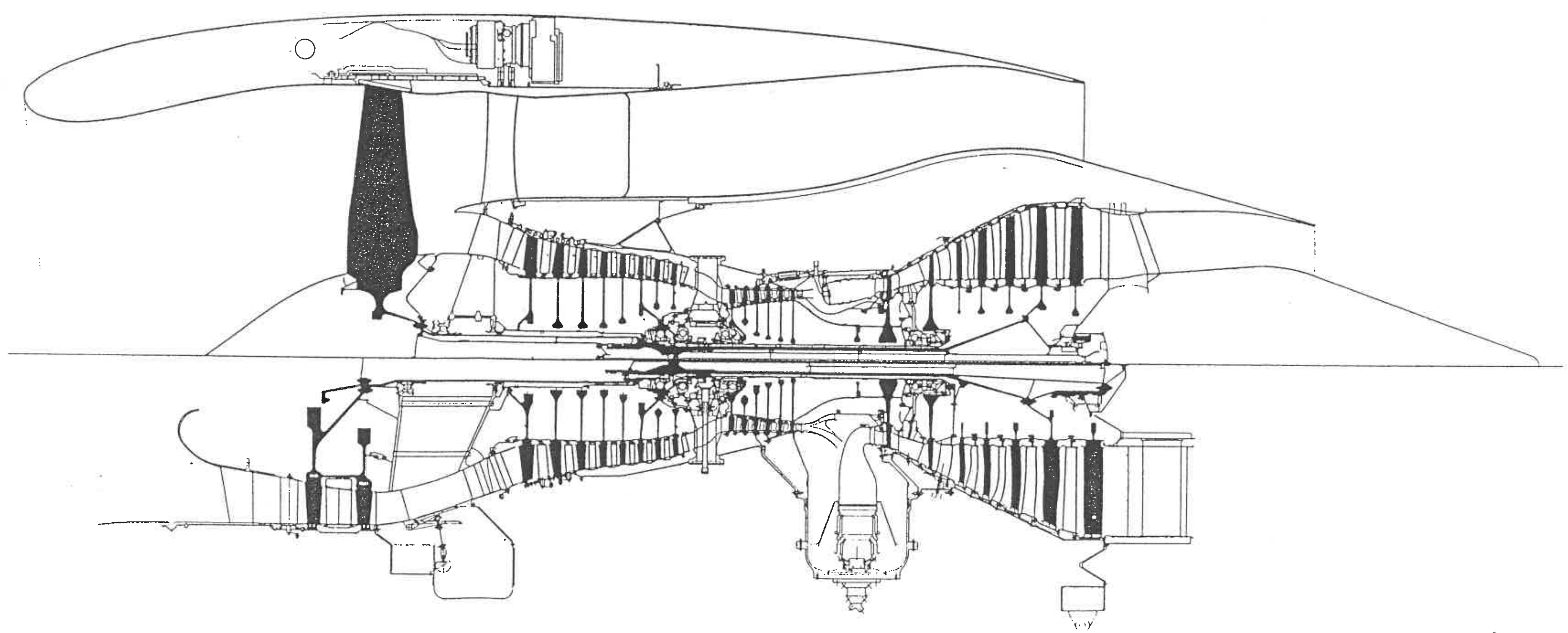

Figure 4 Aero Trent VS Industrial Trent

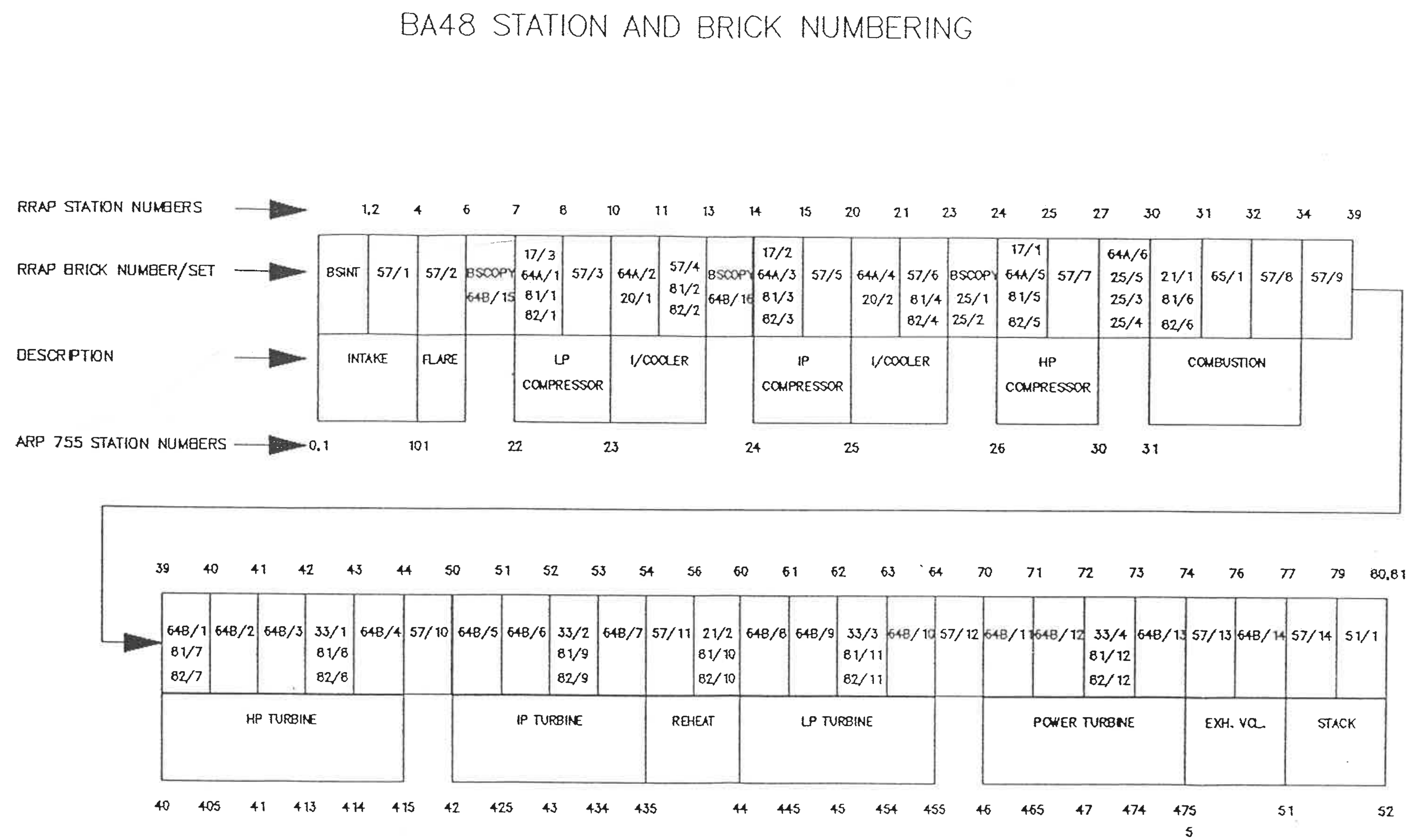

Figure 5 Rolls-Royce Aerothermal Program Schematic

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