CRANFIELD UNIVERSITY

Raja S R Khan

TERA for Rotating Equipment Selection

School of Engineering

January 2012

Cranfield University

School of Engineering

Department of Power and Propulsion

EngD Thesis

Academic Year: 2008 – 2012

Raja S R Khan

TERA for Rotating Equipment Selection

Academic Supervisor's: Prof. P. Pilidis, Dr. S. Ogaji
Industrial Supervisor: Prof. Ian Bennett (Shell)
Management Supervisor: Prof. John Nicholls

January 2012

This thesis is submitted for the degree of Doctor of Engineering

Tundi-e-baad-e-mukhaalif se na khabra eh Aqaab,
Ke ye to chalti he tujhe ooncha uraaneh ke liyeh!

Fear not the fierce and opposing wind oh Eagle,
For it flows only so that you may rise higher!

Guzar awqaat kar leta hai yeh koh-o-bayaan baan mein,
Ke Shaheen ke liyeh zilat hai kaar-e-aashyaan bandi!

And he endures the torment of the barren mountain top,
For it is not within his dignity for the Eagle to build nests like the other birds!

(Muhammed Iqbal, 1898)

Disclaimer

1. This thesis is confidential from the date of publication till at least three years after publication (subject to further review) and should not be viewed by anybody without due agreement of Shell Global Solutions Limited, Cranfield University and without written consent to a Non Disclosure Agreement.

2. The author does not claim the performance of gas turbine engines as detailed ANYWHERE in this thesis as identical and fully representative of the engines actually manufactured by the OEM or that the simulations are accurate to the point that they reflect exactly the performance and all other attributes (including materials and design aspects) of the real engines. The GE and Rolls Royce engines simulated herein are <u>based on</u> the information found in the public domain and using the Cranfield in-house simulation software. Indeed there will be differences and discrepancies between the actual and simulated engines and all critique and evaluation hereafter should be taken in light of this comment and cannot be taken as an absolute evaluation of the original engines but rather a commentary on engines <u>based on</u> the original engines.

Abstract

This thesis looks at creating a multidisciplinary simulation tool for rotating plant equipment selection, specifically gas turbines, for the liquefaction of natural gas (LNG). This is a collaborative project between Shell Global Solutions and Cranfield University in the UK. The TERA LNG tool uses a Techno-economic, Environmental and Risk Analysis (TERA) approach in order to satisfy the multidisciplinary nature of the investigation. The benefits of the tool are to act as an aid to selection, operations and maintenance planning and it also acts as a sensitivity tool for assessing the impact of changes in performance, environmental and financial parameters to the overall economic impact of technology selection. The aim is to not only select technology on the basis of techno-economics but also on the basis of risk analysis.

The LNG TERA tool is composed of a number of modules starting with the performance simulation which calculates the thermodynamic conditions in the core of the engine. Next, life estimates of the hot gas path components are made using a mixture of parametric and probabilistic lifing models for the turbine first stage blades, coatings, and combustor liner. This allows for a risk analysis to be conducted before maintenance and economics issues are dealt with. In parallel, emissions estimations are made based on empirical correlations. The modelling exemplifies a methodology which is uniquely applied to this application and there are no studies previous to this which look at so many aspects before making conclusions on plant machinery selection.

Comparisons have been done between industrial frame engines based on the General Electric Frame 9E (130 MW) and Frame 7EA (87 MW) engines as well as more complex cycles involving aero-derivation and inter-cooling such as the LM 6000 (42 MW) and LMS 100 (100 MW). Work has also been carried out to integrate the tool to Shell based systems in order to utilise the database of information on failure and maintenance of machinery as well as its performance.

The results of the integrated TERA show a clear favour for the aero-derivative engines and the main benefit is the fuel saving, though the life of the hot gas path components is deteriorated much faster. The risk results show that the industrial frame engines have a wider variation in expected life compared to aero-derivatives, though the industrial frames have longer component lives. In the context of maintenance and economics, the aero-derivative

engines are better suited to LNG applications. The modular change out design of the aero-derivatives also meant that time to repair was lower, thus reducing lost production.

Application of the LNG TERA tool was extended to power generation whereby a series of 6 engines were simulated. The changes required to the modelling were minimal and it shows the flexibility of the TERA philosophy. This study was carried out assuming a given ratio of load split between the engines and hence is sensitive to the way an operator demands power of the engine as opposed to LNG application where the operator tries to drive the engine as hard as possible to get the most production out of the train.

The study was limited in the modes of failure which were investigated, a major further work would be to extend the methodology to more components and incorporate fatigue failure. Further, the blade creep and probabilistic coating models were very sensitive to changes in their respective control parameters such as coating thickness allowances and firing temperature.

The contribution to the project from the MBA is the statistical techniques used to conduct the risk analysis and data handling as well as financial management techniques such as the Net Present Value (NPV) methodology for project evaluations.

Acknowledgments

I would first of all like to thank Allah Almighty for giving me the opportunity, strength, courage and patience to complete this doctorate.

Amongst the academic staff there are many to name given the scope of this thesis. I went outside my supervision zone to seek help and guidance from so many people. Professor Pilidis is to be thanked for his unwavering guidance, support and belief in me, without whom this thesis could not be completed. Doctor Ogaji played a pivotal role in the way he gave time and expertise to the entire project, especially the modelling. Professor Bennett at Shell must be thanked for putting his faith in this partnership and allowing me to take control of the research and letting me shape the work independently and uniquely. Professor Nicholls must be thanked for his support as the management supervisor and in providing guidance on statistics and materials expertise, as well as Dr Ramsden, Dr Laskaridis, Dr Jackson, Dr Haslam, Dr Li, Professor Singh, Dr Di Lorenzo, Dr Sethi, Dr Mba and the all administrators, especially the ever helpful Gillian Hargreaves.

Amongst my friends at Cranfield I would like to thank Badr Al-Abri, Abdulkarim Nasir, Alice Stitt, Simon Parsons, Samir Eshati, Abdelmanam Abaad, Mohammed Fahmi Abdul Ghafir, Wanis Mohammed, Emad Hassani, Mohammed Mohseni, Thierry Sibilli, Rajeev Verma, Pablo Bellocq, Ben Tarver, Andy Duncombe, Jafar Alzaili, Zaka Quraishi, Abdullatif Al-Alsheik, Esmail Najafi, Panos Giannakakis, Panos Kazanas, Pavlos Zachos amongst many others and the Fridays VSFT (Very Serious Football Today) group.

A crucial role is played by the numerous Masters researchers who worked directly with me in the modelling of the LNG TERA. They are:

Maria Chiara Lagana, Javier Barreiro, Joseph Ekanem, Carlo Andrea Baioni, Tuboalabo Wellington, Vasanth Ramaswamy, Adinweruka Mba,   Dennis Uwakwe, Matteo Maccapani, Vincent Desnos , Julien Karlsson, Lukasz Snajder and Noureddin Azhari.

Finally, thanks go to my family, my parents and my sisters and brothers who always believed in me, and to my wife and children who have been my strength.

Table of Contents

List of Figures

xiv

List of Tables

Nomenclature

A_{ann}	annular area
AFT	adiabatic flame temperature
AGARD	Advisory Group for Aerospace Research and Development
APCI	Air Products and Chemicals Inc.
ATR	auto thermal reformer
AZEP	Advanced Zero Emissions Power plant
bcf	billion cubic feet
bcm	billion cubic meters
C	Larson-Miller constant / cost associated with failure
$C_{1,2}$	convective heat transfer (subscript denotes internal, external)
C3/MR	propane / mixed refrigerant
CAPEX	capital expenditure
CBM	condition based maintenance / monitoring
CDF	cumulative distribution function
CO	carbon monoxide
CO_2	carbon dioxide
CPC	constant pressure combustion
CVC	constant volume combustion
d	discount rate
DARWIN	Design Assessment of Reliability With Inspection
DLE	dry low emissions
DMR	dual mixed refrigerant
DS	directionally solidified
e	combustor liner wall thickness
$EINO_x$	emission Index (NOx)
$EICO_2$	emission Index (CO2)
EGT	exhaust gas temperature
FAA	Federal Aviation Authority
F_t	cumulative distribution function
FR 7EA	General Electric Frame 7 EA engine
FR 9E	General Electric Frame 9 E engine
GC	gas compressor
GJ	gigajoules
GT	gas turbine
H	enthalpy

h_{sec}	blade section height
HCF	high cycle fatigue
HPC	high pressure compressor
HPT	high pressure turbine
HX	heat exchanger
IEA	International Energy Agency
IGV	inlet guide vanes
i	discount rate
ICAO	International Civil Aviation Organisation
ΔI_0	initial investment costs
ΔI_t	additional investment costs in year t
K	degrees Kelvin / conduction heat transfer
K_f	risk of failure
kg	kilograms
kJ	kilojoules
k_w	combustor liner wall thermal conductivity
kW	kilowatts
kWh	kilowatt-hours
LCF	low cycle fatigue
LMP	Larson-Miller Parameter
LMS 100	GE intercooled aero-derivative engine
LNG	Liquefied Natural Gas
LPC	low pressure compressor
LPT	low pressure turbine
$\dot{m}$	mass flow rate
mmtpa	million metric tonnes per annum
MCM	mixed conductive membrane
MCS	Monte-Carlo simulation
MJ	mega joules
MLE	maximum likelihood method
MTBF	mean time before failure
MR	mixed refrigerant / median ranks
MW	megawatt
N	rotational speed / number of components
N_f	number of components failed
NETL	National Energy Technology Laboratory
NCF_{ann}	annular net cash flow
NIMS	National Institute for Materials Science (Japan)

NO_x	oxides of Nitrogen
NPV	net present value
OEM	original engine manufacturer
$OPEX$	operating expenditure
OPR	overall pressure ratio
p_f	probability of failure
ppm	parts per million
P	total pressure
P_{amb}	ambient pressure
PDF	probability density function
PFM	probabilistic fracture mechanics
PM	preventive maintenance
PR	pressure ratio
PT	power turbine
r_{cg}	radius to centre of gravity for blade element
R	universal gas constant
$R_{1,2}$	radiation heat transfer (subscript denotes internal, external)
RPM	revs per minute
R_t	reliability distribution function
s	seconds
sfc	specific fuel consumption
S	survivability
S_t	savings in operation
SAC	single annular combustor
SBM	simulation based maintenance
SSI	single spool industrial gas turbine
SW-HX	spiral wound heat exchanger
t	time / Weibull random variable (time)
tcm	trillion cubic meters
t_{ev}	fuel evaporation time
t_f	time to failure
t_r	residence time
T	total temperature
T_b	blade metal section temperature
T_{cool}	coolant air temperature
T_g	gas path temperature
T_{pz}	combustor primary zone temperature
T_r	time to rupture

xxi

T_{st}	stoichiometric flame temperature
T_w	combustor liner wall temperature
TBC	thermal barrier coating
TCL	technology comparison level
TE	turbo expander
TM	Turbomatch
TMR	Turbomatch results file
TBF	time between failure
TET	turbine entry temperature
TRL	technology readiness level
TTR	time to repair
TERA	techno-Economic, Environmental and Risk Analysis
TTTR	total time to repair
U	blade speed
UHC	unburnt hydrocarbons
V_a	axial velocity
V_c	combustor volume
V_e	combustor evaporation zone volume
W	mass flow rate
X_{Na}	Sodium deposition rate
ΣTC	total capital employed
ΣP	total profit before income and tax
Γ	gamma function
α	location parameter
α_f	cumulative time to failure for coating
β	shape parameter
γ	location parameter
ε	cooling effectiveness of blade / strain
η	scale parameter
μ	mean
Σ	summation
σ	standard deviation
σ_a	axial stress
σ_{CFMAX}	maximum centrifugal stress
$\sigma_{centrifugal}$	centrifugal stress
σ_{tan}	tangential stress

σ_{VM}	von Mises stress
ρ	density
ω	angular velocity

1. Introduction

1.1 The Rationale for LNG

Liquefied natural gas (LNG) has been a major worldwide source of energy for many decades. It is a form of natural gas which is cooled and kept under pressure so as to keep it in a liquid state, thus reducing the volume of the commodity by 600%. The benefits of turning gaseous natural gas into LNG can be summarised using an economics argument. Typically, natural gas is transported over long distances; the source of the natural gas is usually thousands of miles from the destination market.

The traditional method of transporting natural gas has been to use gas pipelines. Since the source is usually far from the market, the cost to the operator and utility companies is substantially aggravated due to power requirements at pipeline compressor stations which keep the gas flowing towards the destination. These compressor stations are required in higher numbers with increasing distance of transportation thus accumulating higher costs of transportation, and this increased cost is reflected in prices at the consumer level. Whilst over shorter distances of up to 2000 miles between source and destination, it is more feasible to utilise the pipeline, there is however an argument for using LNG over longer distances of 2500 miles and more. The natural gas can be liquefied at the source and shipped to the destination by container, or specialised LNG vessels which carry the LNG under low temperatures and at the correct pressure and this method proves to be cost effective over longer distances since the need for a large number of costly compressor stations and pipeline is reduced. It also can benefit from a political point of view, for example, a pipeline going through a politically unstable region increases the risk and thus perhaps the price of the commodity.

The graph in Figure 1 shows the comparison between pipeline ad LNG shipment methods of transporting gas. It can be seen clearly that over shorter distances it is beneficial to utilise the pipeline but not over distances greater than circa 2500 miles.
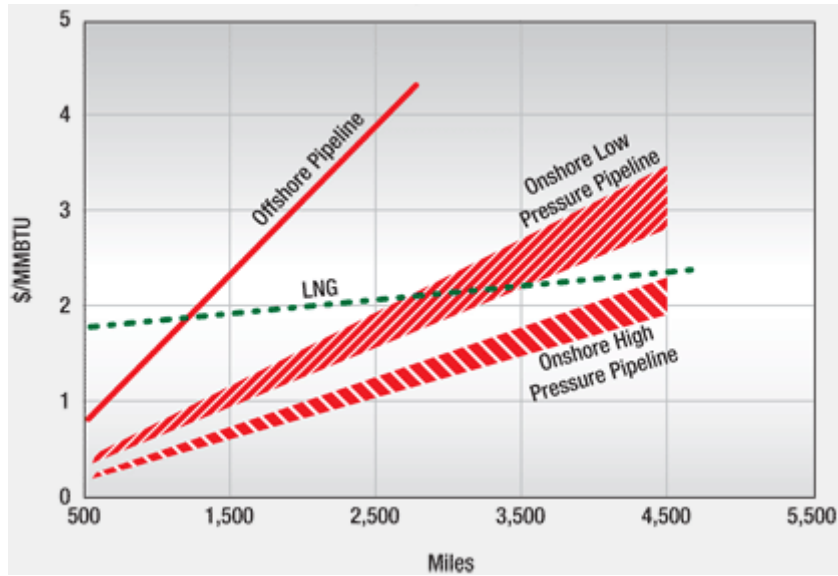
Figure 1: Gas Transportation costs; a comparison between LNG and gas pipeline (Economides and Mokhateb, 2007)

1.2 World Energy Outlook

The demand for natural gas and oil reserves is projected to rise after the recent economic crisis (Figure 2). The World Energy Outlook report by The International Energy Agency (IEA, 2010) shows that China will dictate the long term demand of gas and that natural gas is set to be *'the only fossil fuel for which demand is higher in 2035 than 2008 in all scenarios.'* The demand in 2035 is projected at 4.5 trillion cubic metres (tcm) and this is a staggering 44% increase over the figures in 2008.

The report states that the economic crisis caused a depression in global gas demands during 2009 thus creating a 'glut' or difference between global gas supplied and total capacity of existing pipelines and LNG export terminals; this difference is estimated at around 180 billion cubic metres (bcm) in 2009 and projected to rise to 200 bcm by 2011.

Further, the glut may mean that gas prices move away from a system of pricing linked to oil and become more independent; this can be useful in the sense that the prices can be lowered and demand encouraged to increase. China is assumed to create demand and a healthy market for natural gas in the foreseeable future. More importantly for the subject of this thesis, gas

trade between WEO countries is projected to rise from 670 bcm to 1,190 bcm, an 80% rise, between 2008 and 2035 and more than half this growth is attributed to LNG markets.
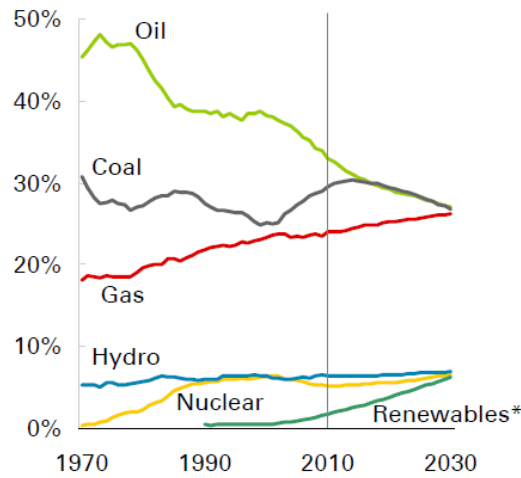
Figure 2: Trends for share of worldwide primary energy sources, showing natural gas on the rise compared to other resources (BP, 2011)

1.3 The Market for LNG

There is definitely a growing market for LNG and prospects look good even through the current economic crisis. Major natural gas reserves exist in Russia and in the Middle East, most notably Qatar and Iran. Russia, Qatar and Iran make up for circa 50% of the world's proven reserves, whereas the target market is mostly Europe and Japan. Amongst the largest consumers in Europe are Britain, France and Spain. Japan is the single largest user of natural gas by nation accounting for 93.5 tcm of consumption in 2010. A very interesting fact is that *all* of Japans gas imports are LNG and none is through natural gas via pipeline!

Further, the total reserves of natural gas were estimated at 187.1 bcf in 2010 and this information is displayed in Figure 3, showing that the majority lies in the Middle-east and Eurasia. It must be noted that the Eurasian split is concentrated in the former Russian states of Kazakhstan and Azerbaijan.
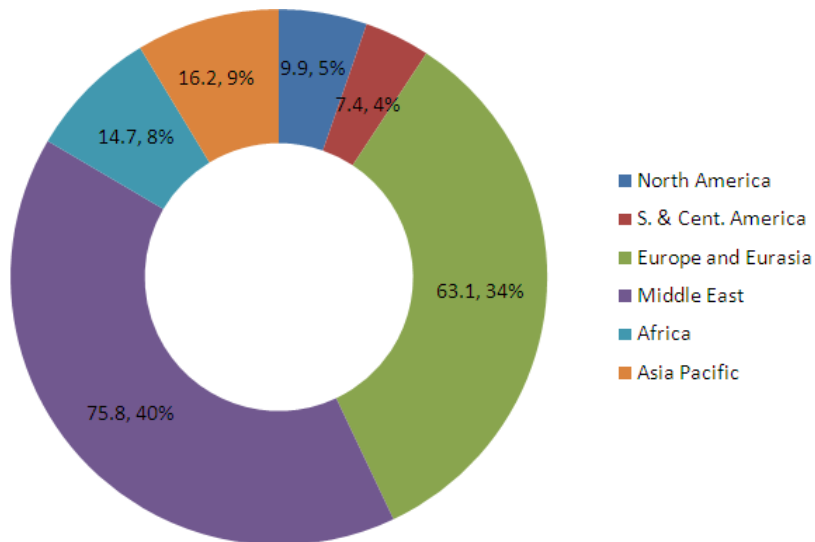
Figure 3: A chart detailing the split in gas reserves and as a percentage of the total 187.1 tcf of gas reserves in 2010. Reproduced from data (BP, 2011)

Figure 4 shows that transport routes for the gas pipelines and LNG tankers. It is clear that the LNG strategy has been adopted for the longer distances and this is likely to continue expanding as distances between source and market are long.
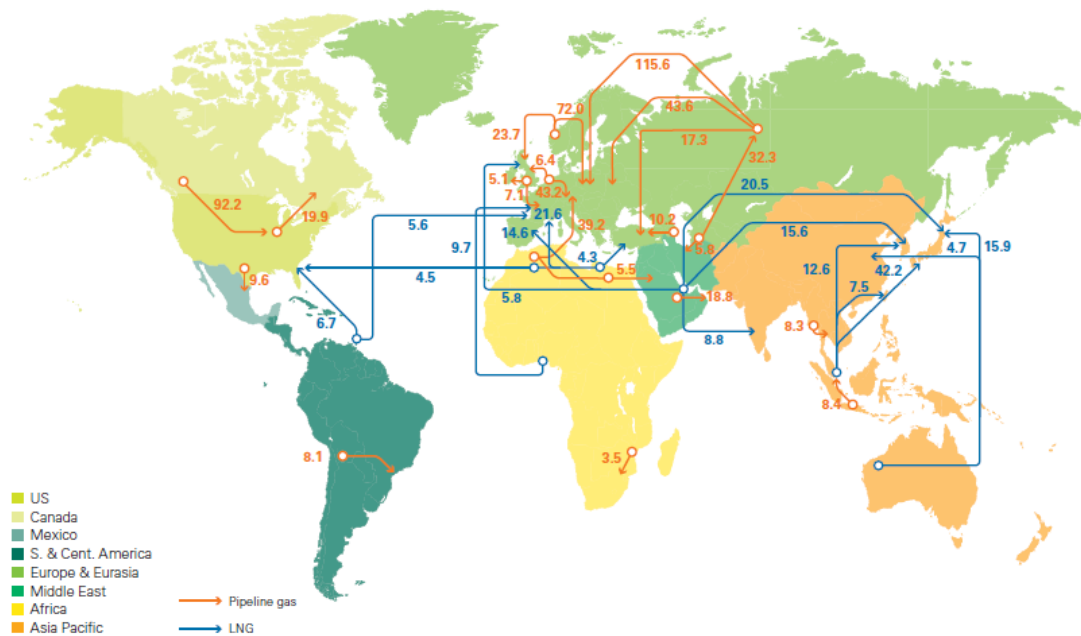
Figure 4: Shows the major trade movements for both pipeline gas and LNG, highlighting the source and destinations (BP, 2011)

4

Recently there has been activity in Britain pertaining to the opening of new import terminals at Teeside (Reuters, 2009) with imports from Trinidad, North America and Milford Haven, Wales (BBC, 2009) with imports from Qatar in the Middle East. The latter is a joint venture between Qatar Gas and ExxonMobil based in Wales with two terminals; the South Hook terminal and the Dragon terminal. These two terminals could provide 25% of UK gas supply in the future; this is a critical resource especially since the north sea oil reserves are fast depleting. Further, LNG can also be stored underground in large quantities so as to provide protection against supply and demand oscillations, and thus the prices can potentially be kept under check.

There is also activity in the Middle East especially in the Qatar region. It must be noted that though Iran has large reserves, these are mostly not being utilised at the sort of rates that other fields are being depleted; Figure 5 shows the difference in production and reserves for major gas producing nations. The graph is not necessarily a picture of the largest producers but rather a selective summary of some of the key players. It is expected that Iran will play a major role the near future as to the future of gas supply and it is possible that Iranian supply may increase to the large consumers in Asia such as India, China and the Far East nations such as Korea.

Additionally the graph depicts indirectly the reserves to production ratio. One can see that though the US has moderate to low reserves, they are depleting those reserves very quickly. Indeed, the UK only has circa 5 years of gas left based on current rates. This is due to depletion of north sea reserves. The key players are clearly Russia, Iran and Qatar, who have both large reserves and are also producing relatively large amounts of gas.
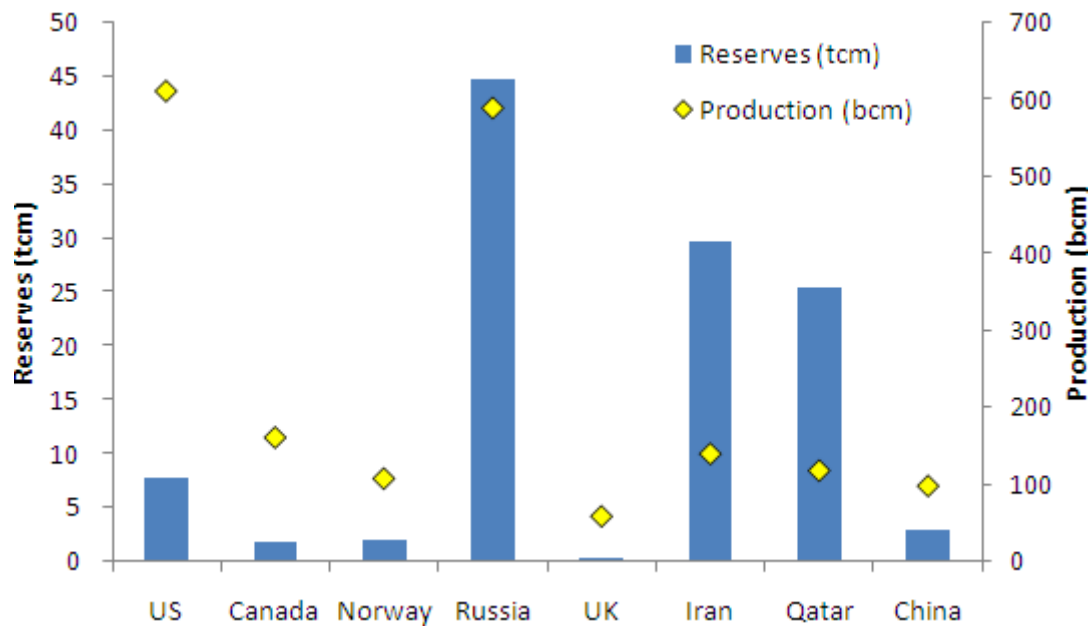
Figure 5: A figure detailing the reserves and production for significant nations in the LNG industry. Reproduced from data (BP, 2011)

1.4 LNG in Context – The Value Chain

The overall process of producing, shipping and supplying the LNG from source to market is known as the LNG Value Chain. This chain consists of four main segments:

1. Exploration and Production:

   The first stage of the process requires the company to search for, and estimate the reserves in particular fields be it onshore or off shore. This stage can account for up to between 15% to 20% of the capital cost related to the entire value chain.

2. Liquefaction:

   This is the most energy intensive step of the process and involves the conversion of the gaseous natural gas to liquid natural gas. The capital costs here can be up to 45% of the whole process.

3. Shipping:

6

This stage involves the transport of the LNG in container ships from liquefaction plant to destination market. There may be a short pipeline taking the LNG from the plant to the port. It can account for between 10% and 30% of the capital costs.

4. Re-gasification:

Once at the destination market, this stage involves the re-gasification of the liquid gas, the loading terminal and consequent distribution of the gaseous natural gas to the network supply of that market.

The value chain is summarised in Figure 6. Since this project is focused on the liquefaction of the natural gas, some more details will be given.

	Exploration & Production	Liquefaction	Shipping	Storage & Regasification
	Gas production and preplant processing and transport	Liquefaction plant, including preliquefaction processing, storage, and carrier loading	Shipping	Receiving terminal, including unloading, storage, regasification, and delivery
% Total Capital Costs (EIA, 2003)	15 to 20	30 to 45	10 to 30	15 to 25
Example Capital Costs	Varies widely	$1.5 to $2 billion for a plant that produces 8.2 million tons of LNG per year	$155 million to purchase a single 138,000 cubic meter ship, or $60,000 per day to charter	$400 million for a U.S. terminal capable of delivering between 180 and 360 Bcf per year

Figure 6: Showing the four main steps of the LNG value chain (NETL, 2005)

The liquefaction stage involves an energy intensive process which consists of a liquefaction plant. Herein, there is process technology which can be likened to a refrigeration system. The raw feed gas comes in and is cooled through a varying number of stages or cycles in order to drop its temperature and turn it into a liquid. The number of cooling loops depends on the process technology that is being utilised. The refrigeration loops are typically powered by a gas turbine, though steam turbines and electric motors can also be utilised. This project looks

at the selection of the gas turbines and focuses on the alternative solutions available to operators.

1.5 The TERA Philosophy

At this point, before introducing the aims and objectives, it is important to understand the concept behind the philosophy of the modelling used in this thesis.

The TERA, a Techno-economic, Environmental and Risk Analysis, is a philosophy whose main function is to exploit the potential design space of an engineering problem and identify solutions, thereby minimising computational time and costs. In this way, the optimum solution can be selected with reduced error in the decision making process.

Furthermore, it can be used to develop an optimisation tool, given an objective function. The objective function of this project is to minimise the total plant life cost whilst making sure the other requirements pertaining to performance and risk are met. According to Kyprianidis et al. (2008) the TERA frame work can be described as:

"an adaptable decision making support system for preliminary analysis of complex mechanical systems"

TERA has also been described as a multi-disciplinary tool for the modelling of gas turbines and engine asset management. Gayraud (1996) was first to base his studies on techno-economic assessments of industrial gas turbines at Cranfield University. His work was also related to the selection of gas turbines for the industrial field, later moving on to look at decision support within combined cycles (1998). Whellens and Singh (2002) describe how the TERA approach can be used to model the design procedure to make the traditional decision making process easier.

The different modules that incorporate the TERA are extensively explained by Ogaji et al. (2008). This work also illustrates how the modules come together and how an optimisation can be perceived using this tool. The author presented an architecture and details of the emissions, risk, economics and performance modules (Khan et al. 2009, 2010, 2011) and the current architecture is an extension and final version of that (the architecture will be presented later).

1.6 Aims and Objectives

<u>Aim:</u>

Create a multidisciplinary simulation tool based on a Techno-Economic, Environmental and Risk Analysis (TERA) framework, in order to select gas turbines for the liquefaction of natural gas.

<u>Objectives:</u>

1. Create robust thermodynamic performance models for typical aero-derivative and industrial frame engines used in LNG service (Performance Module)

2. Simulate failure of critical hot gas path components as a function of the thermodynamic performance of the GT and investigate the uncertainty in failure of critical hot gas path components (Lifing / Risk Modules)

3. Consequently, create maintenance schedules based on failure trends simulated and conduct a full TERA study including environmental and financial appraisal (Environmental / Maintenance / Economics Modules)

4. Conduct a financial analysis (NPV and sensitivity) to denote which parameters, financial/performance, affect the financial feasibility of selecting technology

The tool is envisaged to be used in-house in Shell and will act as an aid for equipment selection. It is important because it helps to quantify the relationship between operation and maintenance of turbomachinery, and quantify the technical risks/variation in failure.

1.7 Commercial Benefits of the Research

It is important to highlight the commercial benefits of the research to Shell:

1. <u>Selection:</u> The tool is essentially a basis for selection of plant equipment and employs the TERA philosophy as a platform to do so. The tool enables the operator to economically and efficiently reduce the design space and evaluate projects in terms of

Techno-economics, **E**nvironment and emissions, and technical and financial **R**isk **A**nalysis (TERA). Thus, a number of disciplines are taken into account in order to evaluate each technology option.

2. <u>Operations:</u> It acts as an aid to operations, mapping the effect of how we operate the engine and what this means in terms of failure and can aid in designing maintenance schedules. It aims to quantify risk in operation and aid in decision making. This will also help the operator to make decisions about repair and replace of components.

3. <u>Sensitivity Analysis:</u> Finally, it can also be used as a tool for sensitivity analysis using a particular parameter, be it performance related or financial, to evaluate the sensitivity of that parameter to the overall suitability of the technology for a particular application.

The tool gives Shell another useful point of reference to aid decision making when selecting technology and allows entire plant life cycle simulations.

1.8 Structure of Thesis

This thesis is split into 10 chapters. After giving a broad introduction to the LNG trade and why it is significant in the oil and gas arena, the thesis looks at the cycles in LNG refrigeration and the prime movers used to power the refrigeration cycles mechanically. These engines are analysed for their performance capabilities. Next, there are a series of chapters which look at the literature and methodology of each module within the LNG TERA code. Finally, there is a section on scenarios which shows how the tool has been utilised.

Chapter 1: A broad background of the LNG value chain as well as projected demands and potential markets. Defines where the present study sits in the LNG chain. The aim and objectives are outlined in the context of selection of rotating equipment for an LNG plant.

Chapter 2: Explores the different technologies and processes involved in the LNG business and highlights the importance of the driver technology to the rest of the process as well as assessing the thermodynamic performance simulation of the gas turbine engines involved.

Chapter 3: Looks at the technical risk analysis of gas turbines in order to map the uncertainty in failure. Various methods and statistics are charted here. Highlights the requirement of lifing hot gas path components.

Chapter 4: Lifing model explained here and how it is set up to feed into the risk analysis. The parametric model for blade creep life as well as probabilistic models for combustor liner and blade coatings are explained in detail. Review of techniques available.

Chapter 5: Addresses the use of the risk analysis results by creating maintenance schedules based on the likely failure trend of the engine. The maintenance acts as a transitional link between risk analysis and economics/financial studies. Gives background on the maintenance methods and philosophies that can be used.

Chapter 6: Predictions for the emissions for each engine under particular operating conditions are made using empirical methods. The trend of emissions is mapped by use of emissions indices which help dictate the total emission based on the duty of the engine. The method of empirical correlations is charted here as well as a literature on other methods available.

Chapter 7: Looks at the economic appraisal method used to carry out the financial calculations. The Net Present Value method is utilised to assess the time value of money and all other modules feed into this final module. A broad explanation of the algorithms used and how the assessment of total LNG production, revenues and costs will be carried out.

Chapter 8: Looks at the case studies resulting from the application of the TERA tool for equipment selection. The first case study looks at the baseline engine already in use in the LNG industry and sets this up as the engine for comparison basis. The second case study looks at larger industrial frame machines to capitalise on economies of scale. The third case study looks at aero-derived machines with higher firing temperatures and some with more complex inter-cooling cycles and boosted efficiencies and asks the question whether it is beneficial for operators to use these machines given a multidisciplinary perspective. The final case study looks at pseudo engines which represent modified existing engines in order to enhance performance by simulating better materials technology and compression capabilities. There was an extension to the application in which an additional case study was explored looking at power generation instead of LNG. This exemplifies the flexibility of the models created.

Chapter 9: Conclusions of the modelling and the case studies are summarised here as well as suggestions for further works.

Chapter 10: The management report detailing how the management aspects have been brought into the research project. It looks at the commercial applicability of the research, the management knowledge used in the research and the management of researchers within the project amongst other aspects.

2. LNG Process Technology & Gas Turbine Performance Simulation

2.1 The Liquefaction Process

The emphasis is on the gas turbine as a driver for the gas compressor, in effect providing the power for cooling the natural gas. The gas compressor compresses the refrigerant which the heat exchangers use to cool the gaseous natural gas into LNG. Figure 7 shows the diagrammatic set up of a typical LNG liquefaction plant.
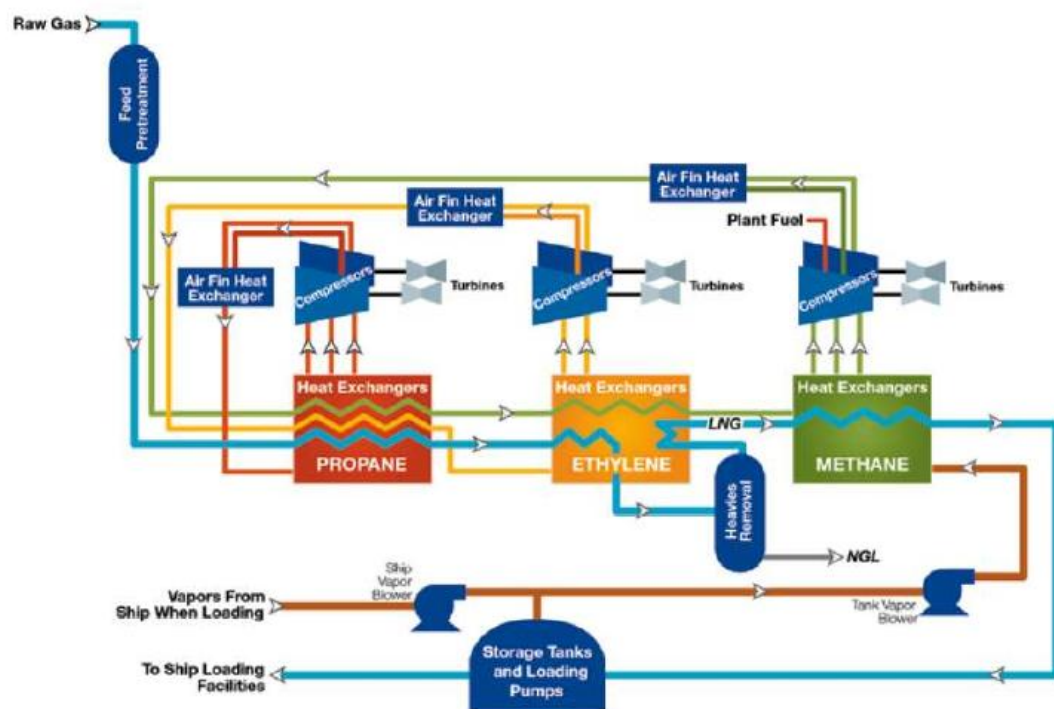
Figure 7: A diagrammatic view of a typical LNG plant (Ransbarger, 2007)

The diagram shows the raw feed gas entering at the top left hand side, and then this feed gas goes through a number of heat exchangers where it is cooled in three stages. The final stage with methane as the coolant produces the LNG that is then tapped off for storage in tanks. The major components are (a) the gas turbines powering each cooling loop, (b) the gas compressors which compress the coolant gas, and (c) the heat exchangers where the cooling

13

takes place. This is one typical set up with three single component coolants. Variations can also include dual and mixed refrigerants.

The very basic cycle of the system can be likened to a fridge and summed up thus (Moran et al, 2003):

1. The gas turbine produces mechanical power which drives the gas compressor in the refrigeration cycle. The gas compressor takes in the refrigerant as a low pressure two-phase liquid-vapour and then raises the pressure and temperature via compression. This turns the two-phase liquid-vapour into a saturated vapour.

2. The now gaseous refrigerant goes on to the condenser which is equivalent of the heating element pipes seen at the back of a normal household fridge. The condenser removes the heat and reduces the temperature but the pressure remains high. Now the refrigerant becomes a saturated liquid.

3. Next the high pressure refrigerant is expanded via either an expansion valve or a turbo-expander which turns it into a cold liquid. There is a major pressure drop and associated temperature drop also. The expansion device does the opposite to the gas compressor.

4. Finally, this cold liquid refrigerant then goes through the heat exchanger where it absorbs the heat from the natural gas and turns it into LNG, whilst itself becoming a two-phase liquid-vapour again. The warmer gaseous refrigerant then returns to the compressor to be compressed again.

Duty curves, why different types of process, all other process types and case studies

2.1.1   Current Process Technology

Currently, there are various processes which are being used. Some are traditional and dated whilst other new process technologies are up and coming. By process we mean the physical set up of the heat exchanging cycles, including number of trains, number and type of refrigerants, and finally the size and power of gas compressors and gas turbines. The Phillips Cascade Process, APCI (Air Products), Linde Process (Statoil), Axens Liquefin Process and the Shell Dual Mixed Refrigerant (DMR) Process are some of the front runners (Akhtar,

2004). Both the Phillips and the Linde Processes use three refrigerants whilst the others use dual refrigerants.

The Phillips Cascade is known for its simplicity and reliability. It uses Propane pre-cooling, then Ethylene and finally Methane cooling, traditionally using two General Electric (GE) Frame 5 C's for each stage running in parallel, thus numbering in 6 drivers in total for a train with 95-96% reliability levels (Akhtar, 2004), since the parallel set-up means the loss of a single train does not stop production.

Traditional APCI plants were similar to the Phillips process but were upgraded with Frame 6/7 drivers, increasing capacity to 4.7 mmtpa (million tonnes per annum). Further increases of up to 7.9 mmtpa are possible with Frame 9 machines. The Axens process uses a mix of Frame 5 and 7 machines whilst the Shell process is similar but with twin parallel compressor trains for each stream, with higher production (4.5 to 5.5 mmtpa) and lower costs claimed (Nibbelke et al., 2002).

Since 2000, the trend is to go higher with train sizes between 3 and 8 mmtpa. Plans for some plants, possibly Sakhalin, this may go up to 9.6 mmtpa (Dam and Ho, 2001). A large plant called the Qatar II is in form currently operating with large GE Frame 9E machines (Salisbury et al., 2007). Traditionally, Shell have used the propane/mixed refrigerant (C3/MR) process where the pre-cooling is done with a single propane refrigerant. The newer double mixed refrigerant(DMR) process is better because its pre-cooling refrigerant is made up of two components which adds flexibility to the process technology capabilities (van de Graaf and Pek, 2005). Essentially there are two MR processes which gives (a) better use of the power available from two gas compressors and (b) acts as a better deterrent to variations in ambient temperature conditions. The latest developments include the Shell PMR process which utilises three GE Frame 7 machines and is purpose built for tropical conditions and can manage 8 mmtpa (van de Graaf and Pek, 2005).

2.1.2   The Shell DMR Process

For the purposes of this research the Shell DMR process has been selected. This was done in order to model a process used by the sponsor company. There is no particular technical reason for the choice. In reality a much more rigorous process analysis/modelling is required for the liquefaction process, whereas detailed process analysis was never the aim of the current study. Ideally one would have the capability to model the range of different processes discussed in

the previous sections and be able to make the optimum decision for the particular plant under study.

It is deemed sufficient to select a single process and model all the analysis on that one process; this has a two-fold benefit, first of all it makes the analysis simplified and reduces the need for complex process modelling which is outside the scope of this study and secondly it means the comparisons between technologies are all made on the basis of the same process, which makes any comparison unbiased.

The Shell DMR process uses propane pre-cooling and then a mixed refrigerant and thereby is a dual coolant process with two stages or loops of cooling as opposed to three. The baseline process is modelled on the basis of the baseline engine, the GE Frame 7EA 87 MW engine. The single train uses two of these engines. The research does not go into the complexity of number of trains and number of total engines and total plant capacity. Rather, a single train is the focus of the modelling. The process is mimicked using the idea that we can use a value of total process efficiency and deduce the amount of power required by the gas compressor and the water cooling process for the heat exchange. This way, the total power required by the gas turbine driving the process can be calculated. This calculation is done before the TERA simulation is done, or it can be said this is a pre-simulation knowledge that is required to initiate the TERA.

2.2 Plant Equipment

This section will look at the typical process plant equipment involved in the production of LNG at the liquefaction stage of the LNG chain. Emphasis will be placed on the technology which the current research intends to create a tool to select, however, the philosophy could easily be extended to other equipments so long as failure of those machines can be quantified.

2.2.1   Gas Turbines for Mechanical Drive

Known for its high power-to-weight ratio and compactness with respect to other machines like steam turbines or nuclear reactors, the gas turbine is the choice of many industries from civil and defence aerospace to industrial power production and marine applications. It is a machine which converts fuel potential energy into thermal energy, and consequently a mechanical or electrical output. There are no reciprocating parts which means less tear and wear and less lubrication oils needed (Saravanamuttoo et al., 2001). Reasons for selection

16

specifically within the LNG plant are numerous (Meher-Homji et al., 2007), and almost all boil down to economic advantages.

- Takes up less space compared to steam or nuclear plants

- Lower foundation, installation and transportation costs

- No need for boiler or cooling water (intercooled gas turbines are an exception)

- Shorter delivery time

Essentially there are three core components; the compressor, the combustor and the turbine. Additionally there is an intake to the compressor where the air is sucked in and then compressed. The compressor has two effects, it reduces the speed of the oncoming flow and it increases the density of the air to facilitate combustion. The combustor mixes the compressed air with the fuel and burns the mixture to provide the heat energy. The air-fuel mixture, also known as the *hot gas* is then expanded through the turbine. The system is cyclic in such a way that the turbine then runs the compressor. The compressor is initially started with a starter motor and then it will be run by the turbine. So the power produced in the turbine stage is split between that which is used as useful work and that which is fed back down the system via the rotating shaft, joining respective compressors and turbines, to run the compressor stage.

There are many other variations to this basic design of the gas turbine. Components such as intercoolers, reheat combustors and heat exchangers can be added to boost either power or efficiency depending on what optimisation is required.

2.2.1.1 Function and Performance

It's the expansion through the turbine which produces the power. A compressor is needed because to expand the hot gas coming from the combustor through to the turbine a pressure rise is required, which is achieved by the compressor. Energy is added to the working fluid after the compression stage and before it is expanded so that the useful work extracted at the turbine stage can be increased, and so the turbine can provide useful work as well as drive the compressor. Without energy addition in the form of burning fuel the system would simply be a turbine running a compressor without any useful output.

The two major factors affecting performance in gas turbines are component efficiency and firing temperature, also known as turbine entry temperature. The higher the temperature of the hot gas entering the turbine the greater the work that can be extracted, i.e. more power, simply because more expansion can be achieved. In turn the efficiency of a gas turbine depends on the pressure ratio of the compressor. Hence, high efficiency and high power require the best component efficiencies and high performance turbine materials to withstand high pressure and temperature hot gases entering the turbine. For further information about thermodynamic cycles, especially the intercooled cycle and single shaft and multi-shaft implications refer to Saravanamuttoo et al. (2001).

2.2.1.2 Aero-derivative and Industrial Machines

The aero-derivative is basically a turbine which was previously used for aviation applications and has been modified for industrial use. The last turbine stage the nozzle is substituted for a power turbine or the last turbine is directly coupled to a compressor. An example is the GE LMS100 which has an aviation GT core, but is modified for industrial purposes. The major implication here is the high pressure and firing temperatures associated with these machines. This usually achieves high efficiencies but there are implications of life expectancy. Some core components, like the turbine, are subject to very high temperatures and thus prone to more wear and tear. A further added benefit can come in the form of a combined system to use the waste heat to run a steam turbine or recuperate the heat back into the combustor.

Further, the aero-derivative engines have a higher specific work rating and efficiency than the industrial engines in general (Figure 8), and this can potentially translate to economic benefits.
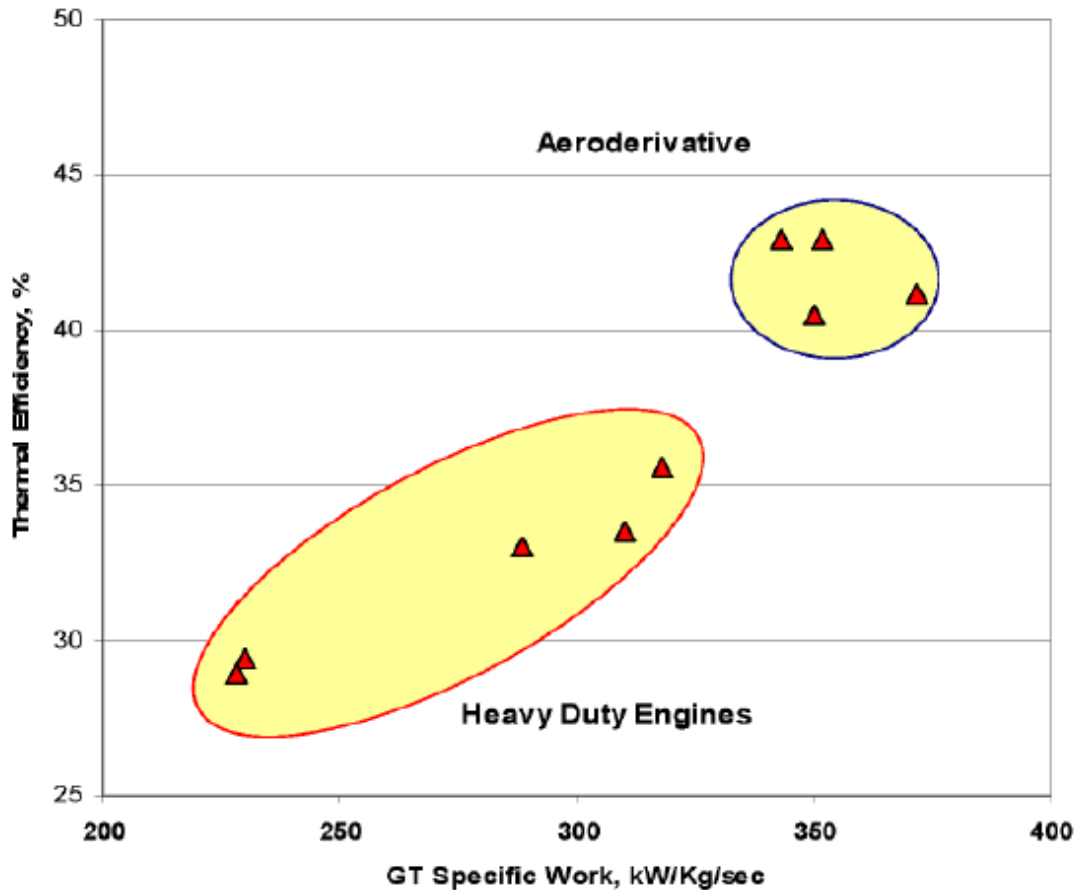
Figure 8: A diagram comparing the efficiency and specific work advantage of aero-derivatives to traditional industrial frame engines (Meher-Homji et al., 2007)

2.2.1.3 Waste Heat Recovery and Combined Cycles

Simple cycles will yield thermal efficiencies generally between 20% and 40% but with the latest machines this can be pushed up to around 50% (e.g. LMS100). To be more efficient, one needs to incorporate waste heat recovery in some way. Methods already discussed were recuperation recycles, where the heat is sent back to the combustor, or sent to a steam turbine for steam generation and electricity production. The latter is a combined cycle which can then increase efficiencies up to about 60% and with combined heat and power 85% overall efficiency is possible. Combined heat and power is using the waste heat for both electricity and power generation. However, the trend since the early days of LNG has been to move away from steam based plants due to the complexities and trouble over water requirements in some locations. More recently, the forerunner in LNG applications is singled out as the simple cycle gas turbine, though intercooled aero-derivatives are of much interest in the last 5 years.

19

2.2.2 Gas Compressors

The core of the actual refrigeration is the gas compressor. There are two main options, centrifugal or axial compressors. LNG plants utilise both depending on requirement of pressure ratio. Generally high mass flows are involved and if the requirement is for high pressure ratios then centrifugal compressors are used and if the pressures are relatively low then the axial machines are incorporated.

The two main set-ups for centrifugal machines are Double Flow or Back-to-back arrangements (Meher-Homji et al., 2007). The double flow is a parallel system wherein the inlet flow is split and enters the casing at separate ends and meets at the final diffuser. This system is used for reducing space taken up, since these machines can be very large due to the compressor diameter and casing size. The system is hard to implement in reality because the two parallels need perfect impellers to match the flow and losses to be identical to each other. However, it has the benefit of speed matching of the final flow leaving the unit if done correctly.

The Back-to-back system uses an approach whereby the flow enters one half of the unit, goes through half the compression and is made to leave the compressor unit and then fed back to the other half. It's a process in series as opposed to parallel like the double flow unit. This is advantageous because the flow can be cooled at half way point and then reintroduced for better compression effects since the second half will see a reduced flow temperature. It is basically a form of inter-cooling.

Axial machines on the other hand are highly efficient, generally more efficient than centrifugal machines (Bloch and Soares, 1998), and have operational plus points in that they inherently have better range control. The IGV's give the axial machines a greater operational range.

The main problem with these compressors is the high Mach number flows the impellers experience. The critical point for sub-sonic design is Mach 1.0 and so incorporation of IGV's for these designs is the solution to going higher with higher mass flows and consequently higher Mach numbers. The underlying problem is the fact that some refrigerants, like propane have a very high molecular weight, which when subject to high compression will sometimes produce super-critical inlet Mach numbers.

2.2.2.1 Compressors for Re-gasification

Re-gasification is indeed not part of a liquefaction plant, but it has been included here since there are a few considerations linked to re-gasification in terms of turbomachinery technology. Re-gasification also requires the use of compressors

2.2.3 Turbo-expanders

Typically one would use an expansion valve to expand the refrigerant coming from the compressor. The advantages of using turbo-expanders are mainly that they are highly efficient, they have a tolerance to a range of flows and they have a proven reliability (Bloch and Soares, 2001). However, in order to achieve high efficiency the expander needs to be run at high rotational speeds. Turbo-expanders have been shown to improve the efficiency of a refrigeration cycle by reducing losses at the throttling process (Cho et al., 2008). In turn, the expansion ratio created between the turbo-expander depends on the mass flow rate and the throttling area.

2.2.4 Heat Exchangers

This is where the actual cooling of the raw natural gas takes place to turn it into liquid form. This study is concentrating on turbomachinery and so it is sufficient to limit heat exchangers to an introduction only. Cryogenic heat exchangers are the most important heat transfer equipment within the liquefaction plant (Neeraas et al, 2002). The process is usually split into three parts since there are three cooling stages; pre-cooling, liquefaction and sub-cooling. There are usually two types of heat exchangers used, the plate-fin heat exchangers (PFHE), used for the pre-cooling, and the spiral-wound heat exchangers (SWHE), used for the liquefaction and sub-cooling stages (Buller et al., 2004).

2.2.5 Storage

Storage takes the form of special LNG tankers or containers. They are specifically designed to withstand high pressures and low temperatures. Once again storage is not of concern here, except to mention one thing. The storage tanks have one problem in that the low temperature LNG gives of gas vapour which is a major concern and source of loss. To this end, boil-off-gas compressors are used to make sure that the vapour is not wasted and is re-liquefied.

2.2.6 Electric Drive and Alternatives

The Snohvit plant in Norway adopts large electric motors as opposed to traditionally fired rotating equipment. Meher-Homji et al., (2007) describe in much detail the possible use of large electric motors for LNG applications as mechanical drive for the gas compressors. Some of the benefits include high plant availability and operational flexibility and further the fact that the plant is no longer so sensitive to the ambient temperature.

The large motors, which would need to be 80-100 MW rated power in order to compete with the increasing size of gas turbines employed in the application (Figure 9), can already be manufactured. However, there is no known and proven application of such a plant and overall cost estimations would have to be done specifically to deduce if such a plant is economic or just a misleading argument.
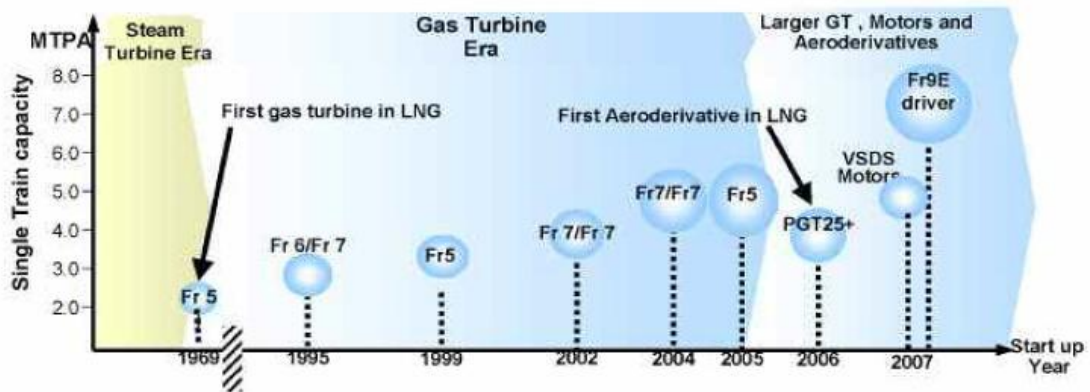
Figure 9: Evolution of LNG drivers over the years (Meher-Homji et al., 2007)

2.3 The System Architecture

Before proceeding to describe the thermodynamic performance simulation of gas turbines and the tools used to do so, it is important to describe the overall architecture of the LNG TERA tool. The system architecture can be seen in Figure 10. During the next chapters reference will be made back to this diagram. The architecture details how all the modules work together and how information and data are transferred between the models.
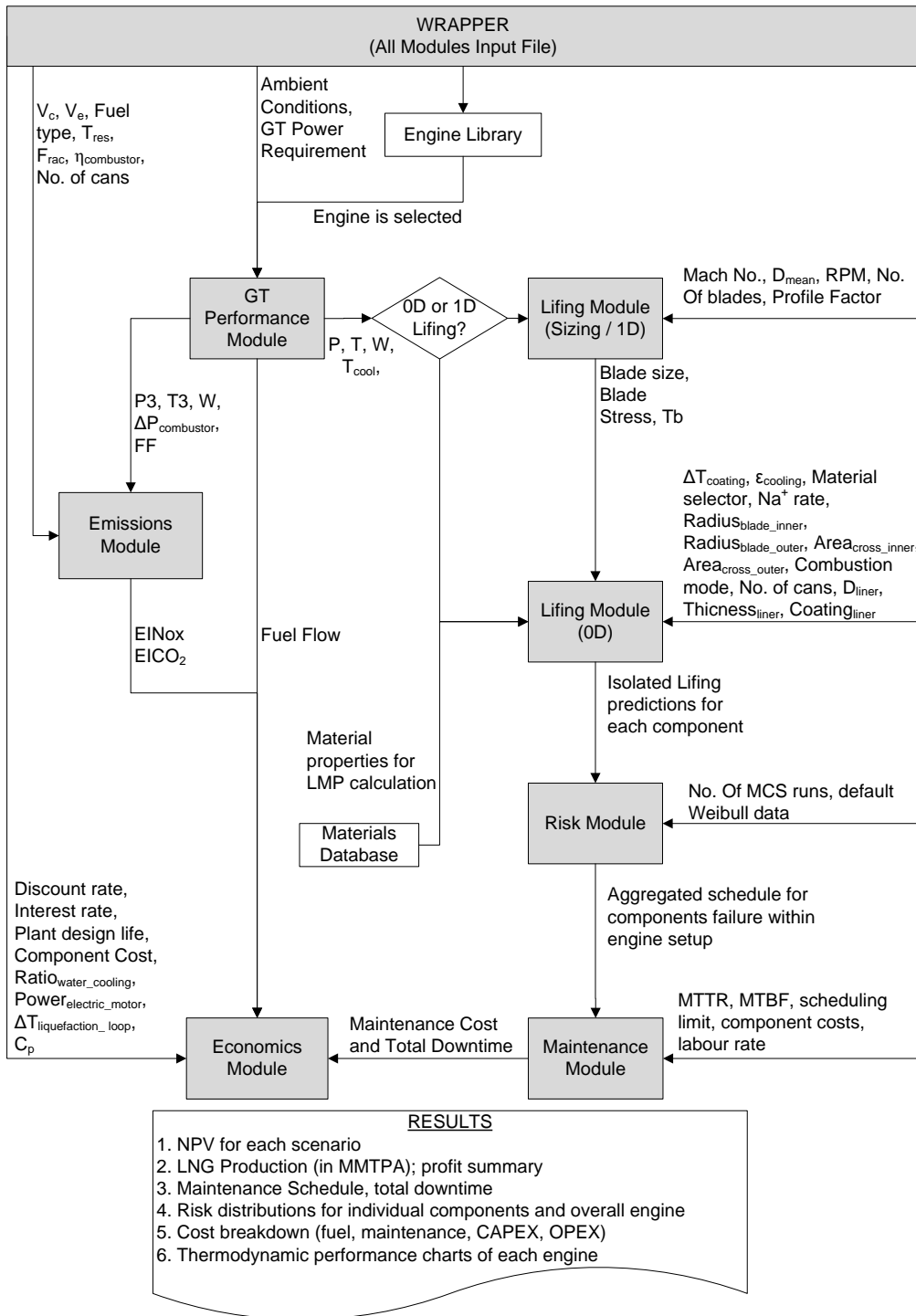
Figure 10: System architecture for LNG TERA tool

The code for the TERA simulation tool has been created in FORTRAN language and is controlled by a *wrapper* code which calls different modules into play depending on the way

the user wants to run scenarios. The wrapper is an integration platform and is *not* an optimiser; it simply controls the flow of information between modules and controls the order of execution. There is an input file which contains all the information about the inputs to each module and the switches which turn module calculations on and off. This allows the user to control the analysis and only executes parts of it which are required or indeed the whole TERA can be run. This code also controls the different engines which are modelled. The whole process is automated and there is no manual transfer of files or data. The user prepares an input file for all the modules, many of these are prepared already and it may just be required that the user selects the file and simply runs the TERA.

The TERA architecture as portrayed in Figure 10 shows the overall risk and emissions modules receiving data from the performance module and data are also passed to the economics module. In this way the performance is the starting point for all the modules. It must be noted here that the overall assessment of risk includes three modules; the lifing, risk and maintenance modules. The initial architecture started with the risk module and later the lifing and maintenance were developed around the risk analysis when it was decided that to conduct risk analysis one would require to life the critical components in the GT and once the risk analysis had been done, to connect this to some sort of economic analysis one would need to create a maintenance schedule from the lifing and risk results since the basic lifing results needed to be interpreted and assimilated to be used as a schedule for maintenance. The details of the modules will form the consequent chapters of this thesis.

The lifing module uses blade and hub measurements coupled with material data in order to carry out parametric and probabilistic creep analysis. This gives the user values of time between failure (TBF). The time to repair (TTR) can be estimated from field data of engine operations or from public domain data. The risk model then uses the TBF and TTR and puts them through a Monte Carlo simulation to get plots of Mean Time Between Failure (MTBF), Mean Time to Repair (MTTR) and Total Time to Repair (TTTR). Finally, the maintenance schedule uses the output from the risk to decide which type of maintenance is best suited for the engine based on the way the engine is run and the engine and the designated life of the plant. The maintenance module also gives maintenance cost data to the economic module to add to the cost calculations. As can be seen in Figure 10, there are two methods for acquiring failure data; either previously published data (specific field data or public domain data of experienced engineers) is to be used, or alternatively the lifing model is to generate the equivalent data for failure using creep analysis.

In addition to the overall risk assessment, engine performance data are fed to the emissions model for predicting the gaseous pollutants and the emissions taxes thereof. Again, emissions tax amounts are fed to the economics module. The TERA can then be used as an integrated platform to assess the selection of technology based on all these disciplines. The Cranfield in-house software called Turbomatch has been used to analyse the performance of the gas turbine engines. The framework is capable of modelling different engine configurations using Turbomatch as the performance code, these include industrial heavy duty frame engines as well as aero-derived engines and more complicated cycles with inter-cooling between compressors, bleed cooling to turbine stages, exotic materials for turbine stage and coatings as well as aero-derivation.

2.4 Thermodynamic Performance Simulation

The thermodynamic performance simulation looks at the operation of the gas turbine driver in detail and based on the duty of each engine, the thermodynamic parameters such as temperatures and pressures are calculated at each station of the engine. The basic level architecture of the code can be seen in Figure 10, which shows where the performance module sits amongst the rest of the LNG TERA, and Figure 11 which shows how the subroutines within the module work.

The performance module itself is a code which works to first take the engine file from a database of existing engine input files and writes to this file the off-design cases that are to be explored (Figure 11). The range of off-design cases to be explored is dictated in the main input file by the user/operator. Once the basic template input file has been prepared with off design cases, the file is sent to the Turbomatch code which runs the actual thermodynamic performance calculations. This consists of matching the compressor and turbine for each off design condition using an iterative numerical process (Pachidis, 2008).
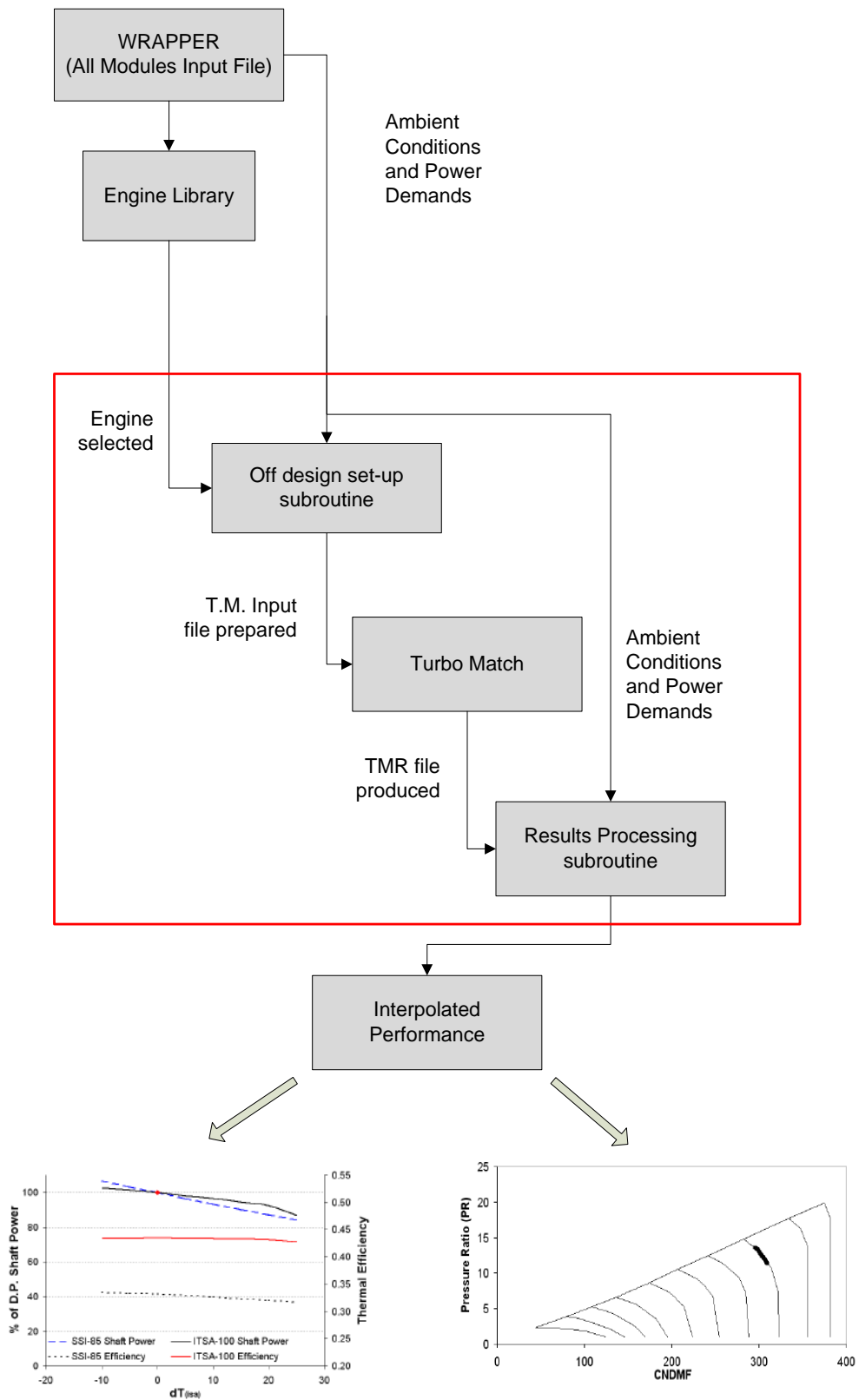
Figure 11: A schematic of the performance module

Once Turbomatch has finished iterating for each o ff-design case, the output is initially a large array of off-design data known as a TMR (Turbomatch Results) file. The TMR file this is then read and condensed by the next subroutine in the performance module (results processing subroutine) which creates a table of interpolated thermodynamic parameters based on the exact operating conditions as opposed to arbitrary values that were first entered by the user. The system uses linear interpolation to find the corresponding thermodynamic parameters such as temperatures and pressures at each station in the engine and the interpolations are based on the required power at given ambient temperatures.

2.4.1 The Engines in Context

The TERA is fully capable of analysing the range of engines including the intercooled aero-derivatives. The design point details of the main engines are shown in Table 1.

Table 1: Design Point Performance Parameters (GE, 2006)

Parameter		Frame 7EA	Frame 9E	LMS100	LM6000
Power output	(MW)	87.3	130.1	99.3	43.7
Mass Flow Rate	(kg/s)	296	410	200	124
TET	(K)	1418	1400	1650	1580
Thermal efficiency	%	33.1	34.6	45.7	41.9
EGT	(K)	808	813	690	728
OPR	-	12.7	12.6	40.0	27.9
Exhaust Flow	(kg/s)	302	421	205.6	126.5
RPM	(rev/m)	3600	3000	3600	3600
Heat Rate	kJ/kWh	10,870	10,400	7,875	8,600

Frame 7EA

The Frame 7EA is a heavy duty industrial machine made by General Electric (Figure 12). It is a long standing prime mover in the oil and gas industry with decades of operation and is a typical benchmark machine in the field of LNG. Rated at 87.3MW for the mechanical drive

version, it has a single 17 stage axial compressor with a pressure ratio of 12.7. This is followed by a can-type combustor with 12 can elements and finally a three stage turbine. It is an older machine compared some others and has had some modifications made to the original design in terms of coatings and others. It has a moderate efficiency at 33.1%. Operators look to improve on this machine by perhaps upgrading it further or moving away to more efficient machines.

Further, it must be noted that the Frame 7EA uses the GE GTD111 directionally solidified Nickel based super alloy and the combustor material is the Hastelloy X material (Ginter and Bouvay, 2006).

Figure 12: The GE Frame 7EA (GE Energy Website, 2011)

Frame 9E

The Frame 9E is a very similar to the Frame 7EA and is in the same class of engine, another very large industrial frame engine boasting a power of 130.1MW for the mechanical drive version (Figure 13). Again it has a 17 stage compressor and 3 stage turbine but of course for the larger engine given the larger power production and mass flow capacity, there are 18 cans in the can-type combustor. However, the engine is almost an exact replica of the smaller Frame 7EA with very similar firing temperature, materials and overall mechanical design of components. The efficiency is slightly, but significantly higher at 34.6%.

The rotational speed is also lower than the Frame 7EA at 3000 RPM. This has an effect on the expected lifetime of the engine since the life is a function of the stress, which in turn is dependent on the size of the blades and the speed at which they rotate. It would be expected

that the life of the components may be a little better according to the speed and stress argument, and it will later be detailed that the creep life of the turbine, which is amongst the most critical components in the gas turbine, is mostly a thermal effects. Since the firing temperature of the Frame 9 is some 10 to 20 degrees lower than the Frame 7EA then this will also serve to enhance the life of the Frame 9 engine. However, final simulations and results will show the behaviour of the engines in their respective environments.

The fact that the rotational speed is different to the Frame 7EA doesn't affect the operation too much since the large gas compressors are flexible enough to take a variation of rotational speeds. However, this does mean that the Frame 9 affords an advantage to the C3 compression stage compressors in the LNG refrigeration cycle due to this lower speed. Examples of the Frame 9E in action include various power generation plants worldwide, but most notably one of the largest LNG plants worldwide, the Qatar plant named Qatar 2 uses Frame 9E engines and has a production capacity of circa 7.8 mmtpa. Later, in this study, scenarios will be based on just such a train using Frame 9E machines.

Figure 13: The GE Frame 9E (GE Energy Website, 2011)

LMS100

The LMS100 is a large aero-derivative by GE. It is widely hoped that this engine will become the mainline replacement of the less efficient Frame series of engines in years to come. The LMS100 is the birth child of   mixture of aircraft engines boasting a very high power rating and high efficiency for its triple shaft simple cycle with inter-cooling.

The power rating of the engine is at 99.3MW and an overall thermal efficiency at a staggering 45.7%. This means a huge advantage over the frame engines in terms of fuel consumption.

This efficiency boost can be attributed to the use of a triple spool system which allows pressure ratios and firing temperatures at the upper end of practice. Further, the engine is derived from aero engines which are capable of achieving high firing temperatures due to the nature of operation in the aviation industry. The firing temperature of the LMS is at circa 1650K, more than 250K higher than the typical frame engines.

The engine has a 2 spool, 3 shaft configuration with a 6 stage low pressure compressor, 14 stage high pressure compressor and 2 stages for each of the compressor turbines. The final shaft is the power turbine which is 5 stages. The combustor is also different since it is a single annular combustion system (SAC).

Further, unlike the frame engines, the LMS is a modular design, again owing to its parent aircraft engines. This means that overhaul and maintenance timings are greatly reduced. However, the flipside to this benefit is that while the change-over is expected to be fast, there may well be more failures in an engine which is run at such high firing temperatures and this may negate the effect of the reduced overhaul time. However, this assessment cannot be made so easily, hence the present study and creation of an elaborate tool for equipment selection which weighs in all these factors.

Interestingly, the low pressure compressor is taken from the first 6 stages of the GE Frame 6FA compressor and the high pressure compressor is derived from the GE CF6-80c2 civil aviation turbofan engine. The high pressure turbine (HPT) is derived from the CF6-80E engine. Finally the power turbine is adapted from the 5 stage LM6000 low pressure turbine.
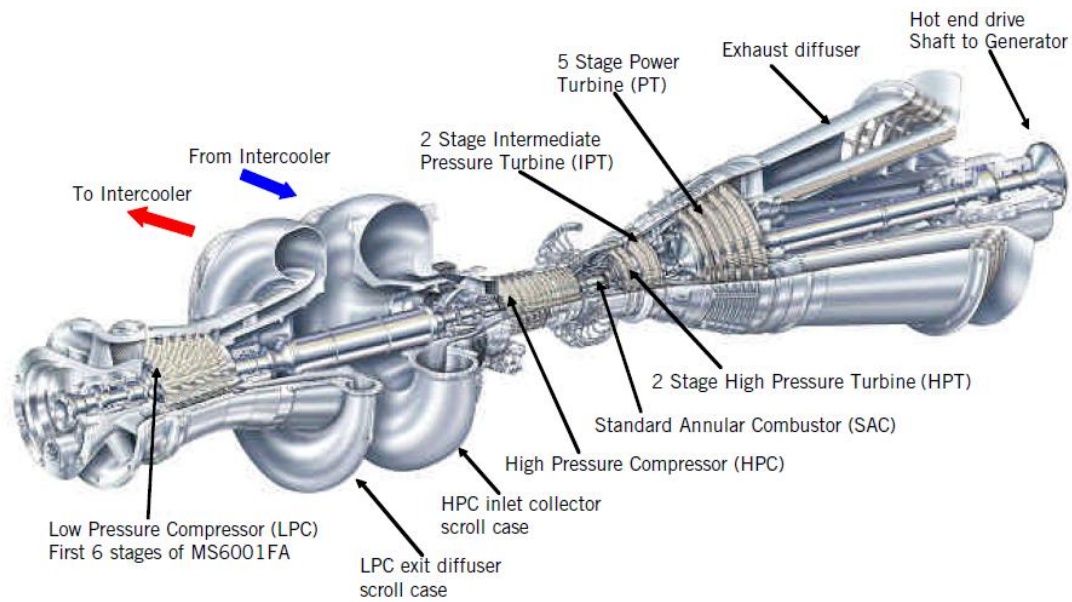
Figure 14: The GE LMS100 triple spool aero-derivative (GE Energy Website, 2011)

LM6000

The LMS100 is another aero derivative by GE with considerable power rating and another front runner to be utilised for LNG service. The power rating of the engine is 43.7MW and an overall thermal efficiency at 41.9% is still substantially higher than the frame engines, although lower than the LMS. This means a huge advantage over the frame engines in terms of fuel consumption. The firing temperature is at circa 1580K, again, not as high as the LMS but well above the 1400K of the frame engines.

The LM6000 is a 2 spool configuration with a 5 stage low pressure compressor, 14 stage high pressure compressor and 2 stages for the high pressure turbine. The low pressure turbine is 5 stages. This is because there is no power turbine and the system is directly coupled to the load whilst the LMS has a free power turbine. The combustor is again a single annular combustion system (SAC). It must be noted that the LM6000 is based on the CF6-80 series and the adaptations based on this civil parent include the HPC, the HPT and the SAC combustor whilst the rest of the engine is specifically designed and is not borrowed.
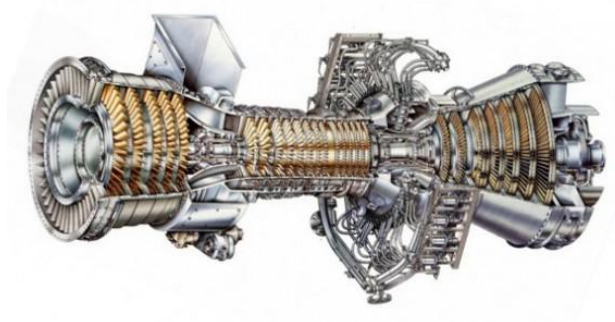
Figure 15: The GE LM6000 two spool aero-derivative (GE Energy Website, 2011)

2.4.2 Engine Schematics

The various engines simulated in this research can be put into some of the broad categories shown below:
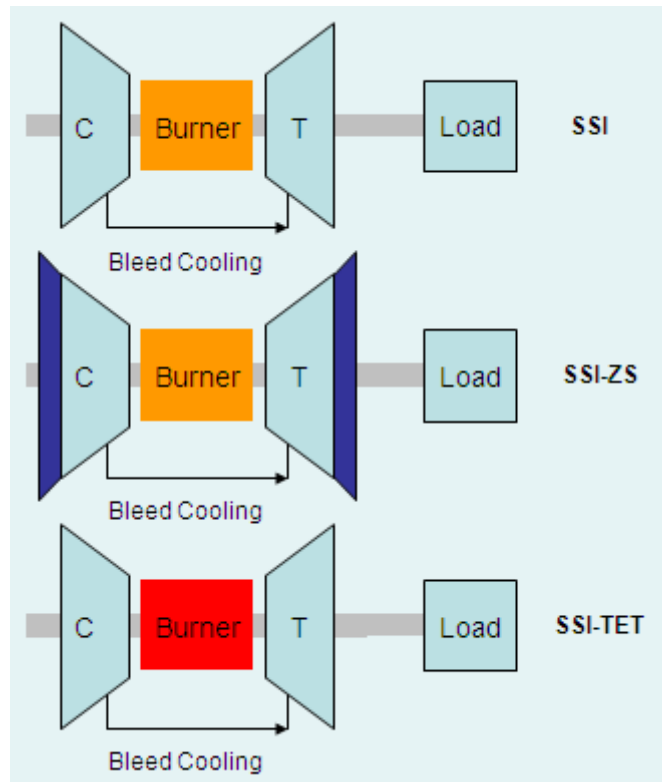
Figure 16: Schematic for a single spool industrial engine

Here, the SSI refers to 'single spool industrial' and this type of engine cycle can represent the GE Frame 7E and Frame 9E machines. The ZS and TET refer to variants which will be

discussed later, which essentially are the same core engine but with modifications with increased firing temperature or a zero staged compressor to boost power output.
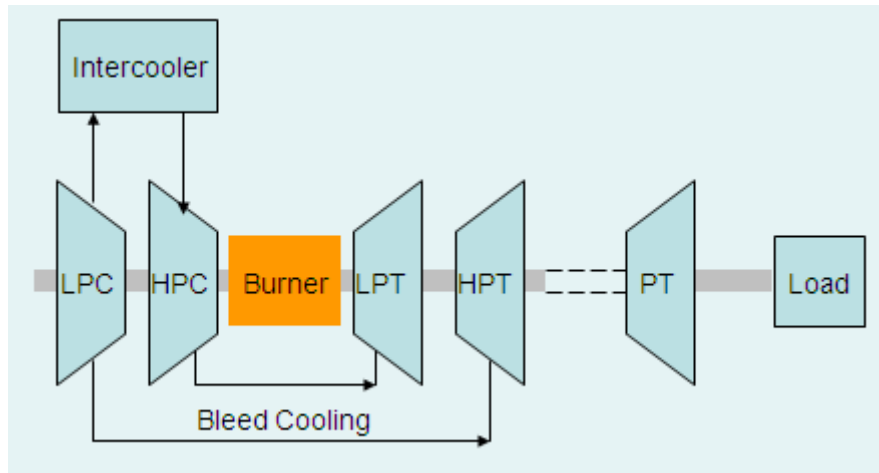
Figure 17: Schematic for the 2 spool, 3 shaft engine with inter-cooling and power turbine

The configuration in Figure 17 can be used to represent the 2 spool, 3 shaft aero-derivative engine with inter-cooling, an example of which is the GE LMS100 machine. The power turbine is linked to the gas generator aerodynamically and this gives benefits in terms of flexibility over shaft speeds and sensitivity to ambient conditions and control aspects of the engine.
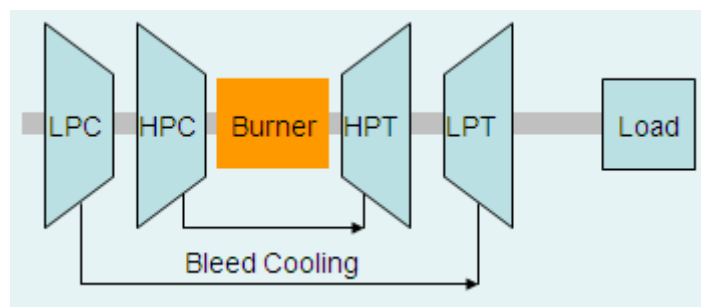
Figure 18: Schematic of a 2 spool, directly loaded gas generator

The engine in Figure 18 could be a representation of the 2 spool GE LM6000 aero-derivative machine which is directly coupled to the load it drives.
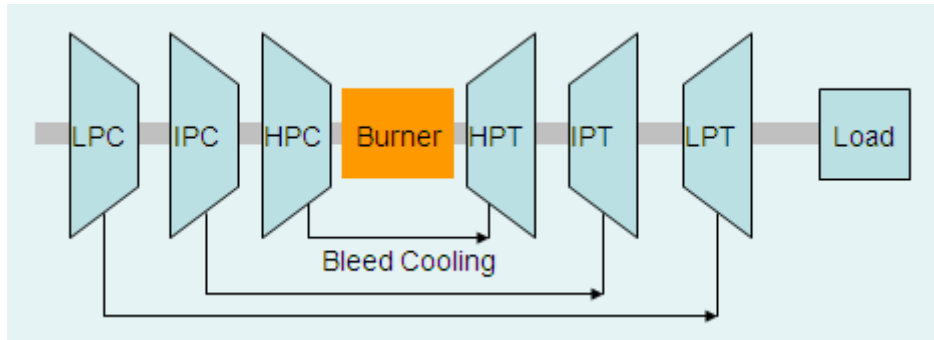
Figure 19 Schematic of a 3 spool, directly loaded gas generator

Finally, the schematic in Figure 19 could represent the Rolls Royce Trent 60 Aero-derivative machine which has 3 spools and is directly coupled to the load.

The detailed performance of the engines is charted in the scenario results section and further performance results including ambient capability, efficiency curves for isolated component and compressor maps can be found in Appendix B: Performance Data & Results.

3. Quantitative Methods for Mapping Variations in Failure of Rotating Equipment

3.1 Introduction

This study uses both parametric and probabilistic lifing and risk analysis to define the failure of hot gas path components in order to better estimate the life of the gas turbines and help create a tool for turbine selection and to aid the operation and performance of selected engines. This chapter looks at the risk analysis, its methodology and development and begins to identify how one might compare technology for the purpose of plant equipment selection.

The practical questions an operator wants to answer are:

'what are the consequences of running a machine to failure?'

'how long can one delay before the next major downtime/overhaul?'

'can one delay fixing a component till the next major overhaul is reached? If so, what level of risk is taken on?'

The idea behind the risk analysis is to create a methodology to analyse the failures of core components. Previously, many lifing studies including Devereux and Singh (2004) and Vittal et al., (2004) have been linked to a financial appraisal or an economics calculator yielding a standalone estimate to predict the life of hot gas path components. For example, if the lifing study dictates that a component fails after x number of hours, then up-time/downtime (revenue pattern) and the maintenance costs will be based on a single estimation. In reality, there can be significant variation in lifetime of seemingly identical components based on the way the engine is operated, and each plant will carry a unique operating signature based on demand for the commodity produced. This in turn is a function of the temperatures, pressures and consequent changes in other thermodynamic parameters generated by the power demand and/or ambient temperature variations. Hence, it is risky to accept conclusions based on a single value for life of a critical hot gas path component when so much variation is possible. This study aims to quantify the variation in failure and use it as a way to denote a certain level

of risk taken on by the operator to run an engine according to a certain philosophy of maintenance and operation.

The present study aims to not only predict the time to failure (TTF) of hot gas path components but also look at the likelihood of achieving a certain value of life for that component. For this reason, a technical risk analysis is conducted which attempts to define a variation of failure for each critical component. This means each component will have a mean value of life and a variation or deviation about that mean. This variation can be described in terms of standard deviations or confidence intervals. The risk exhibited by each component can be aggregated to give the overall risk signature of the engine. This way one can put the financial calculations into perspective by saying how likely or unlikely it is that a certain desired lifetime will be achieved for a component in operation, and thus the reliability with which one can estimate the financial benefits of selecting a particular technology.

The author would like to not only look at the economics based on mean value of failure time, but also explore running the machinery to failure and to be able to quantitatively measure how much risk is taken on and how much more revenue can be generated for given levels of risk.

3.2 What is Risk

The traditional definition of risk is the 'expected loss from failure' (Todinov, 2007). Henley and Kumamoto (1981) give one of the earliest definitions of risk which results in equation 3.1.

$$K_f = p_f C$$
<div align="right">**3.1**</div>

Where K_f is the risk of failure, p_f is the probability of failure and C is the cost associated with that failure. The definition of probability dictates that the probability of failure is a ratio of number of failures to total number of tests. For example, if 10 identical components (N) were tested and 4 failed (N_f) then the probability can be estimated to be $p_f \sim N_f / N$. This gives rise to equation 3.1 where p_f dictates the expectation of loss from failure.

There are two ways of looking at risk within the TERA framework; from technical and financial perspectives. Ultimately, risk will boil down to an economic issue. It will cost a firm if the machinery is off-line and the plant has stopped, and this is related to a technical risk of

the likelihood of the plant shutting down due to failure and the duration of the consequent downtime. Similarly it will cost a firm if the price of fuel rises or fluctuates unexpectedly and there is a risk attached to this also.

What is needed is a way of representing risk in a measurable way. There are various parameters of operation like downtime, availability, reliability, fuel price, and they all have a risk aspect attached to them. One feels the need to measure the risk in a quantitative way and give the risk a numerical value for comparison purposes.

3.3 Typical Methods for Risk Analysis in Rotating Machines

Cruse et al (1997) have detailed how before the advent of computational methods such as FEA and CFD the life estimations of engines were under estimated, such that disks failed before their expected lifetime. Safe life estimations are used by major companies such as Rolls Royce and GE in engine design and at least as far as aircraft engines are concerned, there are set targets for when an engine may be retired based on calculations of safety with respect to size of crack and number of cycles in operation (Kappas, 2002). AGARD discussed the use of Damage Tolerance techniques back in 1985 to reduce the costs of maintenance and operation of engines as opposed to using safe life approach and estimated that 80% of disks were retired before the critical low cycle fatigue count was reached, hence a gross underutilisation of the technology. Many have challenged the authenticity of manufacturer life predictions and raised concerns (Mahorter et al., 1985). Further, Singpurwalla (1988) suggested that OEM's want to sell more components and keep their safety limits in check so as to keep a good record. OEM's are typically using analytical methods which are 50 % conservative compared to the reality of the life of components.

Further, there is little in the way of access to the OEM databases for materials which have been used on the engines, especially exotic materials used in the combustors, and turbine rotors. Indeed, the Sioux City disaster was based on the material anomalies which led to failure and this is not accounted for in typical lifing methods.

It is also understood widely that engines today are exceeding their typical life estimations and are used more often in their critical lifetime phase in the wear out phase of the life cycle. This makes the case ever stronger for detailed lifing analysis coupled with an understanding of the risks involved of operating in the critical phase.

3.3.1 Probabilistic Methods

Probabilistic crack growth and crack propagation are methods which can be utilised to look at the failure of components. These methods are based on either acquiring data from a database of failures that have already occurred or from analytical lifing methods. For the newer engine, such data may well not exist or be very difficult to obtain.

Moore et al. (1990) have described deterministic methods based on deterministic failure modes as inaccurate in the most part either because they were based on conditions of operation which were not fully representative of the real operation or because of lack of data, especially materials data, or safety factors applied. Finally, the sometimes very complicated modes of failure which are interdependent and interlinked make it hard to denote which mode of failure actually led to the final failure. For example, one could observe failure of the turbine blade material which was initiated due to a crack on the coating, hence it will be the coating which is the primary cause and the turbine blade material is secondary, but this is not always identified when using a data base of failures of a record of the engine health, hence the wrong reasons for failure may be assumed.

3.3.2 Probabilistic Fracture Mechanics

Amongst the probabilistic methods the most common is Probabilistic Fracture Mechanics (PFM) which looks at the growth of a crack from initial size to a critical size. It must be noted that the initial size is denoted beforehand, however, if the models of PFM are coupled with stochastic methods, such as a Monte Carlo simulation, one can also investigate crack initiation life. Initiation is a preliminary phase where most of the uncertainty comes in (Yang et al 1983, Graham and Mallinson, 1984).

The crack growth models are mostly based on empirical relationships which use the Paris law in conjunction with stochastic methods to create a calculator of the uncertainty. It must also be noted that almost all such studies are for fatigue failures. Walz and Riesch-Oppermann (2005) describe well the theory and application of the Paris law based crack propagation methods in the context of turbine disks. They also apply this modelling to a stochastic process as is more common with crack propagation models versus parametric models. Critically, they conclude that the process is very sensitive to data that is available and any modelling will fluctuate drastically in its conclusions based on this data. They emphasise the accuracy of the results must be verified.

3.3.3   Stochastic Treatment of Probabilistic Methods

Stochastic crack growth models can help analyse failure for particular modes and be validated against particular experimental results but are not usually very flexible and adaptable when used for predictive methods. The reason is because the simulation is optimised for a given set of parameters and validated against existing data, but does not work well when analysing the failure of an engine or a component which does not have substantial corresponding data. However, there are programs such as DARWIN (Design Assessment of Reliability With Inspection - developed by Southwest Research Institute) which is an analytical damage tolerance tool developed in collaboration with Rolls-Royce, General Electric and Pratt & Whitney. It was initially started by the FAA after the Sioux City disaster. The tool uses FEA and material anomalies such as hard alpha defects on titanium alloy materials and looks mainly at fatigue based failure modes for different operations of gas turbines. Essentially it calculates stress and thermal components of the lifing calculation and applies a stochastic technique to this set-up which includes stress and life scatter factors (Millwater and Wu, 1992).

3.4 Inherent Variation in Material Failure

Lust and Wu (1998) explain the failure of some phenomena such as creep and fatigue to be non-deterministic since it rises from anomalies in the materials and geometric tolerance. Thus, a risk treatment is needed to map variation in failure. The aim is to map the inherent variation in failure for the first stage blade material, the thermal barrier coating applied to the blades, as well as looking at the failure signature of the combustor liner. These components were deemed important by the sponsor company and attention was focused here.

What is meant by inherent failure is failure owing to the manufacturing process/defects and granular structure of the material being analysed. Though identical, no two blades will fail at the same time under operating conditions or in laboratory test conditions. This tells us something important about failure characteristics; that even if thermal and stress conditions are the same to an acceptable degree of accuracy, seemingly identical components will fail at different points in time.

Moreover, the failure is due to the manufactured structure and defects of the specimen under test and not testing conditions. It is the failure due to inherent material variation that one needs to map, since the changes in operating conditions will be captured by the lifing analysis

anyhow, but the different in manufacturing defects and/or differences cannot be accounted for by a straightforward lifing analysis, regardless of whether it uses simple hand calculations or detailed CFD and FEA. Regardless of the methodology used to conduct the lifing, the user needs to build in the variation of the material to the model. As far as simulation is concerned, this requires some statistical handling.

Additionally, it must be noted that the variation due to test house set up and apparatus, as well as measuring devices and equipment like temperature and pressure gauges needs to be accounted for as this is NOT inherent material variation and can lead to over estimations.

3.5 Assessing Technical Risk - The TRL Scale

Traditionally, many methods have incorporated the NASA Technology Readiness Level (TRL) scale to measure levels of risk but the scale on its own is not very useful. It is a very subjective and does not take into account the underlying nature of the risks attached to technology.

It must be noted however that the TRL scale was established by NASA to introduce new technologies in order to assess the technology development. In the case of the current project, new technology is not being developed but rather existing technology is being selected. For this reason it was felt that the NASA scale I not entirely appropriate for the means of selection of technology. It was envisaged that a pseudo-scale would be created to look at risks of selecting technology and this scale would be coined Technology Comparison Level (TCL) and would be composed of newly defined levels based the risk involved in using a certain technology. The risk would be a measure of the technical risk of failure of a given type of machine in a certain operating environment and given particular modes of failure. This research justifies the basis for creating such a scaling system by looking at failure distributions using the Weibull based analysis which allows for the quantitative description of variation in failure of technology.

Roth (2004) talks of the K-σ model which models technology benefit by scaling it against the TRL scale. It uses the K-factor linked to the technology benefit and gives probability distributions of each technology. The idea is that TRL 9 is the point where technology benefit is known precisely, and consequent lower levels have lower degrees of confidence of technology benefit. Thus lower TRL levels are represented by probability distributions since

their technology benefit is not precise, and there exists a range in which they may lie. The greater this range, the wider the distribution. This provides a basic starting point and also dictates that any model proposed be specialised for the purpose and be able to identify with the technology.

3.6 Probability Distributions

The modelling in this project aims to capture the uncertainty of failure and develops a system which will look at the failure in a stochastic way as this was deemed the best way to capture the uncertainty. Since the modelling will require a statistical treatment, it is then important to understand that trends of failure can be mapped by distributions where the likelihood of failure (probability) is charted against the time to failure (occurrence). Such a picture will tell the operator what the most likely time for failure would be given a certain operational philosophy as well as what the chances are of getting a failure slightly below or above that mean time.

A probability distribution can take two basic forms; it can either be a probability density function (PDF) or a cumulative density function (CDF). In each case the probability of occurrence of an event is charted against the event of occurrence. In the case of the PDF, the individual value of the probability is charted versus the event whilst in the case of the CDF, the accumulated probability up to that point is charted against the event.

To model risk for turbomachinery components failure data sets are required in order to create probability distributions for each component. The failure data can be processed to form a failure distribution of probability versus time to failure. The data can be derived from operational data in the field where the engines are working or from test house data for materials testing of the components used in the machine. The following section looks at some of the distributions one can use to analyse failure data. All these distributions are being reviewed with respect to failures with turbomachinery.

3.6.1   The Normal or Gaussian distribution

This is the most common distribution in statistics. The life cycles of many components will follow this distribution. The characteristic is defined by two parameters; the mean and the variance. The variance is the standard deviation squared. The curves on this distribution are also known as bell curves, characteristic of the probability density function.

3.6.2 The Log-Normal distribution

A variable function can follow the log normal distribution if its occurrence is a summation of smaller events that lead to this greater end result. For example, the long term stock investment returns are dependent on smaller period daily returns. By definition this distribution is one where the logarithm of the random variable is normally distributed.

3.6.3 The Exponential distribution

Experimental data and results have shown that new technology follows this distribution. It follows the events of natural occurrence. Teething problems with newly introduced technology follow this trend and it shows how with time, new technology will slowly stabilise and become established to give lesser and lesser faults.

3.6.4 The Weibull distribution

This distribution is one which mimics the effects of many other distributions and is therefore known widely for its flexibility. It also has two parameters; the shape parameter beta (β) and scale factor eta (η).

When the shape parameter $\beta < 1$ then failure rate decreases with time, also known as infant mortality stage. If $\beta > 1$ then failure rate increases with respect to time mimicking the normal distribution at $\beta = 3.5$, the log-normal distribution at $\beta = 2.5$ and the Rayleigh distribution at $\beta = 2$. It follows that $\beta = 1$ is denoting a constant hazard rate with respect to time, and with random failures and so here the Weibull is mimicking the exponential distribution.
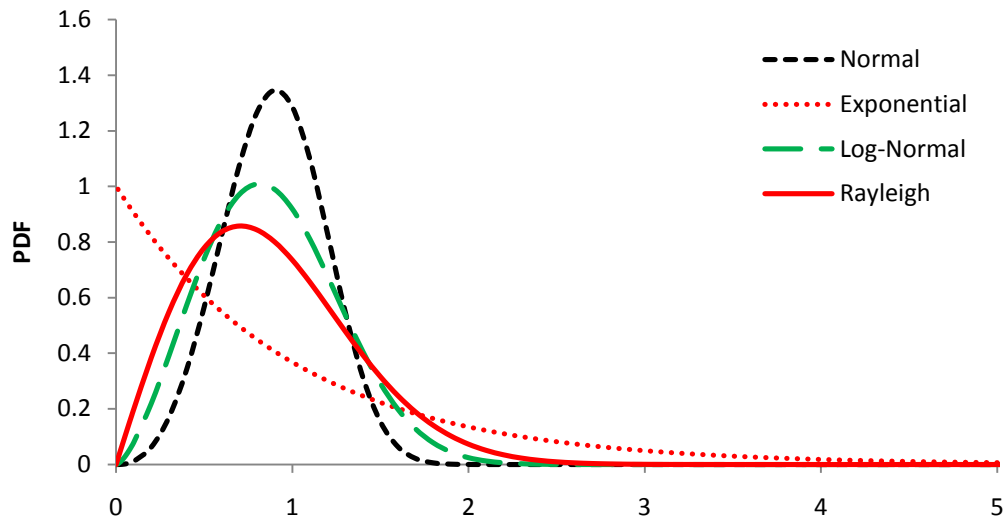
Figure 20: Many common distributions can be mimicked by the Weibull

The graph in Figure 20 shows common distributions being mimicked by the Weibull distribution based on variations in the β parameter. The vertical axis represents some frequency of occurrence and the horizontal axis represents the event of occurrence. For machinery failure analysis, the horizontal axis will represent time to failure as will be seen later.

The figure shows the strength of the Weibull due to its flexibility it can be used to represent different distributions which in turn represent different stages of the life cycle of a mechanical component or system. The importance of this will become clear in the following sections.

Further, changing the β and η parameters yields that the shape of the curve can be further affected in such as way to show increased or decreased variation, as can be seen in Figure 21. Again, the vertical axis represents frequency of occurrence whilst the horizontal represents the event of occurrence itself.
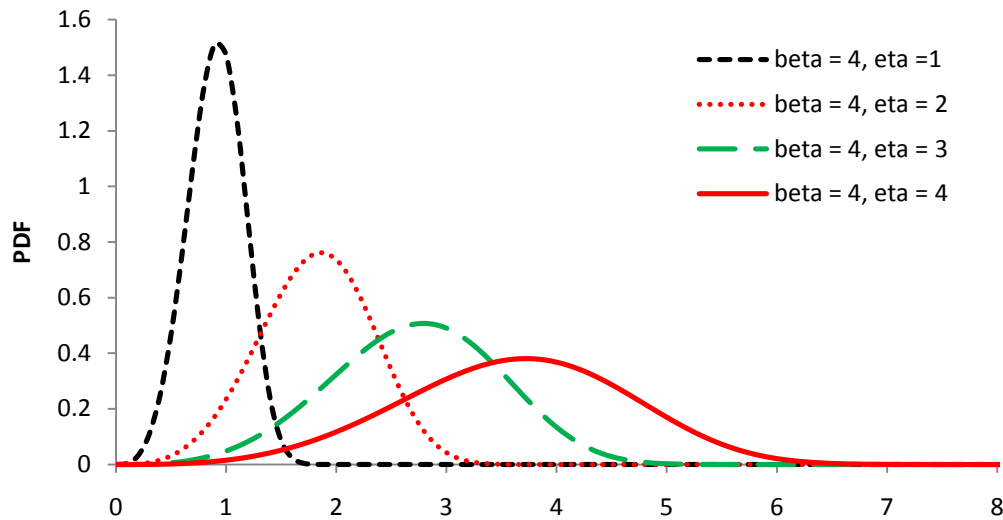
Figure 21: Variation in the Weibull based on changes in the life parameter

In this example, η, the scale parameter, also known as the life parameter is being varied. One can see that the changes cause either a narrowing or a broadening of the distribution. It must be noted that the area under the curve represents the total possibility of occurrence; so all the measured outcomes will be represented by the area under the curve and this will equate to unity. So broadening or flattening the curve means that certain occurrences are more or less likely to happen. This is useful because it can help us denote likely times of failure and assign a probability to a particular value of occurrence. This in turn is linked to risk because a broad distribution means more variation in occurrence and a sharp distribution means concentrated or low variation in occurrence.

Weibull statistics have been adopted to look at the variation of life for components. The Weibull has specifically been selected for the reliability analysis owing to its recognition for flexibility to imitate the various stages of rotating equipment life cycle and also because the literature survey proved its widespread and successful application with Turbomachinery failure analysis (Vittal and Phillips, 2007 and Bloch, 1998). The Weibull has long been established as a useful statistical distribution for quantifying the failure of rotating machinery.

Critically, the Weibull can be a two-parameter or three-parameter distribution. Apart from the scale or life parameter (eta) and the shape parameter (beta), there is also the location parameter (alpha), used when failures do not begin at time $t = 0$, indicating an initial failure free zone (Abernathy, 2000).

44

In a Weibull analysis, the shape of the distribution allows us to map the nature of failure, thus the parameters control the shape of the distribution and the change in parameters can help us measure the change in failure likelihood. A sharp distribution means less variation and the event of failure is more likely to take place in a narrow time span. On the other hand a broad or flat distribution means more variation and less certainty as to when failure will occur.

The probability density function (PDF) of the two parameter Weibull distribution is:

$$f(t; \eta, \beta) = \frac{\beta}{\eta} \left(\frac{t}{\eta} \right)^{\beta-1} e^{-\left(\frac{t}{\eta} \right)^{\beta}}, t \geq 0 \qquad \textbf{3.2}$$

where t is time, β is the shape parameter and η is the scale or life parameter.

The Cumulative Distribution Function (CDF) is given as:

$$F(t) = 1 - e^{-\left(\frac{t}{\eta} \right)^{\beta}} \qquad \textbf{3.3}$$

and the Reliability is given as:

$$R(t) = e^{-\left(\frac{t}{\eta} \right)^{\beta}} = e^{-\left(\frac{t}{MTBF} \right)} \qquad \textbf{3.4}$$

Thus:

$$R(t) = 1 - F(t) \qquad \textbf{3.5}$$

3.6.5   The Bath Tub Curve

In order to link the different stages of the life on the engine or component the Weibull distribution can be utilised. At different stages of the life cycle, the estimation of the likelihood of failure follows a particular distribution. The introduction of new technology will follow the Exponential distribution as experimental results show, with a Weibull shape parameter of beta<1. This is known as teething. Then, the basic life cycles of the majority of

normal operation of established technology will follow the Normal or Gaussian distribution. This leads us to the well known bath tub curve which shows the characteristic trend of failure
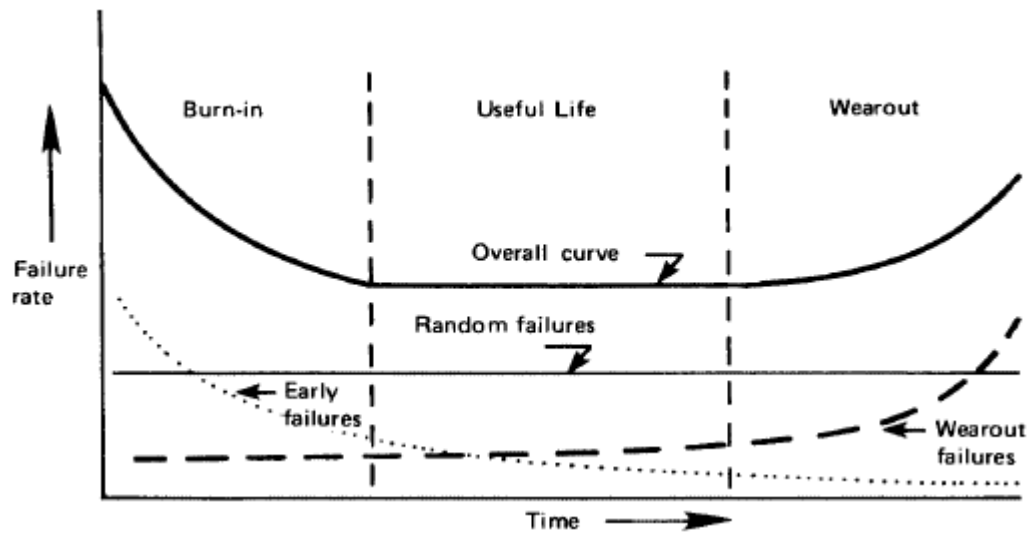
Figure 22: The Bathtub curve (Smith, 2001)

3.7 MTBF and MTTR

Two key parameters of engine reliability are time to repair (TTR) and time to failure (TTF) with different failure characteristics. Consequently, probability distributions of Mean Time Between Failure (MTBF) and Mean Time to Repair (MTTR) can be generated by using Monte Carlo simulations. The life of a machine or component can be summarised by a series of alternations between MTBF and MTTR, with each simulation giving a unique pattern of MTBF and MTTR, also known simply as downtime and uptime (Figure 23).
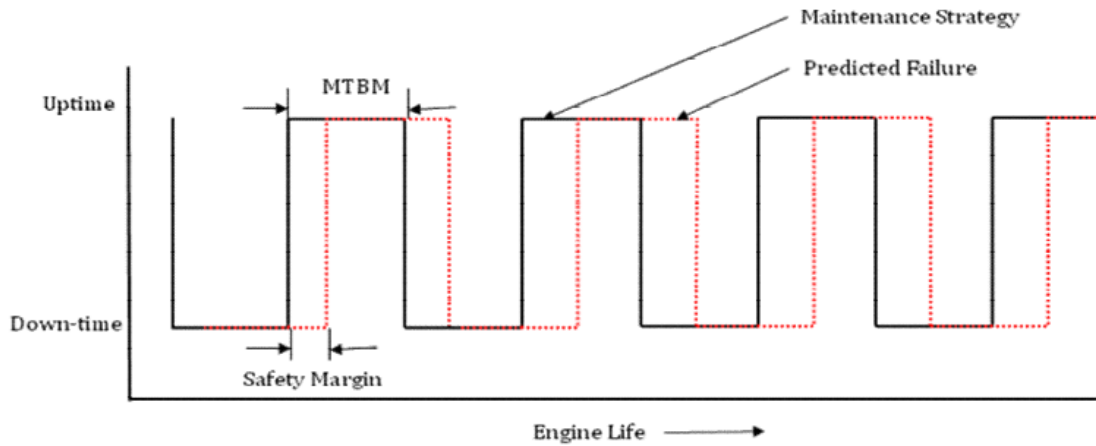
Figure 23: The oscillation between uptime and downtime where maintenance strategy precedes the predicted failure by a certain safety margin (Ekanem, 2009)

This can prove useful if one wants to assess technical risk in terms of downtime. Downtime is the time period for which the technology is off-line and therefore costing the firm in terms of lost production. Availability is another key issue because downtime depends both on the time required to replace a component and the availability of that component. So the difference between a running and an off-line plant depends both on propensity for downtime and component availability.

Reliability of a technology tells us how likely it is to fail. Singh (2007) describes reliability as dependent upon design, manufacture and operating environment. This reliability can be measured in terms of MTBF. Availability on the other hand is a function of both reliability and downtime. Therefore:

Reliability = f (design, manufacture, conditions) - a function of MTBF as per equation 3.4

Availability = f (reliability and downtime)   - a function of MTTR.

The requirement is for highly reliable machines with low downtimes. Thus if a model was created which measured MTBF and MTTR then one would be assessing both reliability and availability. It should also be noted that components like compressors and turbines have high reliability but relatively long downtimes when failure does occur whereas smaller components like control and fuel systems have low reliability but relatively short downtimes associated

47

with their failure (Singh, 2001).   Figure 24 shows the relationship between availability, downtime and MTBF.
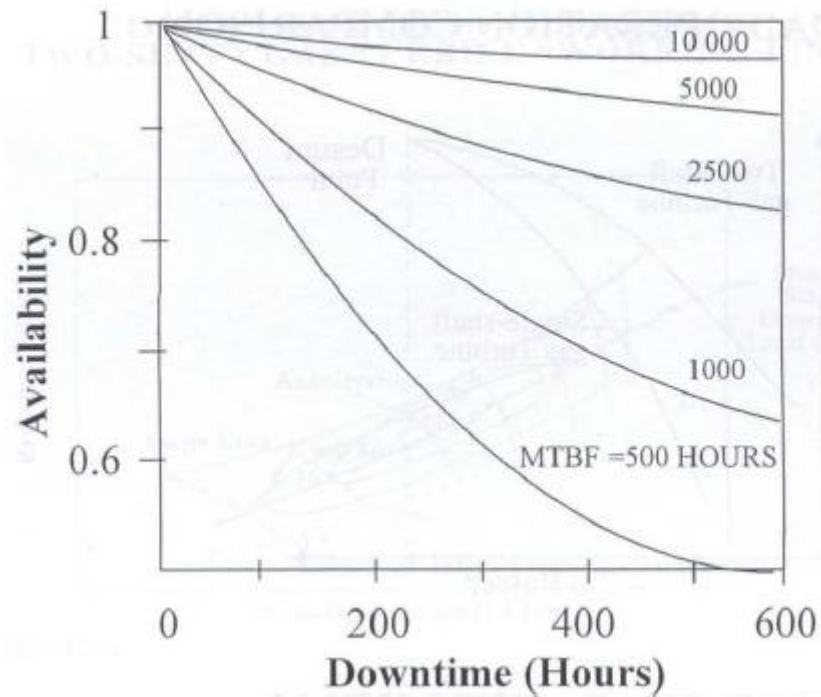
Figure 24: A graphical relationship between Availability, Downtime and MTBF (Singh, 2007)

3.8 Modelling the Risk Analysis – Methodology

The risk module forms part of the LNG TERA. The risk analysis takes into account the unscheduled downtime as well as scheduled downtime. Most importantly, the risk is representative of the performance in that there is a trade of information (thermodynamic parameters such as temperatures and pressures, mass flow etc) which is generated by the performance code for each operating condition and is then passed onto the lifing and in turn to the risk analysis module. The aim was always to change the life and failure trend of components based on how the engine is operated and what thermodynamic conditions were created in the core of the engine. The outline of the modelling can be seen in Figure 25.
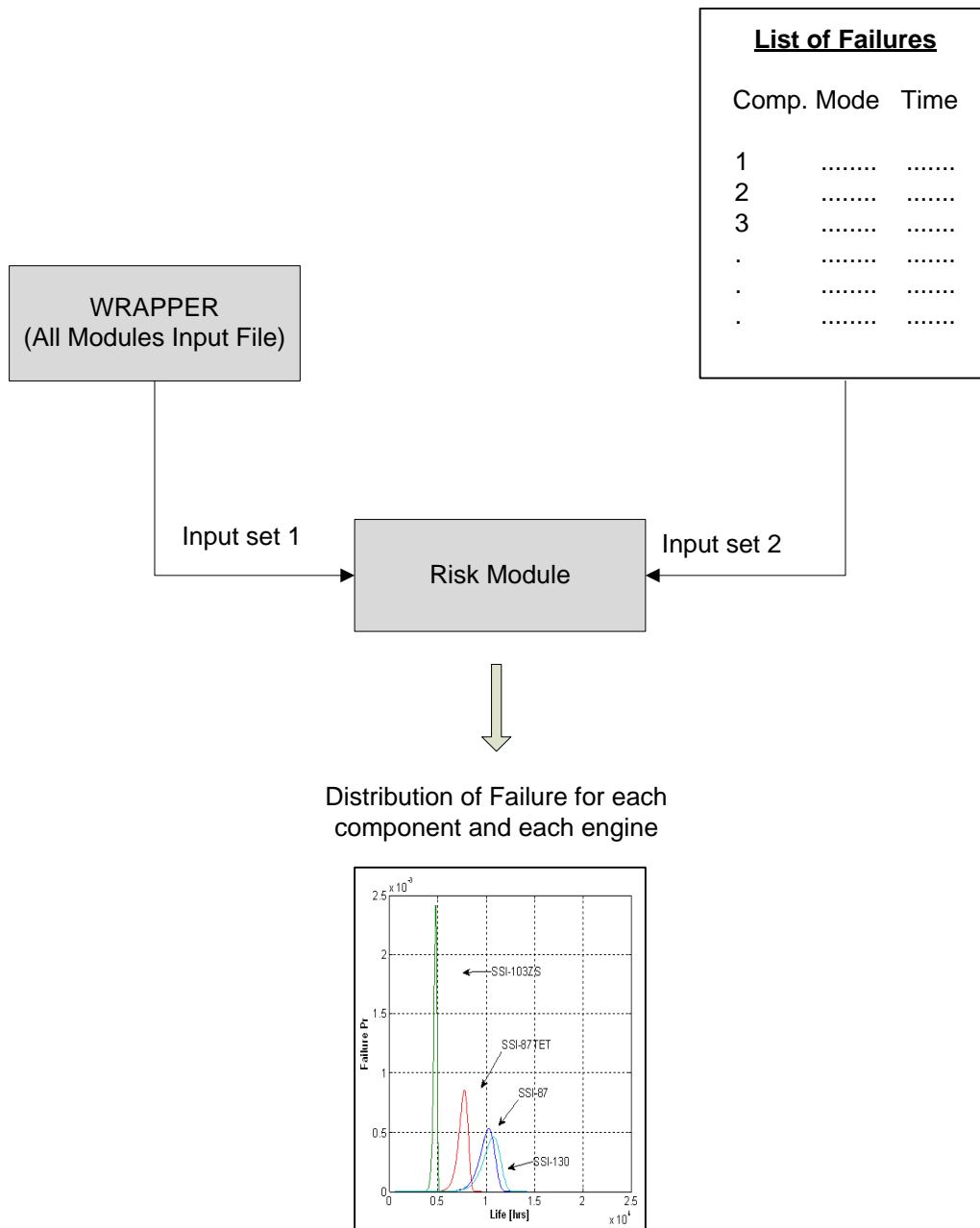
Figure 25: A Diagram showing the isolated risk module

The wrapper contains an input section for the risk module which includes all the user defined inputs. This is denoted as input set 1 in Figure 25. Input set 2 is the automatically generated input from the lifing module. The lifing module will be explained in details in the next chapter, here it will suffice to say that the lifing produces a list of failures based on operating conditions and calculates the aggregated life based on thermodynamic conditions created within the engine.

<u>Input Set 1: (User defined)</u>

1. Switch to define if risk analysis is to be conducted or not
2. Number of Monte Carlo runs (default 10 000)
3. Default Weibull parameters[1]

<u>Input Set 2: (Informed by Lifing Module Results)</u>

1. Mean life of component
2. Stresses and temperatures for component
3. Multiple Creep curves

There are numerous subroutines in the Risk code which are summarised in Burgmann (2010) and the key routine schematics are summarised in Appendix C5.

The modelling of the risk analysis slowly evolved to get to this final stage. The previous two attempts were not fully representative of the performance in that the initial attempt was a risk analysis based purely on public domain data (Bloch, 1998) for failure variation, and the second attempt was based on scaling of public domain data. The final version of the risk uses the parametric lifing module to set a mean life for the component and the distribution is dressed around this mean according to data based on particular material variability.

3.8.1 Weibull Input

The risk analysis module is composed of a number of subroutines which take information from lifing about the failures of components and turn it into distributions of failure. This is done by giving all the components in the engine values for the beta and eta parameters, otherwise known as the Weibull parameters. These values of eta and beta are a function of the lifing module and the models for failure built therein, hence the variation of failure of each

---

[1] If not defined by lifing, in the case that a lifing analysis is not conducted, the risk can be run based on user defined parameters alone

component can be mapped on a probability density function. However, it must be noted that not all the components are lifed using the lifing module, so some components have been given generic Weibull parameters based on field data accessed in the public domain (Bloch, 1998). The list of parameter values are given in Table 2.

Table 2: A Table showing typical predefined values for Weibull parameters (Bloch, 1998)

Component	η	β
HPT	125000	1.6
Combustor	80000	1.5
HPC	250000	2.5
Control Valves	100000	1
Temperature Indicators	222000	1
Pressure Indicators	125000	1.2
Flow Instruments	125000	1

Further, the simulation of risk works in such a manner that the user of the LNG TERA tool does not have to life any components if need be. If no data is available for the engine in terms of materials and sizes of components then all the arbitrary values listed in Table 2 will be used and the risk analysis will be done by scaling the Weibull parameters. This is an undesirable situation but has been incorporate into the code just in case. For the scenarios conducted in this thesis, the component specific data was either available or educated estimates were made and then verified. It is more important however, to focus on the method as opposed to the exact values of the component specific data, since this thesis is exemplifying the use of the methods for risk analysis.

Based on the generic values of beta and eta, curves for the PDF of each component can be generated. It is based on these curves that the final failure distribution of the component and hence engine will be built. However, as mentioned before, these curves are used to create a picture of the entire engine and where possible, the eta and beta parameters are generated from the lifing of the components.

3.8.2 The Gamma Function

As mentioned before, the Weibull can also be used as a 3 parameter distribution and has another parameter which shifts the curve entirely on the x-axis. This thesis will only use the 2 parameter version, however, the Weibull, unlike the normal distribution, works with the eta and beta parameters. These parameters are less tangible in the sense that one may be used to the idea of a mean and a variance or standard deviation as found with the normal distribution. For the user to be able to get a mean value of failure and also a variation around that failure, it is possible to turn the Weibull parameters into more tangible parameters in the form of mean and variance. This translation is mapped by the gamma function.

The gamma function is defined by equation 3.6

$$\Gamma(n) = (n-1)!$$

3.6

It is a continuation of the factorial function and can be written as:

$$\Gamma(n) = \int_0^\infty e^{-x} x^{n-1} dx$$

3.7

The mean time between failure and standard deviation for the Weibull distribution can be then derived as a function of the gamma function as per the following:

$$\delta_x = \eta \left(\Gamma\left(\frac{2}{\beta}+1\right) - \Gamma^2\left(\frac{1}{\beta}+1\right) \right)^{\frac{1}{2}}$$

3.8

$$MTBF = \eta . \Gamma\left(\frac{1}{\beta}+1\right)$$

3.9

Here, the δ is the deviation or the variation from the mean and the MTBF is the mean and both calculations are now simply functions of η, β and the Gamma function.

Hence, it is important to build in the gamma function so as to be able to convert the beta and eta parameters of a given Weibull distribution into mean and variance. The mean is simply the MTBF which forms part of the failure schedule and the variance gives the operator the understanding of the variation about that mean. To understand variation simply from the Weibull plot is difficult since the Weibull parameters shift the shape of the curve in unexpected ways and have a combined effect on the final shape. Further, one can work backwards from the variation and mean to denote the eta and beta parameters; this is precisely how the LNG TERA risk analysis works. However, further statistical treatment is required in order to find the mean and variance.

3.8.3 Deriving α and β

There are various methods to work out the Weibull parameters from sample data which include Weibull probability plotting using median ranks and rank regression in Y which utilises the method of least squares. Again, another possibility is to use rank regression in X which looks at the method of least squares in the horizontal differences between an average line drawn through the data and the data points themselves. The three parameter Weibull can be used where the data do not seem to fit a straight line as per the previous methods; this would denote that the data contains a number of samples as opposed to one sample. Finally, the method of maximum likelihood can also be employed and this calculates, for a given distribution curve, the best values of the estimated parameters using an iterative procedure. Vittal and Phillips (2007) go exhaustively go through the various techniques available to find α and β and utilise the maximum likelihood estimates (MLE) using various forms of the Newton-Raphson iterative techniques. It can be said, based on literature that MLE techniques are the most robust method from all that are typically used. For the purposes of this research, the rank regression in Y is utilised because it is easiest to compute and because the data utilised is not from multiple samples.

3.8.3.1 Graphical Methods

Typically, a collection of field data which shows failure times for a given component can be used to estimate the Weibull parameters. This is a well known method and is charted extensively in literature. The method has been extensively published by Barringer (2005) and Abernathy (2000) and much online material by Barringer Associates Ltd with many online tools allowing one to create basic Weibull analyses. A full example of the method has been charted by Zaretsky et al. (2008) where they chart the methods for predicting the life of turbine blades from a commercial aircraft turbine. The research was conducted at the NASA

Glen Research Centre. These methods focus on the provision of field data which is of course processed to create Weibull failure curves. The comprehensive study also brings in oxidation and corrosion as well as creep and fatigue interactions.

In previous section, the derivation for the cumulative Weibull function was presented. Taking equation 3.3 through some simple logarithmic manipulation gives:

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$

$$e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - F(t)$$

$$\ln e^{-\left(\frac{t}{\eta}\right)^{\beta}} = \ln(1 - F(t))$$

$$-\left(\frac{t}{\eta}\right)^{\beta} = \ln(1 - F(t))$$

$$\ln\left(\frac{t}{\eta}\right)^{\beta} = \ln\left(\ln\frac{1}{1 - F(t)}\right)$$

$$\beta \ln\left(\frac{t}{\eta}\right) = \ln \ln \frac{1}{S}$$

$$\beta \ln t - \beta \ln \eta = \ln \ln \frac{1}{S}$$

Where S is survivability and is equal to $1 - F(t)$

So finally, the equation can be written in the useful form:

$$\ln \ln \frac{1}{S} = \beta \ln t - \beta \ln \eta \qquad\qquad \textbf{3.10}$$

Can be likened to the equation of a straight line:

$$y = mx + c$$

Where

$$y = \ln \ln \frac{1}{S}$$
$$m = \beta$$
$$x = \ln t$$
$$c = -\beta \ln \eta$$

Thus if one was to gather field data for failure of a particular component and plotting $\ln \ln \frac{1}{S}$ versus $\ln t$ will yield a curve such that the gradient would be the Weibull parameter beta and the cross at the y-axis would be a function of both eta and beta, thereby yielding both the parameters (Abernathy, 2000). In this way, utilising Monte Carlo in a stochastic manner as an input for time t, one can evaluate the reliability of a component and aggregate to find reliability of the entire system. An example plot for a turbine component can be seen in Figure 26.
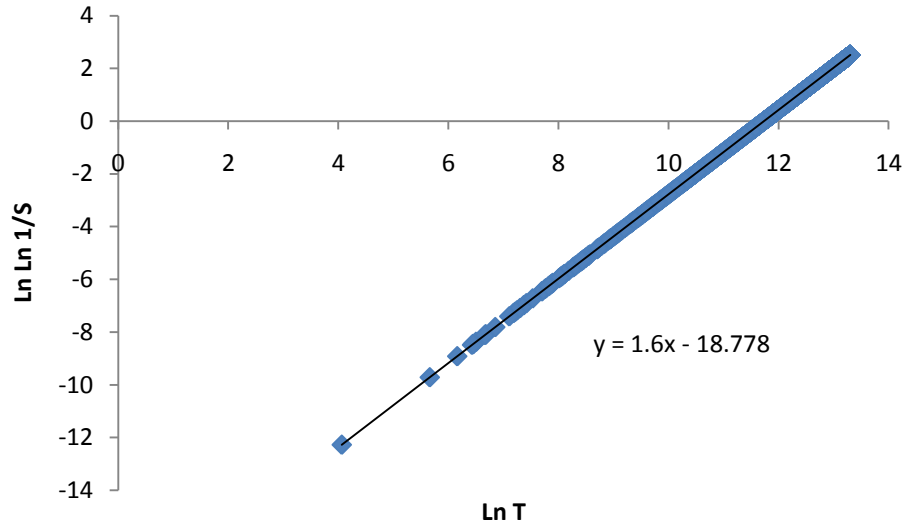
Figure 26: Example of (ln ln 1/S) versus (ln t) plot for a turbine. The beta value is 1.6 and the eta value is circa 125000 hours.

3.8.3.2 The Rank Regression in Y

The task however is to reverse the process and go from knowing the mean time to failure and standard deviation of a component to finding the Weibull parameters using equations 3.8 and 3.9. The method of doing this requires one to know the mean time to failure. This is precisely the value that the lifing models calculate. This leaves us with denoting what is the standard deviation. This standard deviation is derived from the material variations as discussed in the section on inherent variations of materials and will also be further discussed in the lifing chapter.

It has been shown that plotting the logarithmic function of survivability against the $\ln t$ will yield a straight line with equation $y = mx + c$. Whilst this maps a continuous distribution, one must now look at the discrete values of m and c and this is done by looking at what is called the median ranks method which evaluates the cumulative probability of failure of the sample population at the 50% confidence level. This can be denoted as in equation 3.11.

$$\sum_{k=i}^{N} \binom{N}{k} (MR)^k (1-MR)^{N-k} = 0.5 \qquad \textbf{3.11}$$

Where N is the total number of sample and i is a particular sample where all samples have been ranked accordingly. This can be further reduced to Bernard's approximation as seen in equation 3.12.

$$MR \sim \frac{i - 0.3}{N + 0.4}$$

Comparing equation 3.10 to the equation of a straight line:

$$y = \ln(-\ln(1 - F(t)))$$

Here, using the idea of median ranks, equation 3.13 can be rewritten as:

$$y_i = \ln(-\ln(1 - MR_i))$$

The rank regression in Y requires the least squares method to be applied, thus:

$$\hat{m} = \frac{\sum\limits_{i}^{N} t_i y_i - \frac{\sum\limits_{i}^{N} t_i \sum\limits_{i}^{N} y_i}{N}}{\sum\limits_{i}^{N} t_i^2 - \frac{\left(\sum\limits_{i}^{N} t_i\right)^2}{N}}$$

$$\hat{c} = \frac{\sum\limits_{i}^{N} y_i}{N} - \hat{m} \frac{\sum\limits_{i}^{N} t_i}{N}$$

Now, using equations 3.15and 3.16 it is trivial to compute the values for β and η.

3.9 Requirement for a Lifing Model

It has been established that in order to conduct a technical risk analysis the distribution of failure needs to be mapped out. Further, it is also shown that a Weibull based statistical analysis can help deduce the distribution of failure for turbomachinery. The statistics dictate that a mean value of life, as well as the variation around that mean need to be acquired in order to build the distributions. For this reason, a lifing analysis is required in order to find the mean and variations in life of the critical components in the engine. Further it is important that statistics can be incorporated into the model so as to be able to use stochastic techniques to generate simulations of the life of components which makes the failure trends more realistic. Monte Carlo based simulations are used to generate random numbers and incorporate a stochastic methodology for generating times to failure. These simulations can then be assimilated to produce a distribution of failure values for every component.

4. Lifing of Hot Gas Path Components

4.1 Introduction

Following on from the risk analysis, it has been established that key hot gas path components need to be analysed for predictions of life-time in order to analyse the uncertainty in their failure. This chapter describes the typical modes of failure affecting the hot gas path components and the models available to calculate estimates for life of components. Further, it details which models were selected and why and shows the method in terms of the LNG TERA tool. The chapter describes the models used to conduct the lifing for the turbine blades, turbine coating and combustor liner material.

4.2 Modes of Failure: Creep and Fatigue Considerations

According to Balevic et al., (2004) *'creep, oxidation and corrosion are the dominant limiters of life for continuous duty machines.'* A summary of the typical modes of failure experienced in different components along the gas turbine are summarised in Table 3 (Dibbert, 2006). The table provides a good overview, however it is another question as to what modes of failure affect which type of operation. By operation it is meant application, such as aircraft or power generation. Different duties will mean different operating philosophies and hence specific or a mixture of modes of failure will be experienced for that particular application.

Further, Table 4 summarises the likely modes of failure in different applications. This thesis is interested in looking at the land based applications where gas turbines are used for mechanical drive.

Table 3: Summary of which modes of failure affect which components in the gas turbine (Dibbert, 2006)

	Design Criteria and Life Expenditure						
	Time dependent Effects				Cycle dependent Effects		
	Yield strength, stiffness	Oxidation, corrosion, erosion	Wet corrosion	Creep	LCF	HCF	Crack propagation
Turbine blading	X	✓	X	✓	✓	✓	X
Compressor blading	✓	X	✓	X	✓	✓	X
Inner Casing, mixing chamber, exhaust liner	X	✓	X	✓	✓	●	X
Rotor Parts (excluding blades)	✓	X	X	X	✓	X	✓
Pressure Tight Casing	✓	X	X	X	✓	X	X
Piping	✓	X	●	X	✓	✓	X

Key: Significant contribution   (✓)
       Affects only locally   (●)
       Irrelevant   (X)

Table 4: Summary of predominant modes of failure for different applications (Sourmail, 2003)

	Oxidation	Hot Corrosion	Inter-diffusion	Fatigue
Aircraft Engines	Severe	Moderate	Severe	Severe
Land based/ Power generation	Moderate	Severe	Moderate	Light
Marine	Moderate	Severe	Light	Moderate

Due to the nature of operating conditions and the components which were deemed critical based on theory and experience of the operator, the main mode of failure was established as being failure under creep for the turbine blades. Additionally, the coating of the blades was considered and this is modelled using a probabilistic pit formation model based on the critical thickness of the coating.

For an Oil and gas company, maintenance and shut down are not critical until they occur without notice, in other words, planned maintenance is acceptable so long as plan B can be

executed and production is not affected too much. In this way, one would want to be selecting machinery which will not cause a huge variation in failure and thus will be hard to predict when the maintenance actions will be required.

The Creep, as opposed to fatigue and other modes of failure, will exhibit a different trend of failure, since creep tends to produce sharp and defined point of failure whereas fatigue is a less certain phenomenon. Previously, probabilistic methods have been used for fatigue analysis using SNP curves by Golden et al., (2009) and Vittal et al., (2004), as well as statistical failure linked to creep by Corran and Williams (2007), Enright et al., (2003) and Wu et al., (2002). This study adopts a novel approach which is explained in the next section.

4.3 Crack Propagation

Probabilistic fracture mechanics was mentioned earlier as a possibility for lifing and then conducting risk analysis for turbomachinery components. The Paris law can be used to look at the growth of a crack from an initial size to a critical size. As mentioned in the previous chapter, much research has shown that probabilistic crack growth models offer no greater accuracy compared to other estimation methods and are difficult to verify (Walz and Riesch-Oppermann, 2005).

4.4 Parametric Methods

The works of Pascovici (2008) and Holland (2007) were examined in the build-up to the selection of the methodology. Pascovici used statistics and Monte Carlo simulations but the focus was on financial management and financial risk. The technical risk was represented by common Weibull parameters and do not seem to be derived directly by lifing or any such equivalent as far as the author is aware. The parameters are based on data collected by operators or OEM's. The approach used in this study is based mostly on analytical techniques and material properties and predicting the endurance of components via simulation as opposed to data from the operation of machines.

A parametric approach was used to carry out the lifing analysis for the present study. Vigna Suria (2006) developed a lifing module and code for lifing of rotating equipment at Cranfield University and this was further developed by the author. Vigna Suria utilised both creep life and low cycle fatigue using techniques such as the Larson-Miller parameter and Miner's

cumulative law for creep lifing and the Coffin-Manson method for low cycle fatigue, but the present research only uses creep analysis as fatigue was not deemed a critical mode of failure after discussions with the sponsor based on operational experience. It is also known that for the operation concerned, creep is the common mode of failure (Dibbert, 2006). To this end, the Larson Miller Parameter (LMP) has been utilised. The main reason for using a parametric approach compared to the crack propagation method was that multiple creep curves were obtained for the specific exotic materials that were being analysed for the engines under consideration.

Holland (2007) describes the use of probability and statistics along with Monte Carlo simulations to devise a methodology of predicting failure of rotating equipment. The focus was material anomalies but the key is that the approach is different to Pascovici (2008) and Vigna Suria (2006). The Larson-Miller parameter and lifing regime are not utilised but rather the work is rooted in fracture mechanics and going back to first principles to predict failure due to specific material properties and anomalies which cause failure. This is the alternative method of linking the thermodynamic performance of the engine to the risk analysis. A summary of the different techniques used to conduct lifing are shown in Table 5.

Table 5: Table of common techniques used in lifing analysis (adapted from Abdul Ghafir 2011)

	Stress Model	Thermal Model	Gas Path Data	Creep Model	Accumulation
Naeem	Analytical	Analytical	Simulation	LMP	Life Fraction
Vigna Suria	Analytical	Analytical	Simulation	LMP	Life Fraction
Tinga	Numerical	Numerical	DAQ & Simulation	Unknown	Unknown
Liu	Numerical	Numerical	Simulation	Graham-Walles	Life Fraction
Wallace	Numerical	Numerical	Simulation	OSD	Life Fraction
Cerri	Unknown	Unknown	Simulation	Life Consumption rate	Unknown
Kofi	Analytical	Analytical	Simulation	Life Consumption rate + LMP	Life Fraction

However, the LMP technique was used because crack propagation methodology would require undisclosed information about materials which was not available, whilst the author was able to obtain creep curve data from the Japanese National Institute for Materials Science (NIMS, 2010); the data was accessed during 2010 and 2011.

It must be noted that both techniques are proven and many publications have backed their use and crack propagation methods are more commonly linked to probabilistic techniques of failure. Detailed reviews of techniques, methods and models for lifing are presented by Abdul Ghafir (2011) and Kappas (2000).

4.4.1 Creep Analysis Methods

Parametric methods used in this research are based on the creep mechanism. This is a phenomenon which causes progressive deterioration of a material at constant temperature conditions. Typically, creep is idealised as a three stage process as shown in .
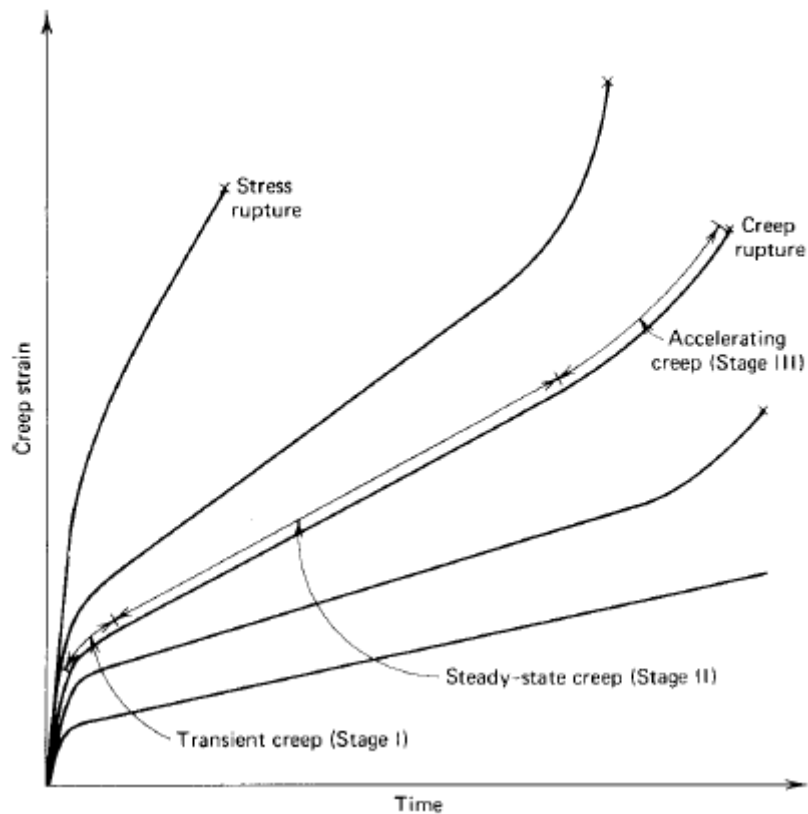
Figure 27: An illustration of creep effect and modes with respect to time

The slope of the curve in Figure 27 is known as the creep rate. The initial phase known as primary creep (Stage 1) is actually preceded by a phase where there is an instantaneous elastic phase (Haslam and Cookson, 2007). Stage 1 itself is a reduction in creep rate, before stage 2, which is the minimum creep rate and is approximately constant; this is known as secondary creep where there is a balance between strain hardening and recovery. Tertiary creep (stage 3) is an acceleration of the creep rate until fracture or rupture occurs. Throughout this cycle, the load remains constant, as tested under test house conditions. The original attempt to characterise the creep curve was made by Andrade (1914).

4.4.2 Time-Temperature-Stress Factors

In order to understand how parametric lifing works, it must first be understood that the lifing analysis is based on the relationships between time, temperature and stress. The rotating machine is undergoing a number of stresses whilst also endures a thermal effect. The combination of these two factors will incrementally reduce the life of a given component. Time-Temperature-Stress techniques can be derived and explained using the Arrhenius relationship equation 4.1 which relates the creep strain to stress and temperature.

$$\varepsilon = Ae^{-\frac{H}{RT}}$$ **4.1**

where ε is the strain

A is a material constant

H is the enthalpy required for the creep phenomenon to occur

R is the Universal Gas Constant and

T is the absolute temperature (K)

and can be rewritten as:

$$\frac{H}{R} = T(\ln A - \ln e)$$ **4.2**

Further, the Monkman-Grant relationship (equation 4.10) shows that empirically the log-log plot of minimum creep rate versus time to rupture results is a straight line. This is useful

64

because test house data is based on tests of rupture and not creep directly, hence one can deduce the creep rates from the rupture tests.

$$\log t_r + m \ln \varepsilon = B \qquad \textbf{4.3}$$

It can be shown that equation 4.2 can be manipulated and the Monkman-Grant relationship can be used to give:

$$\frac{H}{R} = T(\ln A - \frac{B - \log t_r}{m}) \qquad \textbf{4.4}$$

$$\frac{mH}{R} = T(C + \log t_r) \qquad \textbf{4.5}$$

$$C = m \ln A - B \qquad \textbf{4.6}$$

$$LMP = \frac{mH}{1000R} \qquad \textbf{4.7}$$

where A, B and m are constants relative to material.

Given that H is assumed independent of stress and temperature, rupture life will change with stress in such a way that the Larson-Miller parameter will be a constant. Figure 28 shows a typical creep versus stress curve for a popular gas turbine material (Inconel 738) at a given temperature.
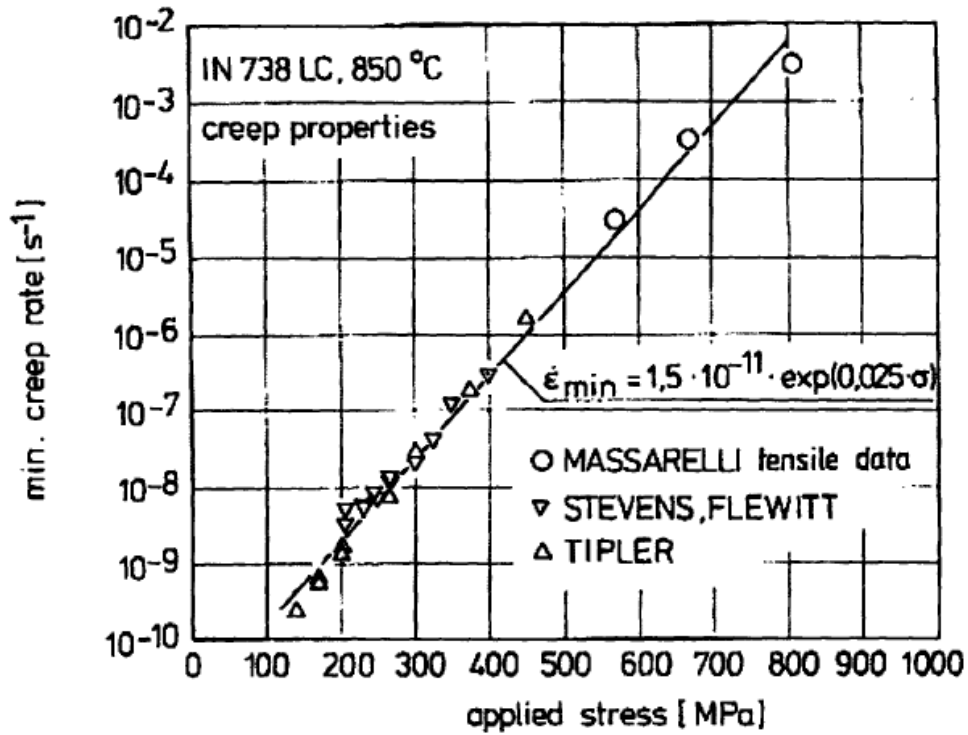
Figure 28: Creep strain versus stress applied to material IN-738LC @850C (Hoffelner, 1986)

More typically however, the LMP curves show the parameter and the temperature too as shown in Figure 29. The curve containing a plot of the parameter versus stress is known as the master curve.
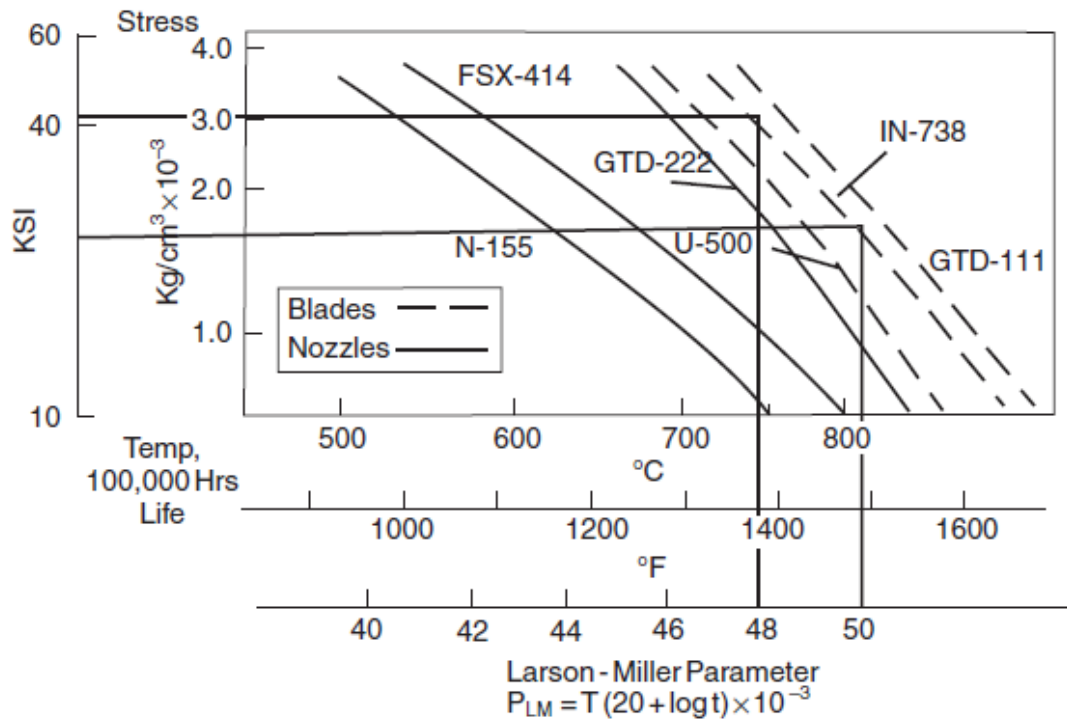
Figure 29: LMP for various blade materials (Boyce, 2002)

4.4.3 Miners Law for Summation of Creep

The creep analysis needs to be summated since the gas turbine will operate at various different conditions. In LNG it is expected that there will be base load operation, but of course the thermodynamics of the core of the engine will change inevitably with varying ambient conditions. Hence, the creep calculations need to be made for a number of different operational settings as will be seen later.

Thus it is required a method for summating the creep life. The popular method here is Miners creep summation law. Whilst the LMP gives a life to failure for a given operating condition, if the time spent at this particular operating condition was divided by the total time to failure then the result would be described as the *life fraction*. Also, the sum of all the fractions at different operating conditions should be unity. This relationship is summarised by equation 4.8.

$$\sum_{n-1}^{n} (LifeFraction)\sigma_n T_n = 1 \qquad \textbf{4.8}$$

67

4.5 A Multiple Creep-Curve Approach

Initial analysis and research deduced that the variation in failure for the turbine blade material could be mapped in one of two ways; either to parametric lifing or probabilistic crack propagation techniques. It was decided to use the parametric approach and this decision will be explained later. Within the parametric creep analysis approach there are further options; either to use a multiple creep curve analysis, or to use a creep curve with inherent variations i.e. raw data and not an averaged out creep curve. What is meant here is that instead of using one creep curve and denoting one value of life based on stress and temperature at a particular condition or point of engine operation, the user is to use many different creep curves for the same material. Each creep curve will then exhibit a predicted life for that particular condition, i.e. the amalgamation of a particular stress and temperature, and all the different values of life generated from the creep curves can be put on the same graph to get a distribution of lives. The idea here is that using many creep curves will give different values for life and thus produce a distribution of lives and bring in the element of uncertainty; a single life based on a single creep curve cannot exhibit uncertainty.

There are however some obstacles here; first of all, the testing set up and testing apparatus for each test house will be different and produce unwanted uncertainty in the results. Secondly, the samples of material tested may not be the same and have some manufacturing variation in them, though this is negligible as far as this exercise is concerned since manufacturing differences are expected to be a very small factor (Boyer, 1988). One solution to the first problem is that the same test house could be used many times in order to reduce the test house variability; so in effect the same test house could do repeated runs for the same material. This is expected and this is how tests are done, but usually the results are an averaged out creep curve and not the raw results. The averaged out creep curve then does not show how the test results varied, it only shows the average of the data based on multiple tests.

The present study uses the latter ideology, creep curves from the same test house but not averaged out, but rather using the raw data from which the variation can be extracted. The reason for doing the multiple creep analysis is, as indicated before, because one wants to look at a distribution of failure values for a given operating condition rather than a single value of failure. The resulting distribution will assign a certain probability to the event of failure,

68

where failure is a time (TTF) and in this way, our predicted failure will have a certain likelihood of occurrence, giving the analysis a second dimension or perspective.

4.6 Oxidation and Failure of Coatings

The coating is a very important part of the blade and its subsequent propensity to failure. The coating in a turbine section usually allows the blade metal temperature to remain lower than the temperature of the hot gas path, sometimes by as much as 150K. This allows the blade to operate in a regime where, without the coating, the blade would simply melt. Figure 30 shows a turbine blade failed in operation and one which is not failed.
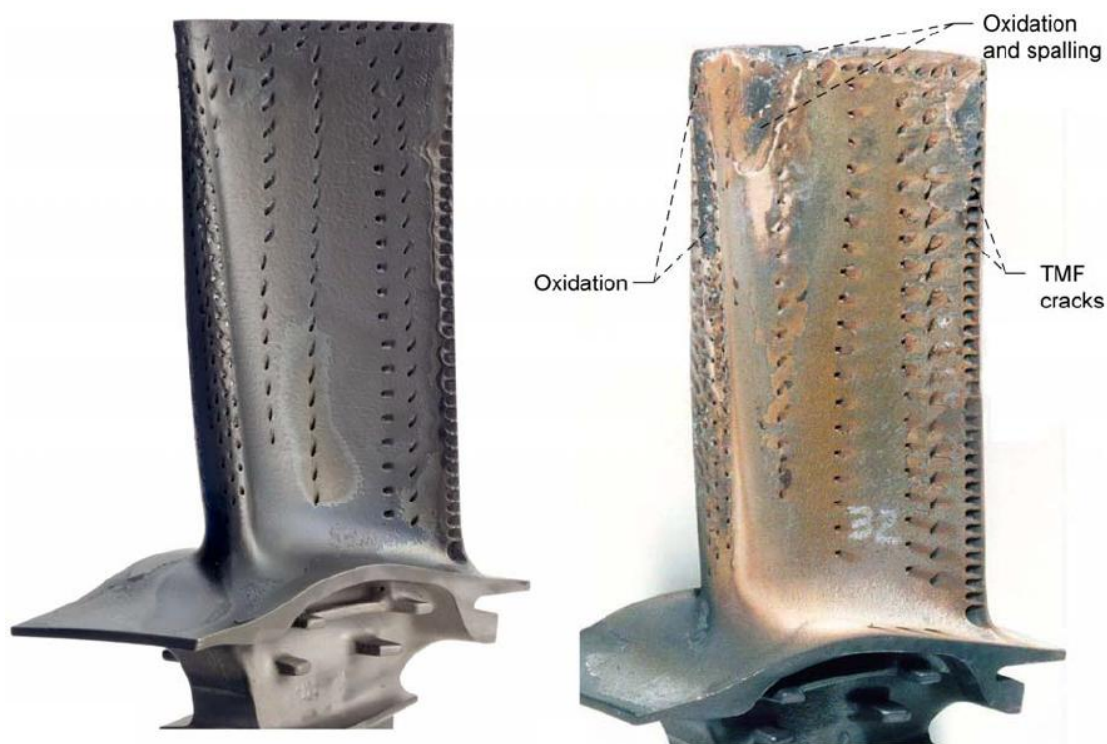
Figure 30: Blade failed due to thermo-mechanical fatigue and oxidation (right) and a blade which has not failed (left) (Zaretsky et al., 2008)

It can be seen in Figure 31 how coating technology has improved over the years. Thermal Barrier coatings (TBC) and overlay coatings are the latest coating technology offering vast improvements, in the order of 20 times the life of coatings from 20 years ago (Boyce, 2002)

69
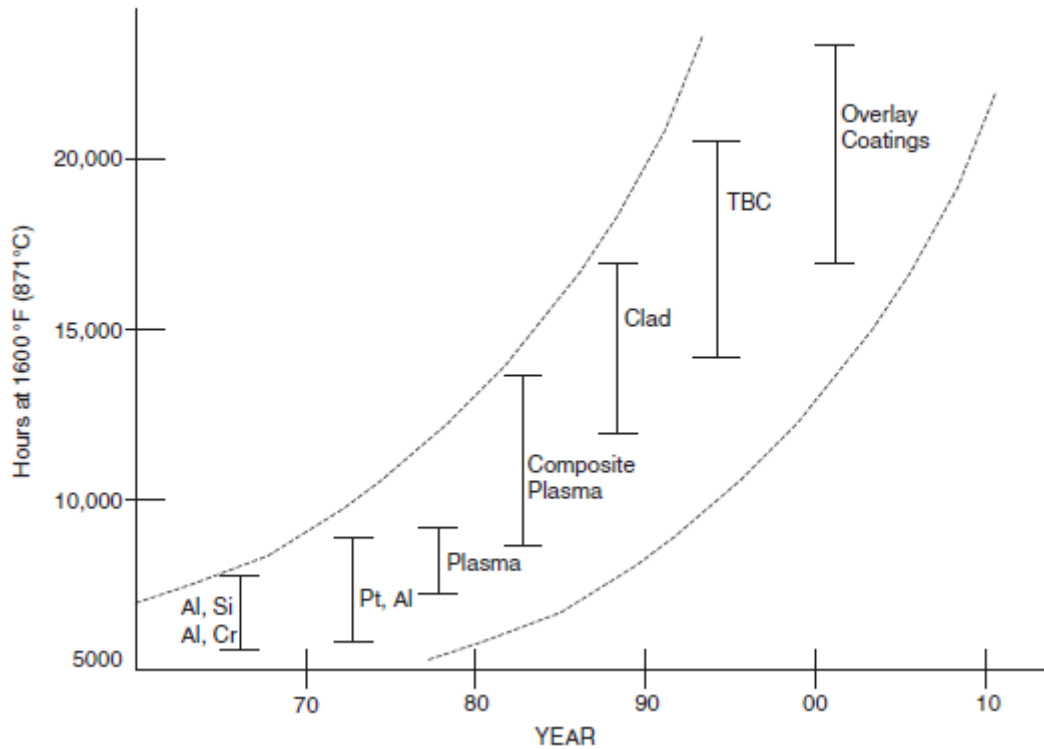
Figure 31: Historical development and improvement of coatings (Boyce, 2002)

The main phenomenon which causes coating failure is actually oxidation, but this happens at the blade material. This is step two however, in the first instance, the coating erodes by the process of erosion because particles of dust or any other unwarranted particles are hitting the blade surface and slowly removing the coating. So, whilst the initial failure can be said to be erosion of the coating, the final failure is manifest in oxidation of the true blade material.

Further, at what can be called moderate temperatures of circa 1100 to 1200K at the turbine, which are experienced typically in industrial machines, it can be said that oxidation is not the main problem, but rather corrosion is the main problem. Figure 32 shows how relationship between which sub-modes of failure have become more dominant and critical in recent years. This would mean one should focus on oxidation, however, given the firing temperatures of the industrial machines in is reasonable to assume that for the most part it will be corrosion that cause the failures.

70
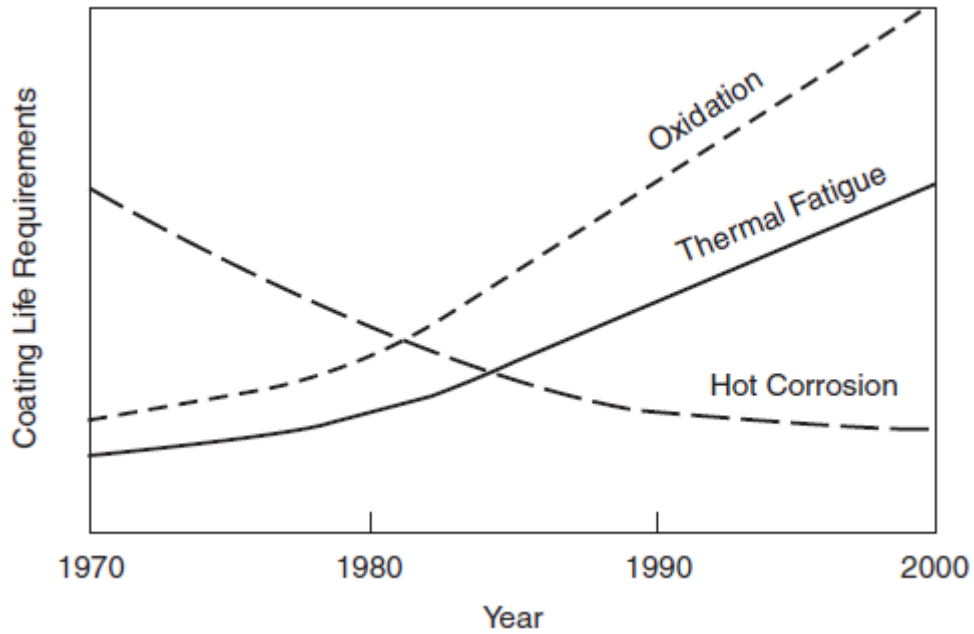
Figure 32: The modes of failure which have become more critical in recent years (Boyce, 2002)

Further, Figure 33shows how coatings are affected by different modes o failure and also shows the comparison between modern coating technologies in terms of the resistance they offer. In Figure 34 it can be seen how sodium deposition rates affect the life of the turbine blade component and significantly shows the improvements that are possible with coating and comparisons to uncoated blades.
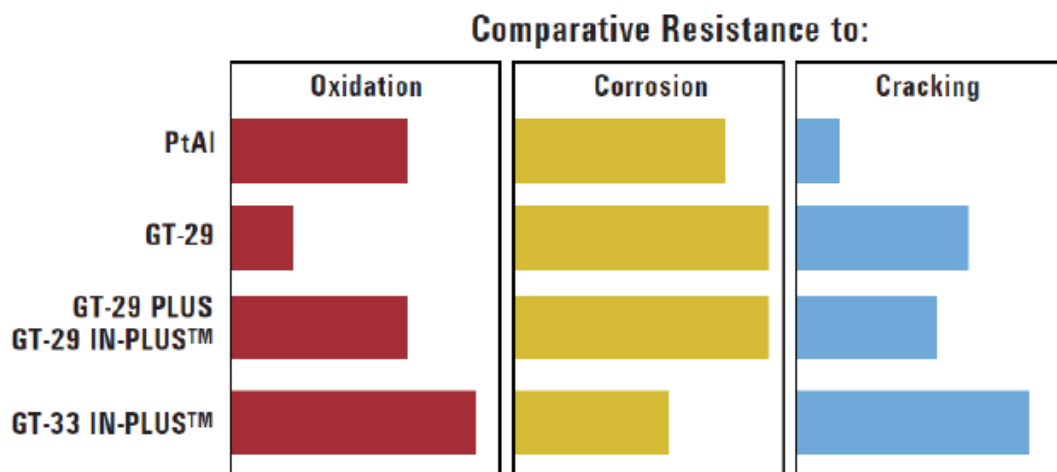
Figure 33: A comparison of coating technology (Ginter, 2008)

71
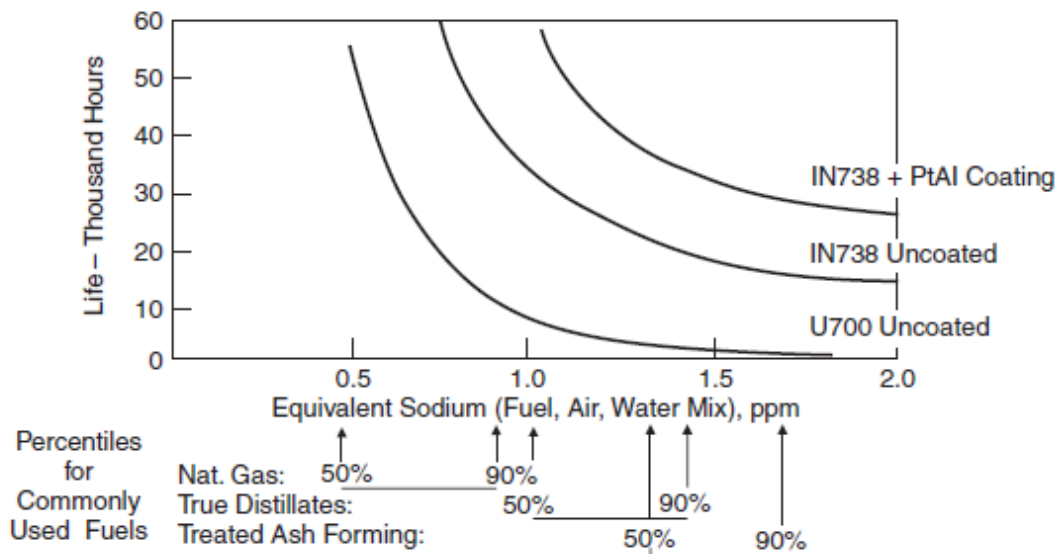
Figure 34: Effects of Sodium deposition on turbine blade life (Boyce, 2002)

4.7 Combustor Liner Cracking

The combustor lifing methodology is a very difficult subject to analyse purely on an analytical basis. Almost all studies use some form of CFD or FEA techniques in conjunction with analytical methods to formulate the life of the combustor.

Indeed there has been much attempt by OEM's to utilise field data to create models which might predict the failure of the combustor. Balevic et al., (2004) and Ginter and Bouvay (2006) describe how GE has made improvements to its frame series of engines in an attempt to increase the life of the combustion system. The attempts of improvement have been driven by the desire to withstand greater firing temperatures as well as reduce the emissions. This has resulted in complex systems such as the low emissions DLE system for example.

Further, it can be deduced from the experience of various operators that combustor liner cracking is one of the reoccurring problems faced by the operators. One of the ways in which GE have improved the design is to replace the original louvered liners with slot cooled liners (Figure 35). The louvered liner had manufacturing stresses introduced into it which later

caused cracking near the cooling holes. The slot cooled liner overcomes this problem by a novel system of spot welding and brazing (Figure 36).
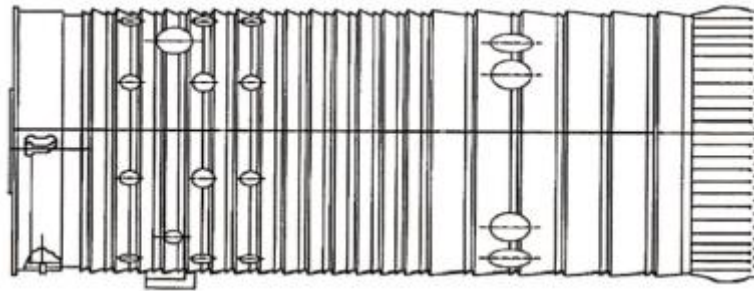
Figure 35: Slot cooled liner (GE, 2006)
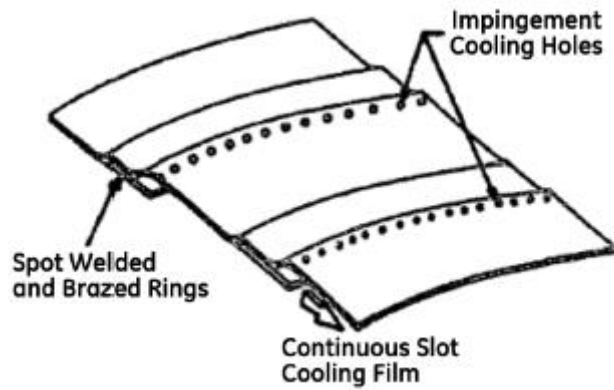
Figure 36: Slot cooled liner - section view (GE, 2006)

Other techniques include reducing the length of the liner to reduce the peak temperatures as well as use of coating technology and thermal barrier coatings to enhance the life of the combustion unit.

The transition piece is also a problem area but this is negated in this study since the critical piece was deemed to be the liner and so for simplicity, the life of the combustor is modelled as the life of the liner, and it was assumed that if the liner goes down, then other sub-components would also be replaced whilst the liner was out.

4.8 Modelling the Lifing

4.8.1   Structure and Methodology

There are three components which are lifed; namely the combustor, the first stage turbine blade and the first stage turbine coatings. This is classed as three components because the turbine coating is treated in a separate calculation. The structure of the new model can be seen in Figure 37.

The data from the performance module is taken as input. The thermodynamic parameters used include the firing temperature, combustor inlet and outlet temperatures and pressures and the rotational speed. The turbine creep lifing itself then splits into a two way analysis whereby the thermodynamic calculations are done as well as the stress calculations. The two then come together in order to conduct the parametric study based on the Larson-Miller Parameter. The LMP creep curve itself is a set of LMP values and stress values. This is generated from a test house where the material is tested under certain temperatures and loadings.

Input set 1: (User Defined)

      a.   Blade material

      b.   Blade geometry and Engine diameters

      c.   Number of segments blade is split up into

      d.   Coating delta T (effective reduction in temperature by coating)

      e.   Cooling effectiveness of blade (for thermal analysis model)

      f.   Time spent in each segment or operating condition

Input set 2: (From Performance Module)

      a.   RPM

      b.   Firing temperature at each operating condition

      c.   Compressor exit temperature

Input set 3: (From Materials Database)

      d.   Density of blade material

      e.   Larson Miller Parameter constant (or entire LMP curve made up of LMP values and stress values)

a. LMP data (essentially test house data for the material)

Further details of the subroutines and model detailed inputs and procedures can be found in Appendix C.
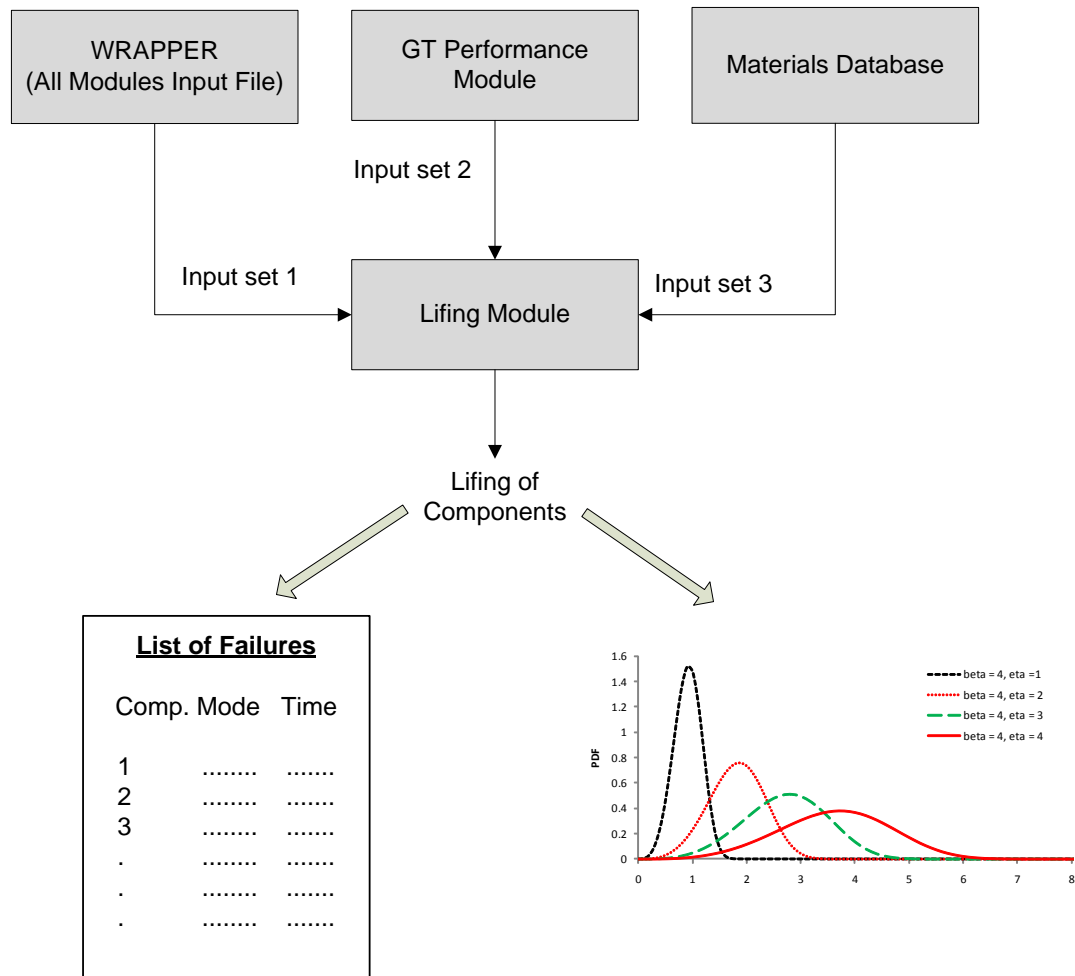
Figure 37: Diagram showing the structure of the lifing module

The idea behind using multiple creep curves is that if one were to use a single creep curve, for a given operating condition, one would only get one value of life, but using multiple creep curves means that one can generate 6 to 10 values of life for the same operating point. This is done in order to create a distribution of life as opposed to a single numerical value of life. The distribution is important because it makes the entire analysis two dimensional, not only is the expected value of life known but also the variation this life is subject to.

Multiple creep curves can be obtained by getting data from different test houses. The author was unable to do this, so the NIMS data was utilised (NIMS, 2010). This data is special in the sense that it doesn't give a creep curve in the conventional way; it gives a series of points from which a curve can be drawn. Once the curve is drawn, a rank regression in y will give the variation about this curve as well as mean values.

Boyer (1988) defines in his Atlas of Creep curves that there is variation in creep due to material affects. No two, so called identical pieces of metal will fail at the same time. The reason is inherent material anomalies and unique granular structure of each piece of metal or other material. Thus, inherent material variation is a function of the variation of failure of the components of the GT. The data from a test house must be cleaned in the sense that it will contain other variations, such as variation due to testing conditions; this is called testing variability. This arises due to apparatus set up and accuracy to which pressures and temperatures were simulated in the laboratory. This can account for up to 15% of the variation (Boyer, 1988), and the rest will be attributed to material variability. Taking this information into account, the author has used the NIMS data and cleaned it in order to obtain the suitable variation due to inherent material variations.

The above is done for creep life estimation of the turbine blade. The other two components are combustor and turbine coatings. The lifing for these is conducted separately using data as input from the performance simulation again. It is very difficult to life the combustor without more detailed modelling, however the author was successful in finding some models which allowed probabilistic calculation of life for the combustor liner and coatings. Details will be provided in the following sections. By detailed modelling it is meant that CFD and/or FEA techniques are required due to the complication in doing the simulation for life of the combustor. This would be ideal but is outside the scope of this study.

4.8.2   Turbine Blade Lifing Model

4.8.2.1 The Thermal Model

The formulae presented here are for the thermal model used to calculate the blade metal temperature. First of all the gas temperature from Turbomatch calculations and some understanding of the cooling technology enable approximations for the blade metal temperature at each operating point. The effectiveness is a measure based on predictions of cooling technology; this is taken from Figure 38.
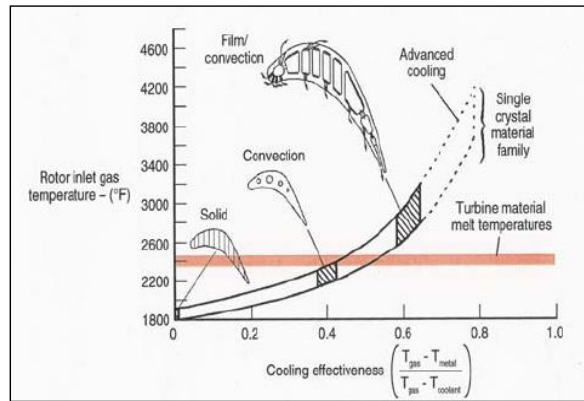
Figure 38: Cooling effectiveness versus TET (Koff, 2003)

Hence an estimation for effectiveness can be made based on understanding of the technology. The values of Tgas and Tcool come from the performance simulation model of the engine.

$$\varepsilon = \frac{T_g - T_b}{T_g - T_{cool}}$$ **4.9**

Where ε is the cooling effectiveness, T_g is gas path temperature, Tb blade metal temperature and T_{cool} is the blade inlet coolant air temperature. The coolant air is bled from the compressor latter stages. This forms the basis for the thermal analysis.

4.8.2.2 The Stress Model

The stress analysis requires some understanding or estimation for the size of the turbine blade; this study looks at the first stage blades because this is deemed critical and is expected to produce the limiting life since the highest temperatures are experienced at the first stage. An argument is that the stresses may be greater downstream the turbine stages, but the thermal effects far outweigh the stress effects on life.

The centrifugal force acting on a section of blade can be calculated via equations 4.10 and 4.11. However, this parametric study requires a thermal value as well as a stress as opposed to a force. So dividing the force by the cross sectional area of the blade gives the stress acting on the blade section. The blade is broken down into sections in order to improve the accuracy of the calculations.

77

$$Force_{centrifugd} = mass \times \omega^2 \times r_{cg} \qquad \textbf{4.10}$$

$$\sigma_{centrifugd} = \rho \times h_{sec} \times \omega^2 \times r_{cg} \qquad \textbf{4.11}$$

Further integration can yield a form of the equation which can be used to look at blades with variable cross sectional area. In reality, it is very unlikely that a blade has constant cross sectional area across its chord, i.e. from root to tip. All steps of derivation of equations is not presented here since the method to get to equation 4.12 is well charted in Haslam and Cookson (2007) and numerous other sources. It is assumed that maximum stress acts at the root.

$$\sigma_{CFMAX} = 2\pi \times N^2 \times \rho \times A_{ann} \qquad \textbf{4.12}$$

4.8.2.3 The LMP Model

Finally, using the values of stress and metal temperature, predefined LMP curves can be used to calculate the life. The original LMP relationship (equation 4.13) is re-arranged to give equation 4.14 which gives the value of life in thousands of hours. The constant C is usually given a value of 20 unless there is data to suggest otherwise.

$$LMP = \frac{T}{1000}\left(\log t_f + C\right) \qquad \textbf{4.13}$$

$$t_f = 10^{\frac{(1000 \times LMP)}{T} - C} \qquad \textbf{4.14}$$

4.8.3   Combustor Liner Lifing Model

The theoretical background for the combustor life calculations is presented here.

Assovskii and Istratov (2008) state that a combustor life can be derived from the kinetic of destruction of its liner. To this end, the temperature and stress of the liner again need to be calculated. The von Mises stress in equation 4.15 deals with both the tangential and axial components of the stress.

$$\sigma_{VM} = \frac{1}{\sqrt{2}} \times \sqrt{\left(\sigma_{\tan} - \sigma_a\right)^2 + \sigma_{\tan}^2 + \sigma_a^2} \qquad \textbf{4.15}$$

The thermal formulation is based on the internal and external radiation and convection of heat on the liner walls.

$$R_1 + C_1 = R_2 + C_2 = K_{1-2} \qquad \textbf{4.16}$$

Where R_1 is the internal radiation transfer to the liner, C_1 the internal convection of the combustion gases on the liner, R_2 the external radiation transfer from the liner to the coolant fluid and C_2 the external convection from the liner to the coolant. All the units are in W/m². K_{1-2} is the conduction heat transfer between the inner wall and the outer wall.

$$K_{1-2} = \frac{k_w}{e}\left(T_{w1} - T_{w2}\right) \qquad \textbf{4.17}$$

Where k_w is the wall thermal conductivity (W/m/K), e the wall thickness (m) and T_w the wall temperature (K), the index 1 designating the inner wall and 2 the outer wall.

The detailed derivations and definitions for these variables can be found with Burgmann (2010). The details of the subroutines and structure of the modelling can be found Appendix C.4.

Details of the kinetics of destruction of combustor liner can be found with Zhurkov (1965) who initially proposed the methods which were developed by Assovskii and Istratov (2008).

4.8.4 Turbine Coating Probabilistic Lifing Model

In line with creating a probabilistic model which will enable stochastic treatment so as to ascertain the failure of the coating, the research led to looking at probabilistic models which could help predict life of the coating and it's time to failure.

The coating life calculations are based on sodium concentrations in the atmosphere and the methodology involves estimating in a probabilistic way the formation and critical nature of pits. A certain pit depth is assumed critical after which it is assumed the coating has reached failure. The theory is taken from Nicholls (1993). The statistics is grounded in use of the Gumbell distribution for which the PDF is shown in equation 4.18.

$$f(x) = \frac{1}{\beta} \times e^{1 - \frac{x-\gamma}{\beta}} \times e^{-e^{-\frac{x-\gamma}{\beta}}} \qquad \textbf{4.18}$$

Where γ and β are the location and shape parameters respectively. The CDF is:

$$F(x) = \int_{-\infty}^{x} f(t)dt = e^{-e^{-\frac{x-\gamma}{\beta}}} \qquad \textbf{4.19}$$

Further, the parameters γ and β can be defined as:

$$\gamma = X_{Na}^{0.8}(B + C\sqrt{t}) \qquad \textbf{4.20}$$

$$\beta = X_{Na}^{0.8}(-Dt) \qquad \textbf{4.21}$$

Where the critical pit depth is taken as 80 μm for a sodium deposition rate XNA (mg/cm²/h) and B, C and D are empirical constants. Finally, the time to failure can be found using equation 14 where CT is the coating thickness and α_f is the cumulative time to failure. The critical thickness is found at 5% of the CDF because this is the limit set for a safe life.

$$CT = X_{Na}^{0.8} \times \{B + C\sqrt{t} + Dt \ln[-\ln(1 - \alpha_f)]\} \qquad \textbf{4.22}$$

Once again, the detailed subroutines structure and procedures can be found in Appendix C.3.

4.8.5   1D Lifing for Turbine Blades

At a later stage of the project there was an addition to the basic lifing routines in the form of what is called a 1D model. This has a twofold advantage; first of all it has the ability to make the lifing calculations more accurate and reduce the need to apply safety factors to the values of life calculated, and secondly it allow the user to be more flexible and be able to run the newer and more novel engines in the simulation.

The accuracy argument is based on the idea that the 1D thermal and stress models are more detailed with respect to the way the calculations are done. The initial model can be described as a 0D model since it takes a single value of temperature along the blade for the creep analysis and does a simplistic stress analysis. The thermal and stress models in the 1D on the other hand use temperature and stress profiles are used instead of single values. To be more specific, the 0D uses the value of turbine entry temperature as a single temperature which is used for all calculations along the blade chord, whilst the 1D model utilises a profile with the maximum temperature between 60% and 80% of the blade chord when measured from the root. In reality of course the temperature is not the same across the chord. When the profile is assessed at combustor exit it has a profile which has a maximum temperature at 50% of blade height, as expected, and after the flow passes the guide vanes, it undergoes a swirl which makes the maximum temperature shift toward the upper end of the blade.

The above is important because the failure of the blade is a temperature and stress interaction or accumulation. Typically it is said that the root has the highest stress and if at the same time the temperature is assumed the same across the blade then o doubt the models will show that the blade fails at the root. However, this is not true since the temperature effect is far the dominating effect, and the profile of temperature means the thermal effects are far higher at certain points on the blade, and the root is certainly not the critical point. Hence, the1D model proceeds to calculate the life of the blade by discretizing the blade into segments and working out the effects of stress and temperature in a segmented way and thus can tell us more accurately when the blade will fail and at what point across the chord length.

The second useful effect of the 1D model is that it allows the user to estimate blade size if the blade size is not known. The author was able to attain drawings and values for some engines such as the GR Frame 7 but not some of the newer more exotic engines such as the aero-derivative machines. This meant that preliminary turbomachinery design had to be under

taken in order to estimate the size of the blade so as to be able to run either of the lifing models.

The preliminary calculations in the 1D model require the user to input the turbine Mach number, a mean line diameter and the rotational speed. All three can be ascertained quite easily, the RPM is known for most engines and appropriate guesses of the Mach number and mean diameter can also be made. One proceeds to calculate parameters such as the flow coefficient and stage loading (V_a/U and $\Delta H/U^2$) and can estimate if the initial guesses were reasonable. This process also tells one, depending on how many stages of turbine there are, as to what the heights of the blades in each row is. One can then proceed to calculate the blade stress and thermal effects created in the core and life the first stage turbine blades.

4.8.5.1 1D Lifing Model

The equations in Appendix D: ID Modelling Methodology show the procedure to calculate the blade size and other basic design parameters in order to check if the design is feasible, which of course it is since it exists and was made by an OEM, but the procedure allows the user of the LNG TERA tool to decide whether the blade size, Mach number of turbine entry and mean diameter estimated herein are reasonable. It also leads on to the Zweifel method which allows the cross sectional area of the blade to be calculated and thus makes the stress calculations easier also. In the 0D model, the cross sectional area of the lade was not used to calculate the stresses as mentioned before, the AN^2 estimate is utilised to find the stress based on the cross sectional area of the entire blade row/gas path. For more information on the blade design methods including Zweifel's method and design of pressure and suction sides of blades using gas path information please refer to Dusa (1964) and Wilson and Korakianidis (1998).

5. Simulation Based Maintenance Scheduling

It is evident that maintenance costs account for a considerable portion of total costs within a power plant of any sort and whilst these costs are very small compared to fuel costs, the cost of maintenance reflects on another very important aspect; costs due to downtime or lost production. Whilst maintenance costs in terms of costs of components that need replacing may not be so significant, the costs of lost production due to downtime are of much significance. Hence it is vital to map the failure of a plant or machinery set and put it into perspective of maintenance required and cost the components and also define how operations will affect the downtime of the machinery.

'Maintenance can represent between 15% and 60% of the operating costs' (Mobley, 2002)

An important aspect then is the OEM guarantees as to how quickly spare parts can be changed over; some OEMs will boast a modular design of engine and claim that machines can be changed over in a number of hours whilst others with a traditional design of the machinery will take a number of weeks perhaps to undergo a major overhaul. Again there is a two pronged situation here; the OEM defined change over times which are a function of the design of the machine, whether traditional or modular, and, the operators maintenance philosophy and spare parts philosophy; both these aspects will affect the final picture of maintenance effects and consequent lost production. It is important to look at the operators philosophy and investigate using a tool such as the TERA LNG as to which philosophy will suit best the LNG operations.

5.1 Types of Maintenance Philosophy

5.1.1 Preventive Maintenance

Preventive maintenance refers to the type of maintenance whereby the operator follows the guidelines of the OEM closely. A maintenance schedule will be built around the OEM guidelines for the specific plant location and some alterations will be had, but mostly the OEM guidelines as to when to stop the engine, when to borescope, do a major overhaul etc will be conducted based on the OEM advice for that particular machine. This is perhaps more stringently followed in the aviation industry especially where OEM's are now providing power by the hour and maintenance is closely linked with the OEM advice.

5.1.2   Condition Based Monitoring

This is one step further than preventive maintenance whereby an operator will use the data coming from the engine whenever possible and to create trends of the performance and chart the performance metrics in such a way so as to be able to ascertain when a failure is likely. This would typically use margins based system whereby the margin for life usage will be based on the deterioration of the engine which in turn is measured by turbine gas temperatures, typically T30, also known as TGT in the aviation industry.

Essentially, according to Li (2008) CBM is *'the regular evaluation of operating conditions to optimise the total machinery'* and hence it can involve a lot more evaluation of the data from a machine.

5.1.3   Run-to-Failure

Mobley (2002) describes the logic to run to failure as simply 'when a machine breaks down, fix it', the idea being that this philosophy makes the best use of the machinery life. It would be used in an environment where the cost of the component would be relatively insignificant compared to the gain in production, i.e. one could afford to run the machine to failure, and either throw it away or have it fixed later. Hence, it implies that the spare parts are readily available and that production will be halted only for the shortest period of time and that this downtime is acceptable. Though this philosophy sounds extreme, it is actually the most widely used practise in the industry due to its simplicity (Piotrowski, 2006)

5.2 Simulation Based Maintenance

The philosophy adopted in the present work is a hybrid of sorts, one which uses OEM defined advice as well as some of the lifing and risk simulation results in order to predict the maintenance schedule, or create a *simulation based maintenance schedule*.

The reason is because the scenarios proposed in this research are feasibilities which look at whether machinery will be suited to the operation demanded of it, and furthermore, which machine will be best suited. Hence, it is a simulation of the machines as opposed to using data from the field. With this in mind, the lifing and risk modules were produced to look at the failures. To merge those aspects of lifing and risk of the problematic components with overall engine maintenance it was necessary to create a maintenance module which would put the lifing and risk results into perspective and estimate overall downtime for a given engine and

given duty/demand. Further, the module then is forced to use partly the OEM defined data for some maintenance actions whilst for others it uses the lifing analysis conducted earlier to produce informed maintenance schedules. The generic structure of the module can be seen in Figure 39.
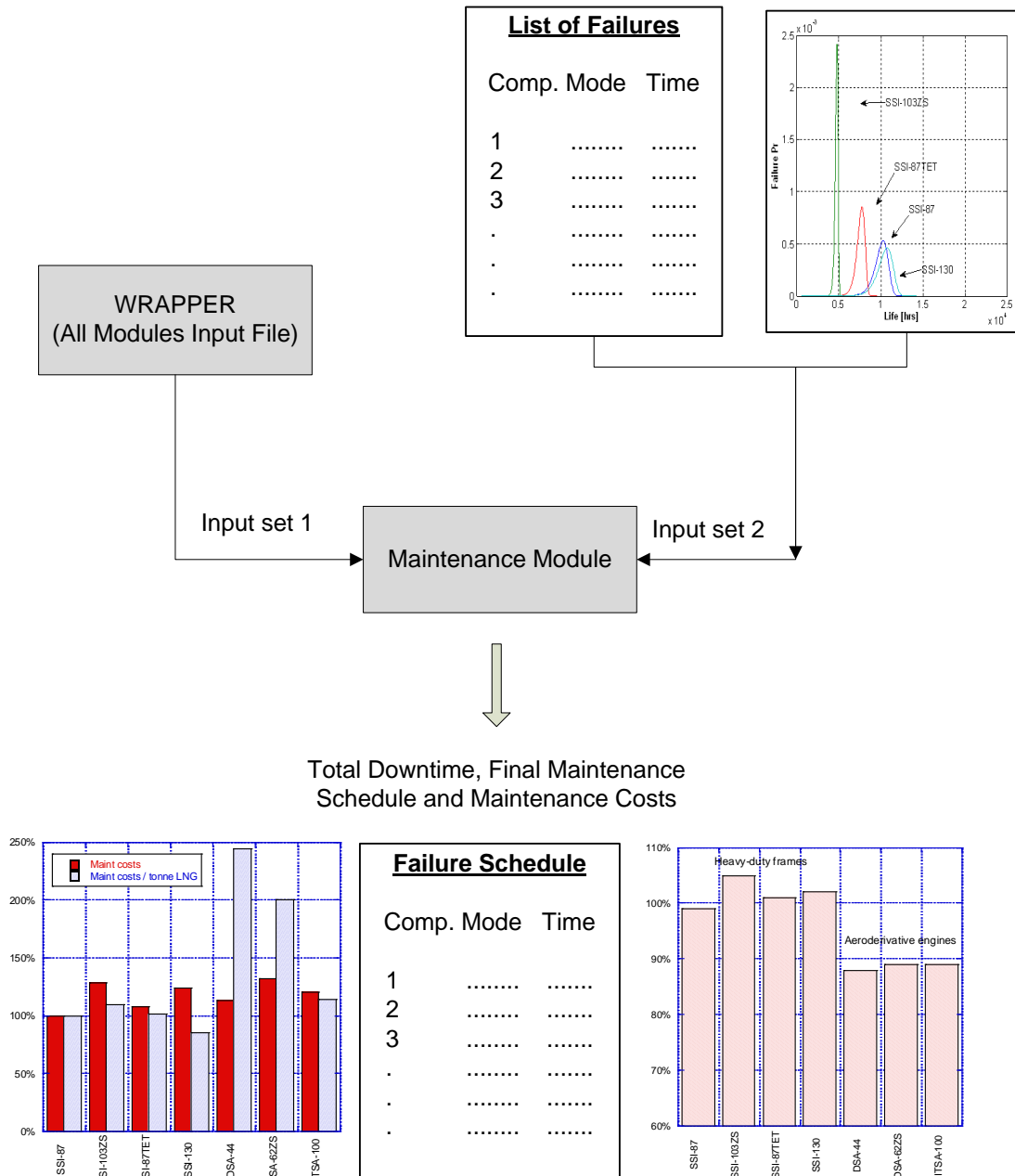
Figure 39: The schematic for the maintenance module

The maintenance module looks at Preventive Maintenance (PM) and Simulation Based Maintenance (SBM) methods. It uses a FORTRAN code with OEM recommended values of

MTBF and MTTR for PM. For SBM the lifing and risk are run and the consequent failure schedule resulting from the risk analysis and Monte Carlo runs is utilised.

Input Set 1: (User defined)

4. MTTR and MTBF values for PM
5. Labour rate (specialised and basic)
6. Number of personnel used
7. Logistics costs
8. Components costs[2]
9. Scheduling limit[3]

Input Set 2: (Results of risk and lifing modules)

1. Failures list[4]
2. Distribution of failure for each component and overall engine

The maintenance module takes the failures list created by the risk and analyses this. The first task is to group certain components based on the time difference between them. This difference is specified by the user and can be set to, say for example, 8700 hrs. So if any two components are predicted to fail less than 8700 hours apart then their maintenance, be it repair or replace, will take place when the first one of them fails. In this way, the total downtime is reduced but some valuable life is wasted. The life wasted costs the operator much less than the amounts saved by adjoining the maintenance actions. This process can be optimised.

---

[2] Component costs are split into groups of components, so it will not be the cost of a single basic component, but rather a group like rotor assembly, blade set, HGP components, consumables etc.
[3] This refers to the limit between any two failures on the original failure list; if two failures occur within the schedule limit, then they are combined as one action, so, for example, if a blade is expected to fail at 10 000 hours and a seal at 11 000 hours then they will be likely combined into one downtime based on the setting of the schedule limit
[4] The failures list contains separate *components* like compressor or turbine or combustor and is amalgamated into a schedule for maintenance based on the algorithms/rules of maintenance for an *engine*

The failure schedule coming from the risk analysis only informs *part* of the maintenance schedule, not all of it. It cannot be expected that the entire schedule will be changed based on the risk calculations; thus only the corrective actions are changed. The rest of the schedule is the same as PM but this small difference converts to a big difference when looking at the costs of downtime and lost production. The model did not utilise data from field since it was not readily available but it did exemplify that if data could be found then it can be inputted to show the difference in life and maintenance cost.

Previously, CBM (Condition Based Monitoring) was simulated as part of the maintenance module but this has been dropped. It mimicked a percentage improvement over PM and the model showed that the longer the engine is run using CBM methods, the higher the NPV value for the maintenance cost. This would require more field data and to actually run the engine and do a CBM operation. The use of the code is now focused on the simulation using PM and SBM.

An advanced version of a the SBM maintenance (NOT used in the results shown in this thesis) is able to select the appropriate components for replace or repair purposes and group them in terms of reliability, the reliability at which maintenance occurs. This is done by a subroutine which decides, based on reliability (or the statistical health or condition of the component) whether it should be replaced or repaired and also sets the life back to zero for the component which has been repaired or replaced. This model runs the performance in an iterative way and needs long simulation times since the Turbomatch code is called into use more than once (usually 20-40 times per scenario per engine), and each time a new deterioration level is fed to the Turbomatch. The details of this advanced model can be found in Desnos (2011).

6. Environmental Aspects of Equipment Selection

The rationale behind conducting a study on emissions control and reduction is based on the Stern report (2006) and the Kyoto Protocol (United Nations, 1998). The Stern review talks of the economics of climate change and highlights that there is a growing need to take timely action against increasing greenhouse gas emissions. The Kyoto protocol sets the government targets for 2012 and 2020 for levels of emission reduction targets. Figure 40 shows that almost a quarter of all emissions are due to power generation and LNG production falls into this category as well as sharing in categories like transport for shipment of LNG containers where ships are giving off emissions.
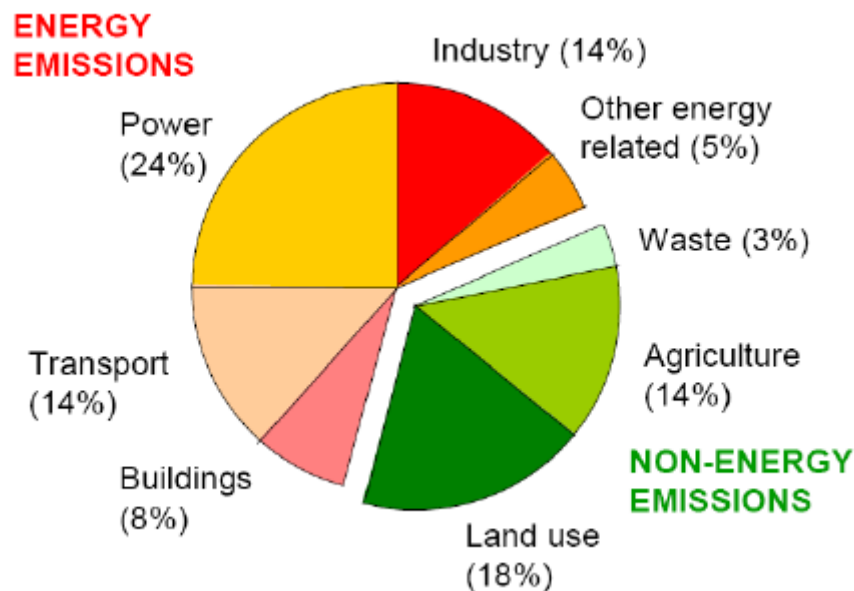
Figure 40: Contributions to emissions by industrial sector, with power production as the largest group (Stern, 2006)

6.1 Carbon and Nitrogen Emissions

The two major pollutants from gas turbines are carbon and nitrogen based oxides. Carbon dioxide is the component which causes global warming and the environment whilst nitrogen oxides are harmful since they promote photochemical smog. The problem is that at low power

and associated low firing temperatures in the combustor one can solve the NO_x problem but the production of unburnt hydrocarbons (UHC), as well as carbon monoxide and carbon dioxide is increased. On the other extreme when the firing temperature is increased resulting in improved cycle efficiency and to reduce unburnt hydrocarbons, NO_x production increases since NO_x increases exponentially with combustor firing temperature (Singh 2007, Saravanamuttoo 2001). This dilemma is pictured in Figure 41.
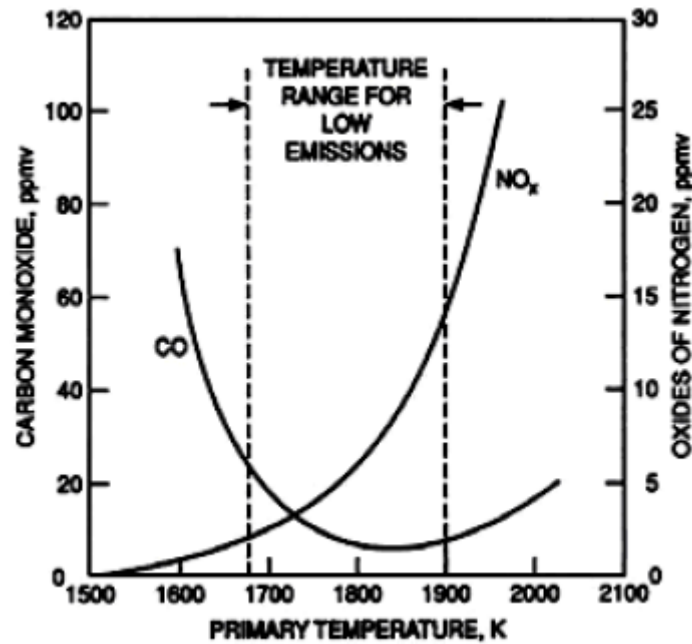
Figure 41: The trade-off between NO_x and CO emissions (Lefebvre, 1998)

NO_x emissions appear to a great extent with high combustion temperatures. High temperatures are related with high power outputs, and owing to compressor drivers working most of the time at base load, this $EINO_x$ has more importance than the other emissions. Techniques such as DLE have decreased the amount of NO_x emissions but the key difficulty in this study is the difference in engine firing temperatures between industrial and aero-derivative gas turbines.

As far as the emissions estimation is concerned the CO_2 can be modelled using stoichiometric calculations assuming near to complete combustion; the balanced equations of the combustion reaction will yield the amounts of CO_2 produced. The NO_x, CO and UHC on the other hand require more specialist treatment as will be discussed later.

89

6.2 Current solutions

There are various solutions to the emissions problem. Cycle efficiency, combustor geometry and fuel type are all factors which affect the level of emissions and so design of the combustion system is key. Methods of emissions reduction include water injection, dry low NO_x systems and exhaust clean-up. The first two are for NO_x reduction whilst exhaust clean-up can be used for carbon reduction.

6.2.1   Water Injection

This is a method for NO_x reduction. Water injection into the combustor can reduce the flame temperature, and reductions of even 100K can lead to half the NO_x production (Leonard and Stegmaier, 1993). However, water and steam injection require huge amounts of water and this is not always easily available. A 4MW gas turbine can use up to 4 million litres of water per annum. In the warmer climate, for example the Middle East, water scarcity can be a problem. Furthermore, the water needs to be treated to stop corrosion to core components and this incurs further costs.

6.2.2   Dry Low NO_x

Achieving low NO_x without the use of water is known as the *dry* system (Saravanamuttoo, 2001). This involves lean or rich burn in the primary zone. Lean burn is most common with emphasis on pre-mixing of fuel and air to get the desired exhaust characteristics.

With industrial gas turbines, the magic point is 40% load. Below this the combustion is restricted to the primary zone. At this point most new machines will burn only in the secondary zone whilst the pre-mixing will be happening in the primary, with fuel being introduced both in the primary and secondary zones (Davis, 1989). Splitting the combustor burn in this way gives the flexibility for low and high power conditions and reduction in overall NO_x and carbon emissions.

Aero-derivatives on the other hand are inherently high NO_x producers simply due to high firing temperatures and water and steam injection are not always feasible solutions. Some engines are retrofitted with different combustion units where, for example, the residence time

may be increased by increased annulus depth for low carbon emissions. An example is the GE LM6000 (Leonard and Stegmaier, 1993). Rolls Royce on the other hand have a radial arrangement which increases volume for longer residence times (Saravanamuttoo et al., 2001). However, the control for fuel introduction at different stages is difficult due to shaft speed relations to load in two-spool engines.

6.2.3   Exhaust Gas Clean-up

An example is selective catalytic reduction (SRC). Used when the requirements are for really low permissible levels of NO_x. Ammonia converts the NO_x to N_2 and H_2O. Limited catalyst operating temperature range means that SRC is often only used with Heat Recovery Steam generator (HRSG) systems.

6.2.4   Fuel Type

Gas Turbines can use a multitude of fuels from gas and oil to even coal in fluidised bed reactors. The majority of machines and plants around the world are using gas. One major issue related to fuel, apart from levels of carbon and nitrogen oxide production, are sulphur components which produce acid rain. Unlike carbon and nitrogen oxides, which depend on firing temperatures, sulphur production depends solely on the amount of sulphur present in the fuel in the first place. Selection of the correct fuel is therefore very important but outside the direct line of this study.

6.3 Potential Novel Solutions

Apart from the general ideas presented above Kvamsdal et a., (2007) talk of various innovative and bright ideas for CO_2 capture in particular.

6.3.1   Oxy-Fuel Concepts

These include the basic Oxy-Fuel Cycle, Water Cycle, GRAZ Cycle and Advanced Zero Emissions Power Plant (AZEP) amongst others. Figure 42 shows the process flow diagram of the basic oxy-fuel cycle. Oxy-fuel helps reduce both NO_x and carbon. The idea is simply that the inlet gas is not air but water. Thus the NO_x is entirely eliminated since there is no air and therefore no nitrogen. The H_2O and CO_2 are fed to the heat recovery steam generator.

Condensation splits the carbon dioxide from the water and the carbon dioxide is recycled back to the combustor.
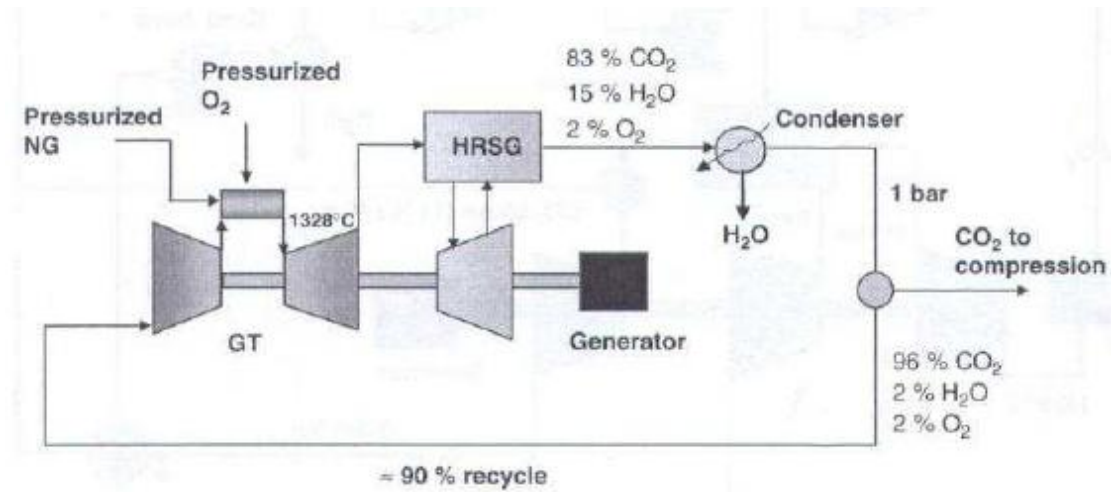
Figure 42: A schematic of the oxy-fuel cycle (Kvamsdal, 2007)

The other variants follow this core cycle with a few changes. The water cycle contains water as working fluid and steam generation and consequent power generation (Anderson, 2004). This is a Rankine cycle. The GRAZ cycle is based on both the Rankine and the pure oxy-fuel cycle. The AZEP is a concept where the combustor is substituted for a mixed conductive membrane (MCM) and this helps separate the oxygen from the intake air (Griffin, 2005).

6.3.2   Pre-combustion Concepts

The two concepts studied here are the Auto-thermal reformer (ATR) and the hydrogen membrane reactor (Kvamsdal, 2007). The ATR system is based around de-carbonising the fuel. Carbon is removed from the natural gas prior to combustion by employing air blown reforming and water-gas shift reactions. The fuel finally burnt is rich in H_2 and N_2. The system also incorporates a HRSG.

The second system uses a methane-steam reformer with a hydrogen membrane reactor (MSR-H2). It is similar to the ATR. The hydrogen produced is continuously tapped off. Heat for steam reforming comes from the gas turbine exhaust and supplementary firing.

6.4 Methods for Modelling Emissions

The emissions of a gas turbine cannot be easily calculated for some of the pollutants since the chemical kinetics are not fully mapped by equilibrium based analysis. What is meant is that systems are not in equilibrium so that estimations are required in order to ascertain the amount of pollutant being produced. This is true for pollutants such as NO_x and other smaller quantities such as oxides of carbon, nitrogen and sulphur, as well as unburnt hydrocarbons. There are a number of options available to estimate the emissions.

6.4.1   CFD Based Approach

This is a method which involves looking at the emissions of a particular combustor design in great details by simulating the flow and its components and discretising the flow into small units so as to be able to summate or map the entire chemical kinetics for a given combustor. This is a time consuming method and is not fitted to the TERA philosophy since it goes into great details and requires long computation times and model construction efforts. It is a high fidelity case. It also requires a lot of details about combustor design which may or may not be readily available.

6.4.2   Physics Based Approach

This is an approach where the chemical kinetics is mapped makes use of the combustor geometry and understanding of the chemical kinetics to produce a detailed picture of the chemistry. It is useful for designing or evaluating new combustor types or design not in production. It goes into a high level of details and again requires information which may only be found with the combustor manufacturer. All the main combustor units/sub-components are considered and the modelling is based on predefined mixing and flow understanding in turbulent phase.

6.4.3   Empirical and Semi-Empirical Methods

In the context of this research the most useful methods are perhaps the empirical methods which make use of the already established trends of emissions from known combustor types and the empirical equations which relate these emissions to the thermodynamic conditions in the engine can be mapped.

Hence, this is a statistical treatment to already existing data for combustors. The limitations are that dry low NO_x combustors cannot be easily mapped using these techniques since the correlations are based on experimental data and therefore usually combustor specific.

Rizk and Mongia (1994) describe the semi empirical methods as *'calculation approaches that simulate the combustion process by global expressions to account for reaction temperature, system pressures, evaporation and mixing and are used to provide insight about ignition, blowout and emission indices'*.

In turn, the variables in these models include the combustor inlet and outlet temperatures and pressures, pressure loss across the liners and combustor, the fuel-air ratio, equivalence ratio, adiabatic flame temperatures, core mass flow and fuel flow, residence time, combustor volume, volume occupied by evaporated fuel and time required for fuel evaporation amongst others. This makes this type of modelling more within reach of an analytical tool such as the TERA.

6.5 Mapping the Emissions: Empirical Correlations

The first emissions module created for the TERA was an empirical correlation based on aircraft emissions and was adapted to the industrial gas turbine usage. Some of the workings of this model are charted here.

The ideal combustion products from the exhaust of a gas turbine would be CO_2 and H_2O when considering complete combustion, as well as O_2, N_2 and other components existing in the air. Of course this situation is near impossible with conventional combustor systems. The reaction will not be complete and thus some unwanted by-product components will appear. It will be assumed from here on in that the gas turbine drivers use only methane as fuel. The ideal reaction for pure combustion would be as follow:

Ideal Reaction: $\qquad\qquad\qquad CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
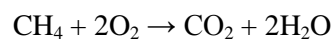
Real Reaction:	Main Reactants	Main Products of Combustion
	Natural Gas	CO_2
	O_2	H_2O
	N_2	NO_x
	S_2	CO
		HC
		SO_2
		C

The emissions produced by each engine need to be predicted in order for comparisons to be carried out. This analysis is needed since engine emissions are regulated and taxed and so ultimately it is an economics issue. It may be the case that one engine with better performance characteristics does not meet the emissions regulations and it will finally be less profitable because of the extra money spent on the emissions taxes.

The emissions model is based on an empirical correlation. It uses known values of emissions of the combustor type which have either been charted by the OEM or are based on an emissions database. An example of an emissions database is the International Civil Aviation Organisation (ICAO, 2005) database. This includes measured emissions at certain power settings for various engines, mostly aviation based. One can use the database to build a picture of emissions at certain power settings for a given engine and then calculate the emission in off design or operating conditions.

This method is known as an empirical method because the emissions of nitrous oxides and carbon emissions including CO, CO_2 and other un-burnt hydrocarbons (UHC) are calculated using an emission index. The index is a way of denoting the rate of emissions production at a given power setting, and thus, a chemical equation of the simplified reaction taking place can be denoted. This will have a parent equation or trend, for example, for NO_x emissions typically the Lefebvre correlation is used as a basis, and then based on the emissions database or OEM trend, the Lefebvre correlation can be tuned or optimised to follow the trend of

emissions for the particular combustor that is being studied. In this way one can tune correlations by their exponents and then once the correlation is tuned it can be used to predict emissions at various power setting or operating conditions in off-design performance.

The charted NO_x trend for one of the GE Frame series of engines (Frame 7EA) is shown in Figure 43. This was taken from a public domain document.
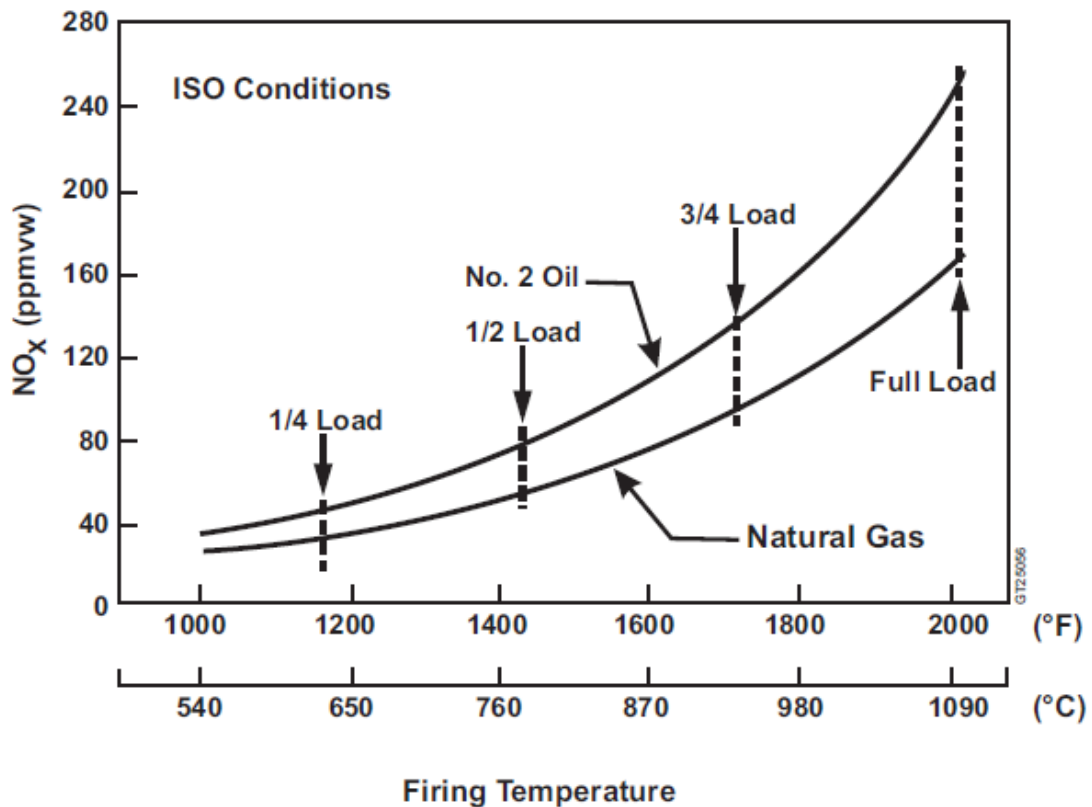
Figure 43: MS7001EA NO_x Emissions Trend (GE, 2003)

6.5.1 Pressure and Temperature Relationships

Efficient combustion depends highly on the temperature and pressure of the air flow in the combustion chamber. Each engine has its own set of characteristic curves relating temperature and pressure at the inlet of the combustor with different ambient conditions. These characteristics dictate the production of different combustion products. The model correlates gaseous emissions with combustor performance parameters.

The model correlates the NO_x emission index, which it then uses to calculate the total emissions throughout the year, as exemplified in Figure 44. The different horizontal axis

under the T_3 axis exemplify the existing correlations of fuel mass flow and pressure with respect to the emission index. The engine P_3-T_3 curves represent the whole range of power outputs for different ambient conditions.
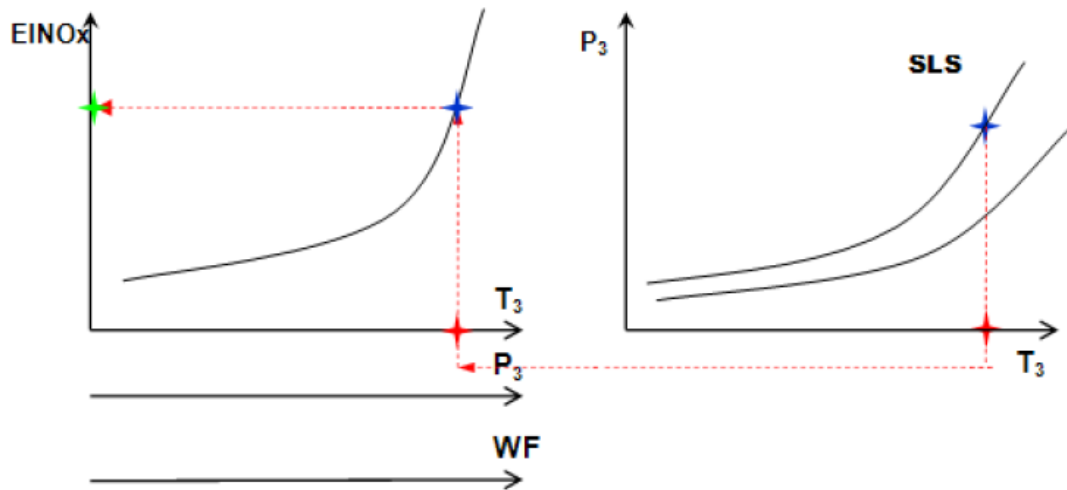
Figure 44: EINO$_x$ related with P$_3$, T$_3$ and mass flow, WF (Left) and engine temperature versus pressure before combustor stage (Right)

The engine P_3-T_3 curve varies with altitude because for a certain height there are different ambient conditions of pressure and temperature. With respect to an aircraft, the program takes altitude conditions into account and estimates a new EINO$_x$ as the plane changes altitude.

The cases under study are simpler than aviation engines due to the fact that industrial engines generally remain at same altitude and are fixed in place. Three typical days during a year are selected; one for summer, one for winter and another one representing spring and autumn (denoted as mid-season), and then make calculations using average temperatures for each type of day in order to build the engine P_3-T_3 curve. The average temperature is simply an average of all the temperature readings for that particular season. Based on accurate data from the location these temperatures are 36°C, 26°C and 20°C for summer, mid-season and winter, the three typical days respectively. The curve is built introducing pressure and temperature data (mass flow and fuel flow data is also introduced to build all the relationships), based on different percentages of full power, i.e. 100%, 80%, 50%, 30% and 20% and later the rest of the intermediate points are estimated by interpolating between the points.

97
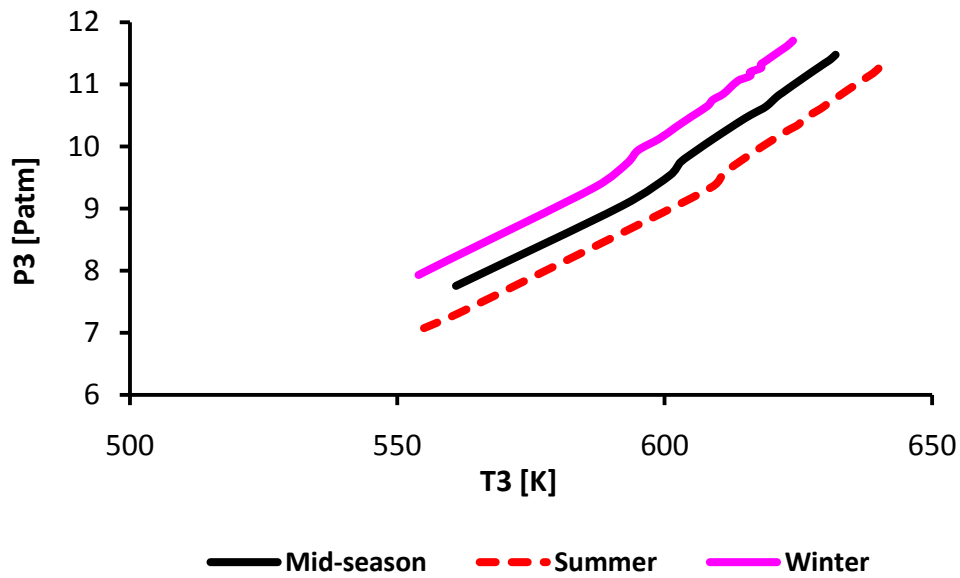
Figure 45: P_3-T_3 curves; temperature and pressure relations before the combustion stage

Three typical days of a year:

Summer: 36°C (90 days)

Mid-season: 26°C (90+92=182 days)

Winter: 20°C (93 days)

For further details on the modelling refer to Khan et al., (2009) and Kyprianidis (2008).

6.6 Adiabatic Flame Temperature

The flame temperature is the highest temperature at the front of the flame of the combustor. The model uses something called the adiabatic flame temperature (AFT) calculation which in turn helps deduce the emissions indices. This AFT calculation can be conducted using one of two algorithms based on constant volume or constant pressure combustion assumptions.

The constant volume combustion (CVC) is the temperature resulting from complete combustion without work, heat transfer or changes in kinetic or potential energy. On the other

98

hand, the constant pressure combustion (CPC) is defined as the same except that there is assumed a change in the volume of the gas and hence is a little lower than the CVC since energy is used to do work in changing the volume of the combustion gases.

The AFT is usually highest close to stoichiometric conditions and is a function of the equivalence ratio. Walsh and Fletcher define equivalence ratio (Figure 46) as *'the local fuel to air ratio divided by the corresponding stoichiometric value'* and this stoichiometry is in turn that condition where all the fuel available can bur completely in air.
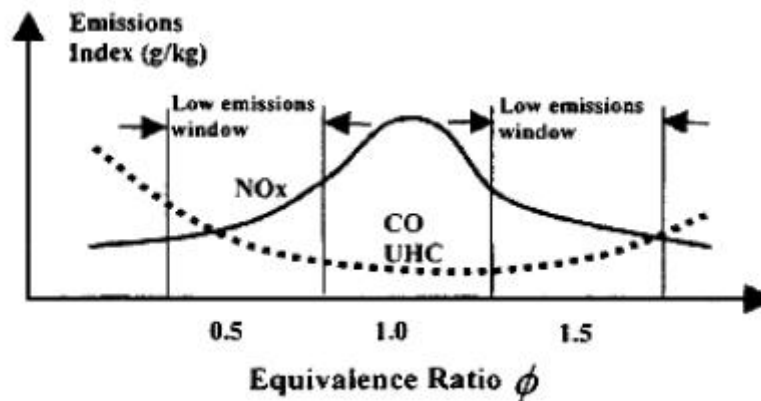
Figure 46: A diagram showing how emissions production is dependent on the equivalence ratio

6.7 Emission Indices

The definition of the Emission Index of an emitted component produced after combustion of the fuel-air mixture is the mass in grams of the emitted component divided by the mass in kilograms of fuel flow as exemplified in equation 6.1. Further, to find the amount of pollutant in grams by mass, the specific fuel consumption must be multiplied by the time spent during that particular power setting and the emissions index (equation 6.2); this is just another form of the previous equation.

$$EI_{pollutant} = \frac{grams_{pollutant}}{kg_{fuel}} \qquad \qquad 6.1$$

The emission index is measured in grams of pollutant per kg of fuel consumed.

$$grams_{pollutant} = (EI_{pollutant})(time)(SFC) \qquad \textbf{6.2}$$

Soot and oxides of sulphur emissions are not taken into account in the study. This does not change the result significantly because firstly, the natural gas usage is regulated according to standards and quality is extremely high and thus the sulphur present in the fuel may be assumed to be negligible. Secondly, the insignificance of the weight and size of industrial gas turbines, as opposed to aviation gas turbines, means an considerable increase in combustion chamber size is possible and therefore the fuel-air mixture and consequently the soot has more time to react and form CO_2 particles. It might be added that the FAR and the PR are lower in some industrial gas turbines (higher for the aero-derivative), which helps to avoid production of these pollutants. The present study does not account for the emissions of soot and sulphur and their associated by-products.

6.8 NO$_x$ Emissions Models

A number of models have been proposed in literature including the original Lefebvre correlation which is a purely empirical correlation and some semi-empirical correlations. The method used here is highlighted below.

The generic correlation is given by:

$$EI_{NOx} = \alpha_1 P_3^{\beta} e^{\left(\frac{T_3}{\alpha_3}\right)}.T_4 \qquad \textbf{6.3}$$

Where:
α_1 & α_2 = Coefficient depending on the unit of measurement
β = Pressure exponent
T_3 = Combustor inlet temperature
T_4 = Turbine entry temperature (TET)
P_3 = Combustor inlet pressure

Whereas the generic semi-empirical correlation as per Courtinho (2009) is:

$$\text{EI}_{\text{NOx}} = \frac{\alpha P_3^{\beta_1} V_c e^{(\beta_2 T_{pz})}}{\dot{m}_A T_{pz} (\Delta P_3 / P_3)^{0.5}}$$
6.4

Where:

P_3 = Combustor inlet pressure

ΔP_3 = Liner pressure drop

V_c = Combustor volume

V_e = Volume occupied in fuel evaporation

m_A = Combustion inlet air mass flow rate

T_3 = Combustor inlet temperature

T_{pz} = Flame temperature of the primary zone

α = Coefficient depending on the unit of measurement

β = Pressure exponent

Further, the semi-empirical methods use the adiabatic flame temperature and the NO_x estimation is heavily dependent upon this as well as geometry of the combustor and residence time.

The original Lefebvre correlation (1984) based on data from various aviation based engines is given by:

$$EI_{NOx} = \frac{9\text{x}10^{-8}. P_3^{1.25}. V_c. e^{(0.01.T_{st})}}{\dot{m}_A T_{pz}}$$
6.5

Where:

T_{st} = Stoichiometric Flame temperature

Another prominent relationship for NO$_x$ estimation is given by Rizk and Mongia (1994):

$$EI_{NOx} = \frac{15\text{x}10^{14}.(t_{res} - 0.5t_{ev})^{0.5}.e^{\left(-\frac{71,100}{T_{st}}\right)}}{\left(P_3^{0.05}\left(\frac{\Delta P_3}{P_3}\right)^{0.5}\right)}$$

6.6

Additionally where:

t$_{res}$ = primary zone combustor resident time, in seconds.

t$_{ev}$ = fuel evaporation time (seconds).

The fuel evaporation time is calculated using the values of the Sauter mean diameter and the evaporation based on spray evaporation history. This correlation is of particular interest because it introduces the fuel evaporation factor. It dictates that a reduction in droplet size reduces the evaporation time and increases the NO$_x$ emissions. However for higher pressures, where evaporation time is small compared to residence time, Rink and Lefebvre (1989) have shown that the NO$_x$ is actually reduced.

The Lefebvre correlation was assumed for the modelling herein and this was because it was defined for a fixed combustor with known geometry and the author felt this could be utilised given that some of the key parameters were known for the engines. The correlation is tuned to match the existing correlations as published by the OEM.

The matching of the basic correlation to the OEM defined trends are charted in the Masters theses of Uwakwe (2011) and Maccapani (2011). As explained before, matching or trending is an exercise of matching the coefficients of the correlation to known trends for combustor types. The trending for the industrial combustors was done by Uwakwe whilst the aero-derivative trending was conducted by Maccapani under the supervision of the author. Some of the data was taken from OEM published trends for combustor types, as in the case for the industrial combustor (Pavri and Moore, GE, 2003) and as for the aero combustor types the ICAO database was utilised.

Assumptions and limitations of the modelling:

1. The modelling of the different combustor types was assumed to be feasible with empirical methods i.e. that industrial as well as aero combustors can be modelled

2. That ICAO data represented the different aero combustors that would b used with engines simulated in this research; whilst in reality the exact combustor details were not at hand, a close match according to the core parent engine of the aero-derivatives was utilised

3. The modelling is very sensitive to adiabatic flame temperature and hence any inaccuracies therein will have translated to the results, though none of the results seem unrealistic

4. The modelling cannot be extended to new combustor types. This is important where the LNG TERA tool investigates pseudo engines or engines for which combustor data is not readily available

5. The modelling does not take into account the chemical kinetics and thus again, cannot model variations in combustor type and any one correlation can only be realistically used for one family of engines, though may still give respectable results for other combustor types

6.9 CO and UHC Emissions Models

The emissions indices for carbon monoxide (EICO) and unburnt hydrocarbons (EIHC) have lower relevance both with respect to emissions taxing and as global warming agents when compared to $EINO_x$ because they are produced in lower quantities and so pose a lower problem. They are produced in higher quantities when combustion temperature and/or the time given for combustion to take place (residence time) is low. In fact, with industrial machines the combustor can be designed bigger and therefore these products appear in lesser quantities. However, the main reason for low production of these pollutants is that the engine under consideration is working at base load most of the time. At base-load these emissions are low due to the combustion temperature. The emissions are higher in the start-up phase but time spent in this stage is an insignificant fraction with respect to compressor drivers.

The generalized form of the semi-empirical correlation for describing CO emission can be represented as:

$$EI_{CO} = \frac{\alpha \dot{m}_A T_{pz} e^{\beta_1 T_{pz}}}{P_3^{\beta_2}(V_c - V_e)(\Delta P_3/P_3)^{0.5}} \quad [5] \qquad \textbf{6.7}$$

Where:

α_1 = Coefficient depending on the unit of measurement

$\beta_1 \,\&\, \beta_2$ = Temperature and Pressure exponents respectively

P_3 = Combustor inlet pressure

ΔP_3 = Liner pressure drop

V_c = Combustor volume

V_e = Volume occupied in fuel evaporation

$\dot{m}_A$ = Combustion inlet air mass flow rate

T_{pz} = Flame temperature of the primary zone

α = Coefficient depending on the unit of measurement

There are a number of correlations for CO and UHC, again, developed by the authors who looked at the NO_x emissions:

$$Lefebvre\ EI_{CO} = \frac{86.\dot{m}_A T_{pz} e^{-0.00345 T_{pz}}}{P_3^{1.5}(V_c - V_e)(\Delta P_3/P_3)^{0.5}} \qquad \textbf{6.8}$$

$$Rizk\ \&\ Mongia\ EI_{CO} = \frac{0.18 \times 10^9. e^{(7800/T_{pz})}}{P_3^2(t_{res} - 0.4t_e)(\Delta P_3/P_3)^{0.5}} \qquad \textbf{6.9}$$

$$Rizk\ \&\ Mongia\ EI_{UHC} = \frac{76 \times 10^9. e^{(9756/T_{pz})}}{P_3^{2.3}(t_{res} - 0.35t_e)^{0.1}(\Delta P_3/P_3)^{0.6}} \qquad \textbf{6.10}$$

$$Cranfield\ Modified\ EI_{UHC} = \frac{910.\dot{m}_A T_{pz} P_3^{-2.5} E7 e^{(-0.00345 T_{pz})}}{(V_c - V_e)(\Delta P_3 / P_3)} \qquad \textbf{6.11}$$

For predictions in this work, the Lefebvre correlation is again used for CO emission while the Cranfield-Modified correlation is adopted for the UHC emission. The Cranfield model was developed initially by Courtinho (2009) at Cranfield University and then further developed by the author and Uwakwe (2011) who worked directly on the LNG TERA modelling under the supervision of the author of this thesis. Further, for details of how the emissions correlations were mapped from known trends please refer to Uwakwe (2011), Maccapani (2011) and especially Courtinho (2009). This process was done in Microsoft excel and the mapped correlations were hardcoded into the TERA tool. There are different mappings for different combustors; aero and industrial frame engines.

6.10   The TERA LNG Emissions Model: A Semi-Empirical Approach

The original emissions model was changed to semi-empirical methods since it was felt this gave better estimations for the fixed combustor geometry that was being investigated and was also a simpler method to use. The models are very similar in that they both use very similar inputs but it was felt that the semi-empirical method would be easier to use in order to get estimations for the aero-derivative combustors too and also given that the details of the industrial combustor were at hand.

An emission model was created at Cranfield University to evaluate the amount of emissions produced by gas turbines in aviation. This model simulated the whole flight path with taxi, take-off, cruise and landing. A model like that cannot be applied for industrial gas turbines because they usually operate at the same position and altitude and therefore some modifications were required to the original aviation model. The final model diagram can be seen in Figure 47.
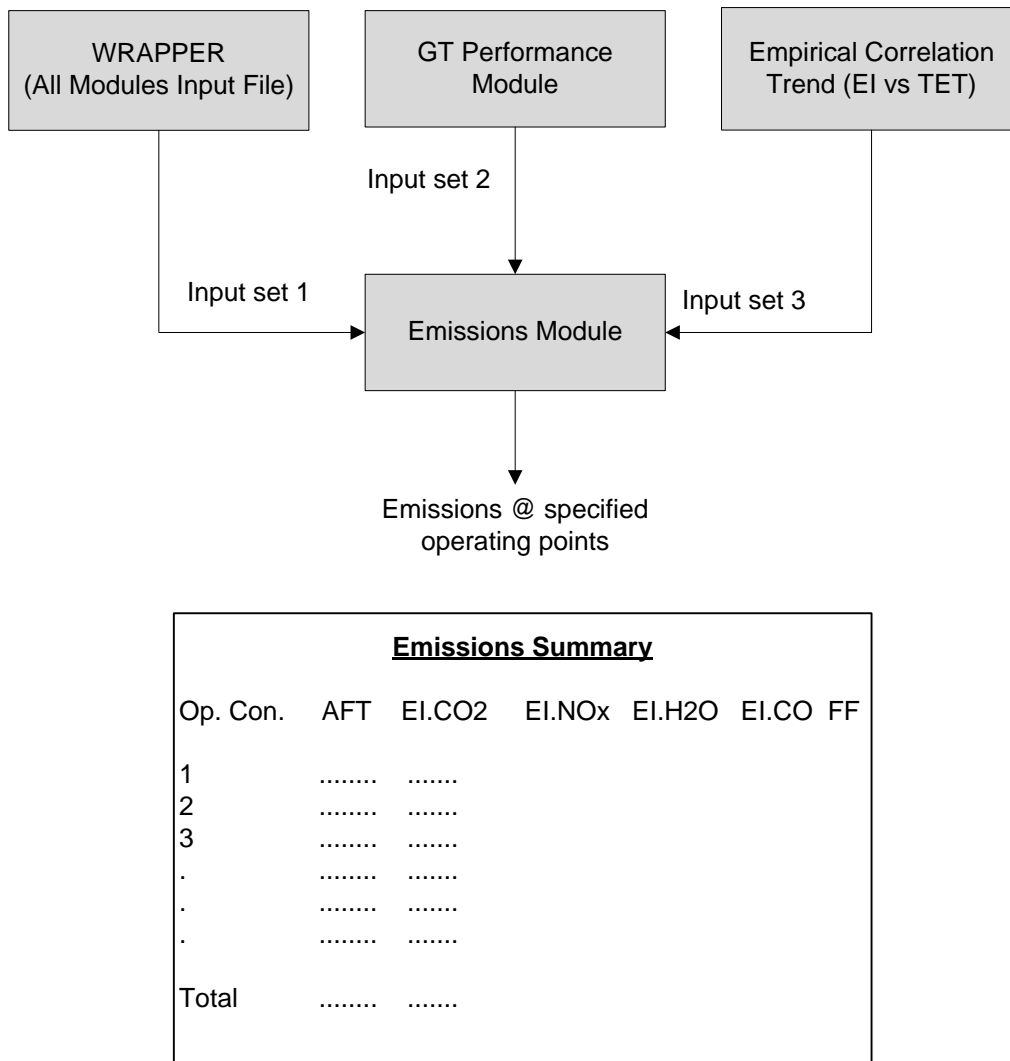
Figure 47: A schematic of the structure of the emissions module

Input Set 1 (User defined values for combustor):

1. Combustor volume (m^3)

2. Primary zone evaporation fuel volume (m^3)

3. Residence Time (s)

4. Fraction of Primary zone occupied by air (%)

5. Combustor Efficiency (%)

6. Combustion mode (Constant volume or constant pressure)

7. Fuel type (Natural gas, Kerosene etc)

8. Altitude (km)

9. Number of combustion chambers

106

10. Switch between aero and industrial frame combustor types

Input Set 2 (Thermodynamic parameters from performance results):

1. Compressor outlet temperature (K)
2. Firing temperature, TET (K)
3. P_4, P_3 (kPa) - Pressure before and after combustion chamber
4. Mass flow rate (kg/s)
5. Fuel Flow (kg/s)

Input Set 3:

1. This is not a set input, but rather a correlation based on known combustor characteristics
2. The known characteristic is mapped as an empirical equation in Excel and then that equation is brought into FORTRAN code and hard coded
3. Each engine type has its own empirical correlation, though for some engines it is the same e.g. Frame 7EA and Frame 9E since combustors are the same but only different number of cans

Broad Procedure:

1. The simplest combustor geometry is known and this, along with fuel type and residence time, combustor efficiency and primary zone information are inputs (set 1)
2. The performance module provides details of each operating condition and the consequent pressures, temperatures and core mass and fuel flows (set 2)
3. The thermodynamic performance parameters P_3 and T_3, along with the proportion of air in the primary zone and the heat enthalpy of the fuel are used to estimate the adiabatic flame temperature (AFT)
4. The AFT, along with core mass flow, pressures and combustor volume are used to estimate the emissions indices
5. The coefficients of the emission index equations are modified so as to fit the known trends for emissions for a given combustor type
6. The correlations are then hard coded inputs (set 3)

7. The emissions are calculated based on correlations for NO_x, CO and UHC whilst for CO_2 stoichiometric relationships are used

7. Financial Implications of Equipment Selection

The value of a product of service is hard to measure and this is why in the stock market people value shares differently. It is hard to ascertain when to value and what or who carries value. Similarly profit does not equal cash because cash has different value at different times. This is the main reason why *cost* is used in accounting and finance.

Another critical implication is risk in the sense that the future is uncertain and so there is no guarantee a certain level of return can be achieved. One can make an important observation here; that value is driven by some factors, including *time*, *risk* and *returns* on the initial investment. Returns can be measured in terms of profits and cash, whilst risk is a measure of uncertainty and volatility of returns. The time factor denotes whether there is sustainability in an investment and looks at the entire life cycle of the returns.

Projects in the oil and gas sector can last for long periods of time, especially an LNG plant which may well have a design plant life of more than 20 years. Hence, it is important to capture the value of the investment taking into account all three factors including returns or profits, risk taken on by investing and the time value of money and resulting profits.

This chapter looks at the techniques one can use to analyse the economic or financial aspects of an LNG plant. This modelling is a conclusion of all the modelling that has come before and in effect the economics module is the one where all the calculations are put into perspective.

The economics module also forms part of the criteria for integration of the management studies (MBA) to the technical side of the research. The project appraisal techniques were studied in the course Financial Management as part of the MBA and this enabled exposure to the ways of assessing a project or an option against another in financial terms.

7.1 Financial Appraisal Techniques

The literature survey showed that various techniques are available for project assessment with respect to economic performance. These include Discounted Payback (DPB) and Simple Payback (SPB), Internal Rate of Return (IRR) and Net Present Value (NPV) methodologies (Arnold, 2005).

The SPB and DPB methods both assess the time taken to recover the initial capital in an investment as explained by Boussabaine and Kirkham (2004) and seen in equation 7.1. The shortcomings of both methods are that they do not allow the user to easily compare across different projects. Such techniques can only really be used to look at a single option as opposed to an array of options since comparisons cannot easily be made.

$$\sum_{t=1}^{y} \frac{(S_t - \Delta I_t)}{(1+d)^t} \geq \Delta I_0 \qquad \textbf{7.1}$$

Where,

y   = length of time over which cash flows considered

S_t = savings in operation in year t

ΔI_0 = initial investment costs

ΔI_t = additional investments costs pertaining to year t

d   = discount rate

General economic value in business is usually measured by a simpler parameter called ROCE (Return on Capital Employed, or also known as RONA or returns on net assets. This is a simple method which assesses based on capital employed less current liabilities. This is more useful for looking at operations but once again does not give us a direct comparison between options nor a good way of measuring value with respect to time.

$$ROCE(\%) = \frac{\sum P_n}{\sum TC_E} \times 100 \qquad \textbf{7.2}$$

Where,

$\sum TC_E$ = total capital employed

$\sum P_n$ = net profit before income and tax

The internal rate of return is again a simple metric which entails choosing a discount rate which will return a value of zero for the net present value, satisfying the expression in equation 7.3.

$$\sum_{t=0}^{N} \frac{A}{(1+d)^t} = 0 \qquad\qquad \textbf{7.3}$$

This means that all options which fall below a certain discount rate will be rejected. This is a way of following the market rate of interest because there is a predefined cut-off rate which is followed and this rate is usually the market rate. This method forces one to select projects that must be generating returns which are at least equal to that available elsewhere on the market. Again, the method is in some ways limited because it will be selective in the way in which projects are selected and will not entail and open and overarching comparison. Some good projects may be rejected and the method also works with today's rates and does not really account for uncertainties or changes in the future; today's rate, and thus risks are controlling the decision.

7.2 The Net Present Value (NPV) Methodology

The technique used to conduct the economic analysis is the Net Present Value method which, essentially, tries to discount tomorrow's money in today's terms. Various costs are accounted for including maintenance costs, fuel costs and cost of acquisition of machinery. The Net Present Value formula can be seen in equation 7.4.

$$NPV = \Sigma\left(\frac{NCF_{ann}}{(1+i)^t} \right) \qquad\qquad \textbf{7.4}$$

Where,

NCF_{ann} = net annular cash flow

i = discount rate (also known as the rate of returns) and

t = time in years at which the accounting was done (usually at end of year)

The present value of each year is summated for all the years that the plant is expected to be operational and finally a single value of NPV is arrived at. A typical discount rate may be 8% but increasing discount rate reflects on a project with greater risks and can be as high as 15%. The discount rate will account for the financial risk analysis.

111

7.3 Risk in Finance

Marshall (1999) summarises the different methods available in finance and economics to assess the uncertainty of a project as can be seen in Table 6. Deterministic is described as that which is based on numerical techniques whilst quantitative uses a statistical or probabilistic approach (Boussabaine and Kirkham, 2004). Qualitative on the other hand involves methods of scoring or and subject grading of options. The risk analysis in his project is of the deterministic type, though some offshoots of the research did apply quantitative techniques (Maccapani, 2011); this is one very appealing basis for further work and development of the present LNG TERA tool.

Table 6: Risk and Uncertainty, common techniques in use (Marshall, 1999)

Deterministic	Qualitative	Quantitative
Conservative benefit and cost estimating	Risk Matrix	Input estimates using probability distribution
Break-even analysis	Risk registers coefficient of variation	Mean-variance criteria
Risk adjusted discount rate	Event Trees (qualitative)	Mean-variance criterion
Certainty equivalent technique	SWOT Analysis	Decision Tree analysis
Sensitivity Analysis	Risk Scoring	Mathematical/analytical techniques
Variance and Standard Deviation	Brainstorming	Artificial Intelligence
Net Present Value	Likelihood/consequence assessment	Fuzzy Logic
		Event Trees (quantitative)

It is not easy to qualitatively assess risk given the parameters of this research. The author wished to provide a quantitative/numerical picture of the economic value of options and nor was it deemed tolerable to make the risk within finance a wholly complicated method utilising techniques such as fuzzy logic or develop complicated mathematical algorithms, though their worth is understood. In the spirit of the TERA philosophy it was felt the Net Present Value technique would suffice. Also, the discount rate in the NPV technique itself *is* a measure of risk.

7.4 Examples of Economic Analysis for LNG Projects

It was mentioned earlier that there are various economic/financial commentaries on the subject of LNG plants. This research aims to gather a greater perspective in the form of gas turbine emissions, performance, lifing and maintenance before doing the economics calculations. The main difference is the breadth of factors taken into account. The other key difference is that the TERA is independent of field data and operation of plant; it is a tool aimed at looking into the basic feasibility of plant equipment selection and hence does not depend on field data and is mostly a simulation which explores the aspects affecting *part* of the plant. The following examples must be taken in light of this fact.

Al-Saadoon and Nsa (2009) present an up to date and comprehensive quantitative analysis of the economics of LNG plants. Further, they look at the entire LNG chain when looking at the calculation, which is outside the scope of the research presented here. Interestingly a base plant of 4.2 mmtpa is selected which is somewhat similar to the case for this research, however, the whole transportation and infrastructure build is accounted for too.

The CAPEX extremes are also cited between $200/TPA and $850/TPA, but the latter is dismissed as an absolute outlier value. Patel (2005) provide further range of CAPEX for typical projects coming in at 375, 275, 230, 210, 200 $/TPA for the Qatargas, Nigeria LNG, Atlantic LNG, Rasgas and Oman LNG respectively. These values cannot be used for the basis for comparison in this research given the very different methods and factors of the analyses conducted. It must be mentioned that verifying the results for this research is near impossible as no comparative basis or study can be found which isolates the gas turbine technology in the way in which it has been analysed here.

Al-Saadoon and Nsa go further to describe the details of the plant in terms of plant set up time, liquefaction and re-gasification ports as well as maintenance factors. This is important, because as mentioned earlier, many studies simply look at the maintenance as a factor, based on experience or OEM data, whilst this present research looks at the maintenance as a factor of the predicted performance of the engine, though based on a simulation. Hence, it is difficult to establish accuracies given the disparities between what is established through publication and available field data and what is simulated here in this research. The study does conclude that the determining factors include the discount rate and for the details of the sensitivity of economic parameters refer to Al-Saadoon and Nsa (2009).

Another comprehensive picture is painted by Lisdonk et al (2010) in the prestigious LNG 16 conference in Oran. They look at various aspects which affect the LNG plant and include scenarios of plants with industrial frame engines, aero-derivatives as well as combined cycle plants. This study points out correctly the benefit in economic terms of using the higher efficiency machines such as the aero-derivatives as well as combined cycle and also looks at the emissions in some detail. However, the maintenance and lifing aspect covered in the present research is not explained, it is assumed that they used either field data for these machines or factored in the maintenance, again, missing a vital part of the entire picture. Again, their analysis is goes further than the driver of the liquefaction process. Some of their results are presented in Table 7 and Figure 48 where chart (a) shows the specific electrical power generated from each plant, (b) shows the specific CO_2 emissions (fuel only), (c) shows the specific CAPEX and (d) the specific NPV of all six evaluated options. CAPEX figures only include process and utility expenditures. Specific NPV is based on total plant CAPEX (Lisdonk et al., 2010).

Table 7: Annual LNG capacities based on 340-345 stream days per annum (Lisdonk et al., 2010)

Options	C3/MR drivers	Power plant	Heating medium	LNG capacity (mtpa)
1	2 Frame 7	4 Frame 6	HTF	4.5
2	2 Frame 9E	4 Frame 6	HTF	5.9
3	2 Frame 9E+ HRSG	3 * 28 MW ST	Steam	6.0
4	80 MW ST / Frame 9 + HRSG	3 Frame 6 + HRSG 2 * 20 MW ST	Steam	6.0
5	2 LM6000 / 4 LM6000	4 LM2000	HTF	5.3
6	LMS100 / 2 LMS100	4 LM2500+	HTF	6.4

114
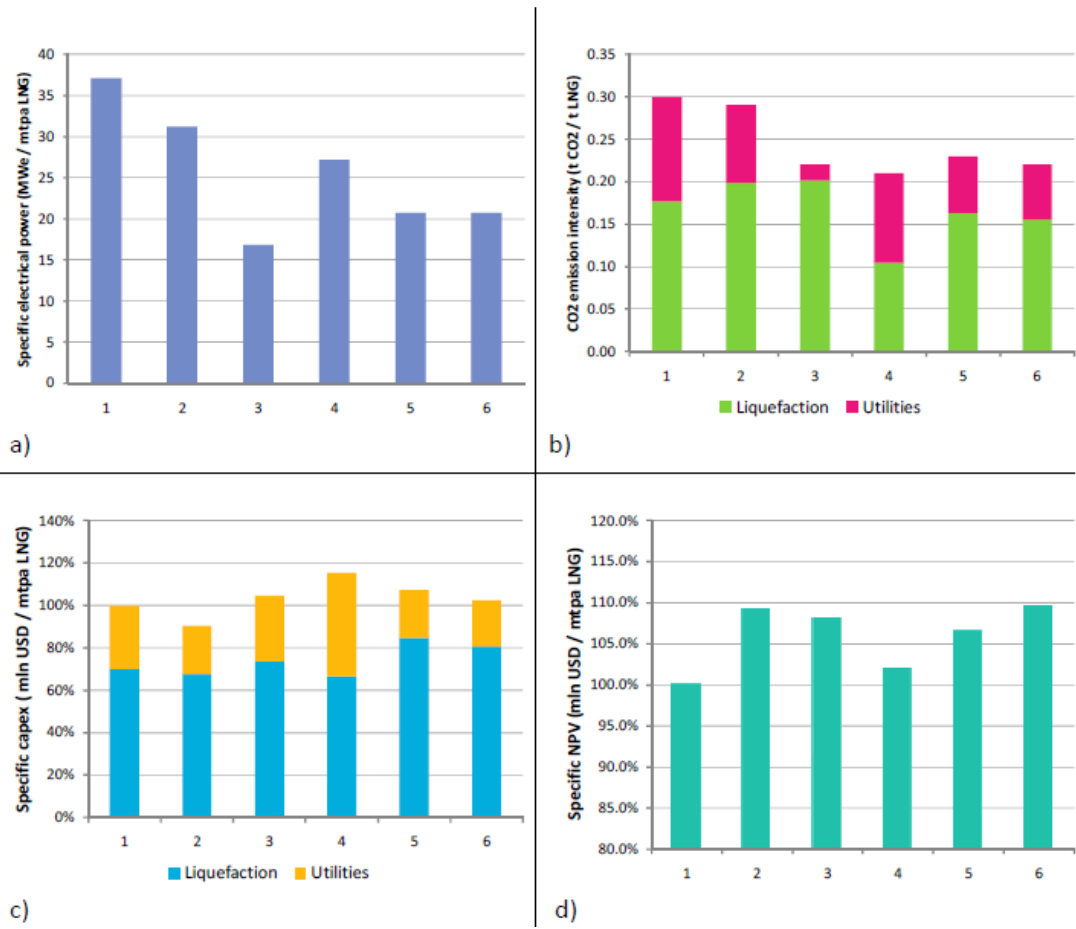
Figure 48: Results summary for Lisdonk study (Lisdonk et al., 2010)

Many more examples of studies can be found with Jeong et al., (2008), a comprehensive research methodology of emissions and economics, process and driver capitalisation (Liu and Bronfrenbrenner, 2001) amongst others.

7.5 Economics Module Structure

The financial calculations are closely linked to the maintenance scheduling in that the revised failure schedule from the maintenance module is adopted and costing of the components that need replacing is done. Implications of lost production are taken into account from the information about total downtime per year. The financial calculations thus incorporate the total maintenance cost.

It is required to represent the process in some way in order to link absolute LNG production with GT operation. This requires detailed understanding of LNG train set-up and compressor and cooling requirements. The current module takes a typical value for overall process efficiency for each cooling cycle and calculates the gas compressor load and water cooling load according to a given baseline. The baseline is made up of two Frame 7EA engines running a train rated at circa 4.5 mmtpa (Akhtar, 2004). This gives the TERA a value for the GT load based on the requirements of the gas compressor and the system can proceed to calculate the power requirement from the GT at given times of the day/year and thus the fuel flow.

The revenue is then calculated by assuming a certain production target in millions of metric tons per annum for a given train with given set of GT's. The economic calculations use an index to change the fuel price over the years of simulation according to estimates of degradation in the technology. This takes account of degradation but is not the ideal method for incorporating degradation. Degradation estimations are not an objective here though this should be looked at in the future.
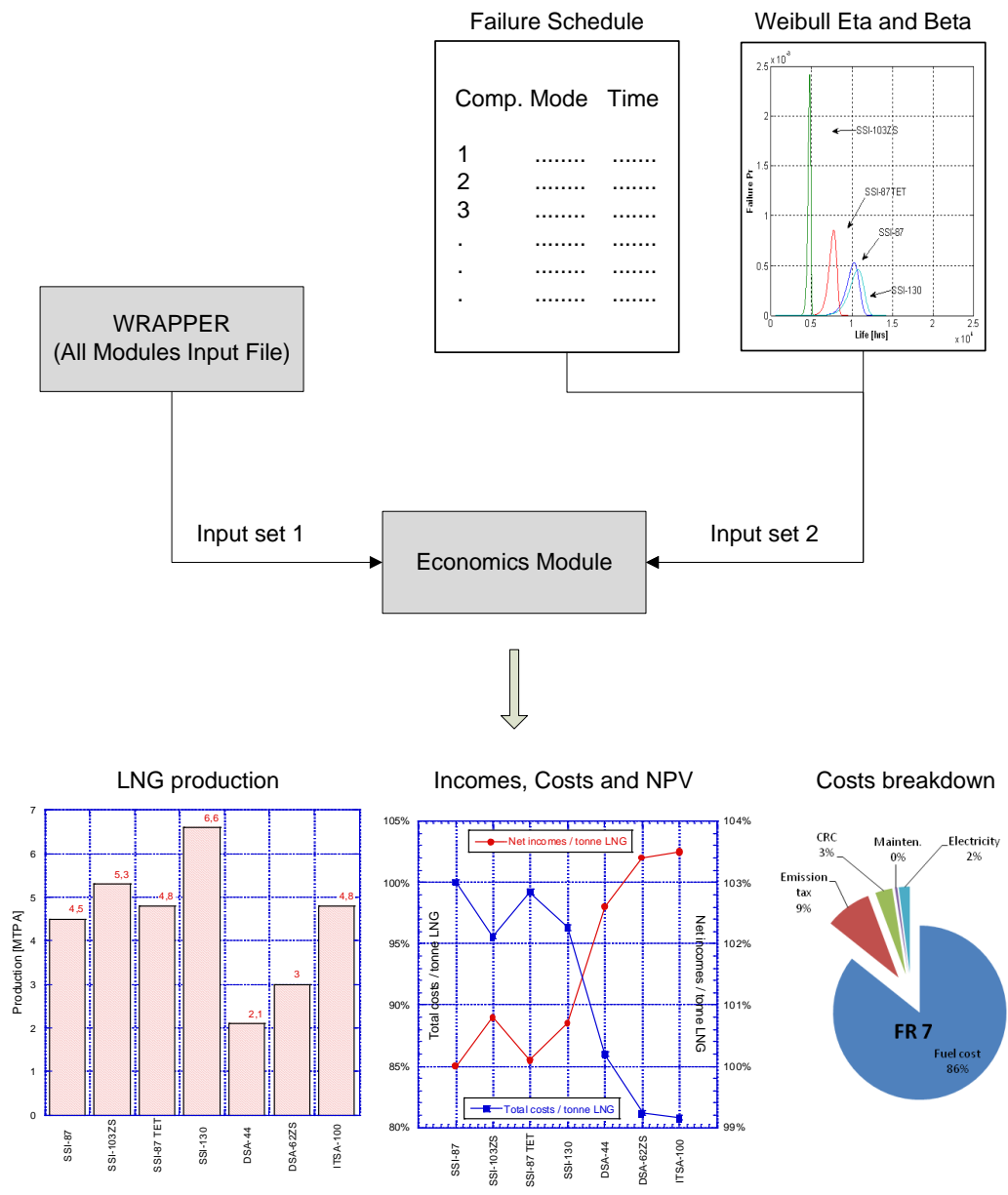
Figure 49: Schematic for structure of Economics Module

Input Set 1 (User defined values):

1. Discount rate (%)
2. Design Plant life (years)
3. Annual Operating hours
4. Fuel heating value (MJ)
5. Fuel Costs ($/GJ)

6. Emissions tax costs ($/tonne)

7. Electricity costs – for electric motor if needed for start up and supplementary power as in the case for industrial heavy duty engines (cents/kWh)

8. Cost of GT (table from which cost is interpolated based on power)

9. Degradation of engine (consequent increase in fuel consumption over the years)

Input Set 2 (Results of Maintenance module):

1. List of failures in the form of a schedule

2. The schedule is used to simulate the costs over the duration of the plant life

8. Power Plant Case Studies

The results section of this thesis is based on various scenarios. The first scenario looks at the Frame 7EA engine in isolation since this is the baseline engine. The results for the Frame 9E engine are then introduced and comparisons made to the Frame 7EA engine. Next the aero-derivative engine results are presented and finally the pseudo-engines are compared.

8.1 Case Study 1: Frame 7EA Baseline

The first case study is centred around the baseline engine which is modelled on the General Electric Frame 7EA machine. This is denoted as baseline because it is the typical engine already in use for many LNG plants. The configuration of a single train is such that two frame 7EA machines are used in conjunction with the Shell DMR process.

It is envisaged that the Frame 7EA will produce 4.53 mmtpa. This is based on the idea that the engine running the first cooling loop, the propane pre-cooling refrigerant, will run at 58MW and the engine running the second loop, the mixed refrigerant, will be running at 85MW. There is also envisaged a large electric motor for start up and also to provide a small amount of power to the gas compressors. This is because of the high start up torque in industrial frame engines. The aero-derivative engine will not need the starter motor. The starter motor is 7MW in size.
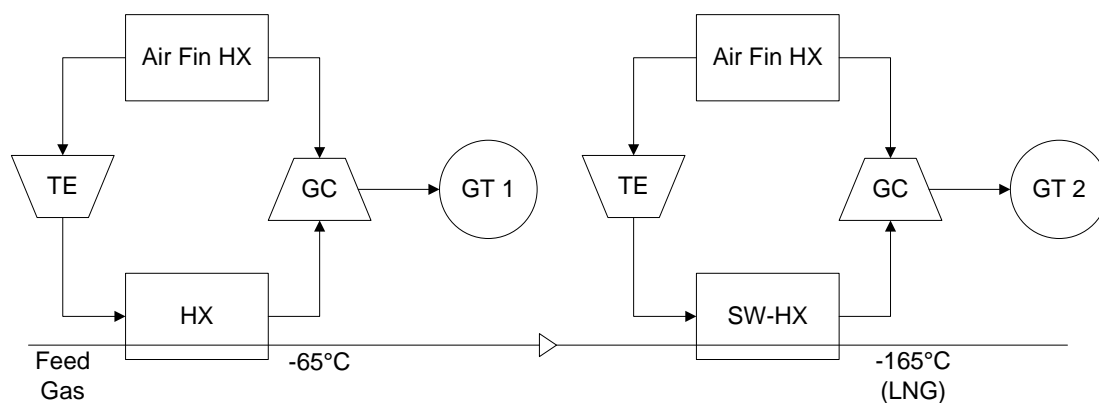
Figure 50: Shell DMR Process layout with two gas turbine drivers

The generic plant set up can be seen in Figure 50 which shows the Shell DMR process where the first cooling loop is powered by the first gas turbine GT1 and the second by GT2. This general layout will be used for all scenarios since only the DMR process has been used for ease of simulation. The SW-HX in the second loop is a spiral wound heat exchanger whilst the first loop uses a basic condenser type. TE stands for turbo expander and GC stands for gas compressor.

8.1.1   Baseline Engine: Thermodynamic Performance Simulation

The engine thermodynamic performance simulation is done based on a given site location with predefined ambient conditions. The ambient variation for the plant location can be seen in Figure 51. The data are taken for three seasons and three typical days are created from each season. Thus, for each season, a single days worth of simulation is carried out and then multiplied by the number of days in that season to get total amounts of fuel usage and emissions and so on. This method reduces computation time.
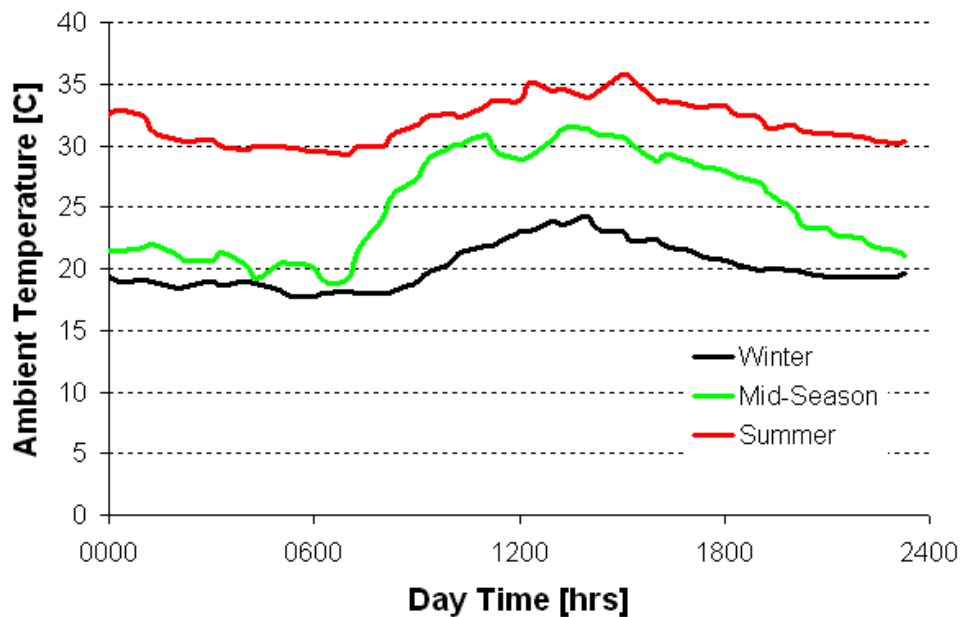
Figure 51: Daily ambient temperature profile for pant location (Australian MET Office, 2008)

And next the variation in power for changes in turbine entry temperature can be seen in Figure 52. The graph shows the variation in power in off design conditions compared to the design point power. The design point power is denoted in the centre at 0K change from design point firing temperature (D.P. TET). The graph shows a measured increase in power with

120

increasing TET and consequent reduction in power with decreasing TET as expected. The graph also shows the change in efficiency with respect to TET change. The design point efficiency is around 32.5% and the efficiency rises with increasing TET; of course there are trade-off's between how much one can increase the TET and achieving a maximum thermal efficiency. The efficiency, according to the simulation doesn't drop off till one gets to an increase in TET of over 200K compared to the design point, but of course there are limitations with respect to the materials technology and how much firing temperature the engine core can withstand. It is important to note that this trend is not taking materials and certain controls of the engine into account; it is a trend based on simulated thermodynamic performance calculations based on geometry and fuel properties. The trend is also isolated to a given fixed ambient temperature.
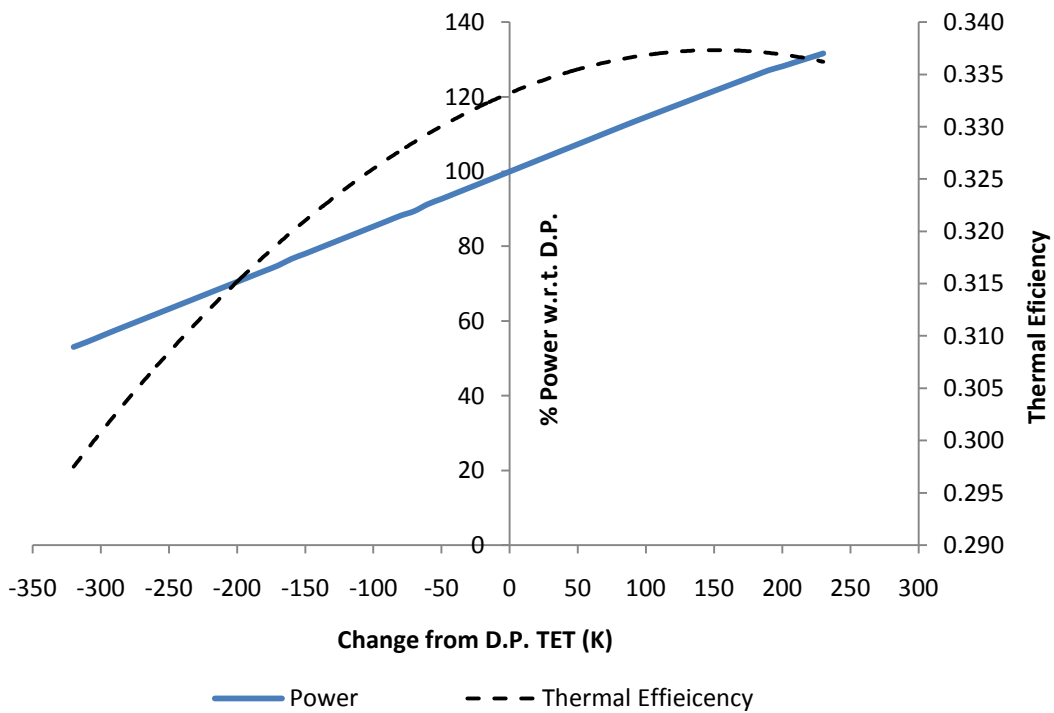
Figure 52: Power output and thermal efficiency versus TET for given T_{amb}

The graph in Figure 53 shows the changes in power and thermal efficiency versus a change in ambient temperature; this is described as the ambient capability of the engine. The drop in thermal efficiency is marginal in terms of percentage points but very significant as it gives

rise to considerably larger fuel consumption. The drop in efficiency is 7 percentage points for an increase between the design point conditions of the engine up to an ambient temperature of 55 C. However, for the plant location, the maximum temperature envisaged is circa 35 C. Also, it can be seen that the drop in power is considerable, and at 35 C the power has dropped to 87% of the design point power. These sensitivities will later be compared with other engines to further comment on the ambient capabilities of the engine.

No doubt certain controls will be used in operation to maintain a certain level of power; for the Frame 7EA engine these come in two forms; the TET control and the IGV control. The TET control is a control of the fuel flow and hence firing temperature. Changes in the ambient conditions are picked up by sensors and the balance is altered in order to maintain a certain power. However, with the advent of low carbon and NO_x technologies, typically the preferred mechanism is to use IGV control and keep the TET constant. It will suffice here to say that emissions controls mechanisms are complicated and require that IGV control be used instead of TET control.
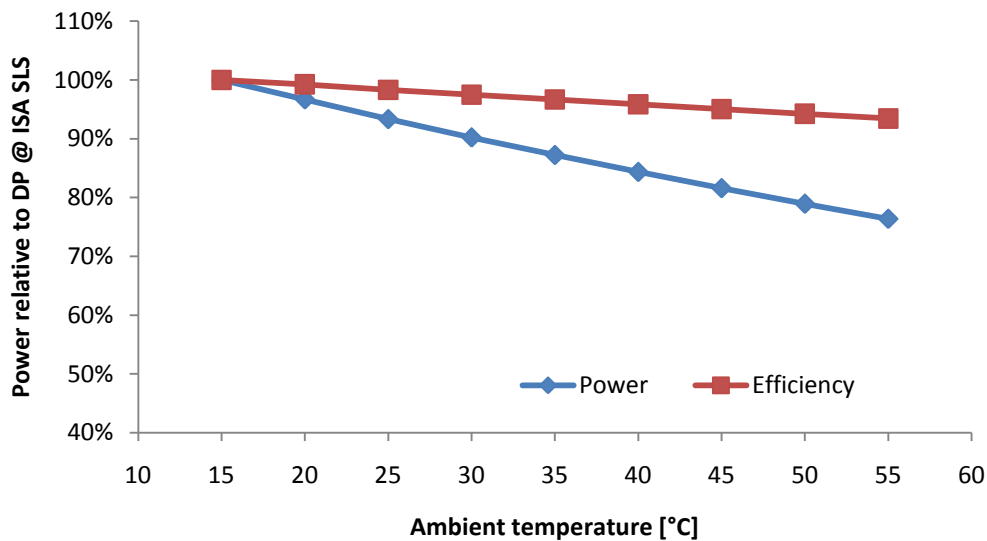
Figure 53: Variation in power and thermal efficiency versus T_{amb}

8.1.2 Baseline Engine: Lifing and Risk Analysis

The results generated by running the LNG TERA from performance through to risk analysis are shown in this section. The first result is a graph comparing the different life estimations of critical component in the gas turbine (Figure 54).
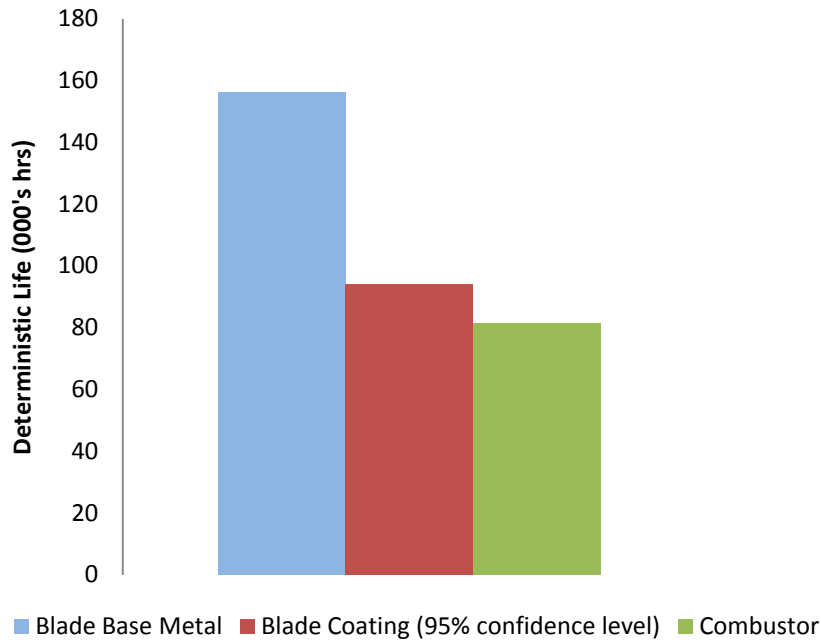
Figure 54: Life estimations for Frame 7EA based on 75MW power demand

This result shows that for a given power demand, the limiting life is that of the combustor and that the creep life of the turbine blade is the longest comparatively. This trend is partly due to the fact that 75MW is a moderate demand, indeed in LNG applications the engines are run at close to design point power. This would be 87 MW for the Frame 7EA engine.

It must be noted that Figure 54 shows a first set of unprocessed results from the lifing analysis. Usually, when conducting creep analysis, safety factors are applied to bring the results into perspective. This is done due to the sensitive nature of the creep curves utilised and because the technique usually involves a lot of discrepancy. Moreover, the system does not boast predicting the life with high accuracy, but rather a basis for comparison which allows the user to compare one component or engine against another. The main conclusion from Figure 54 is that the combustor is life limiting based on a moderate power demand from the engine.

Using the risk analysis module, a Weibull based failure curve for the entire engine is created by running a Monte Carlo simulation and looking at the 95% safe life confidence. The estimated life to first failure is circa 22,300 hours. This is a reasonable estimation. Figure 55 shows the probability density function result. This result is for a constant power demand of 75

MW. The y axis shows the PDF, which is a frequency of occurrence linked to each incremental value of life. In effect, the system is saying that each value of life has a certain likelihood of being achieved, and that values between 15,000 hours and 50,000 hours are more likely. To make this result more useful, it is better to convert the PDF into a cumulative density function (Figure 56), which tells the user of the tool what the likelihoods are in an incremental and cumulative way. This way one can denote what is the total likelihood as a probability out of 1.0 that a certain life will be achieved. Further, this latter result can be used to work out a certain life based on a safety margin. If the user wants to be 95% confident that a certain life will be achieved the corresponding value of life at 95% confidence interval can be read off the CDF. In this case the life for the engine 22,300 hours.
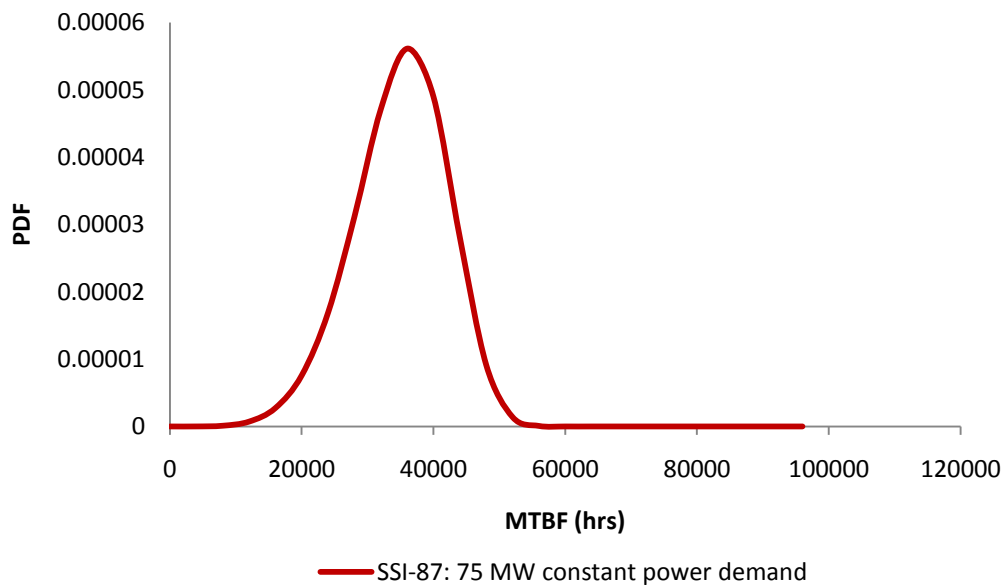
Figure 55: PDF for Frame 7EA at 75 MW

124
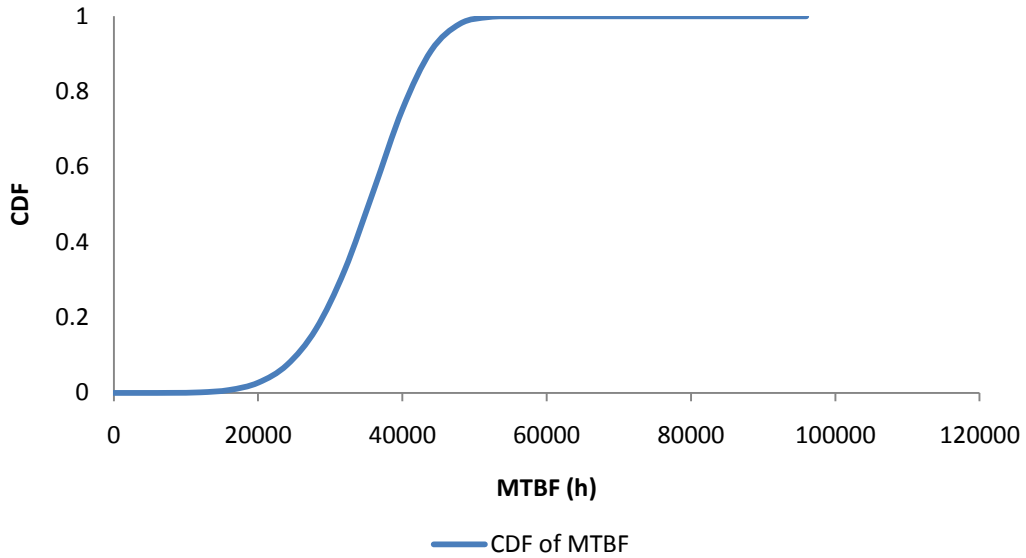
Figure 56: CDF for Frame 7EA at 75 MW with a safe life of 22,300 hrs at the 95% confidence level

The graph in Figure 57 shows how life varies with power demand for the engine. This is a sensitivity which is not specific to a particular scenario but rather which looks at the idea of the isolated engine being run at various power demands. The power demand ranges from 70 MW to 85 MW. It can be seen that the life drops drastically with increased power demand.
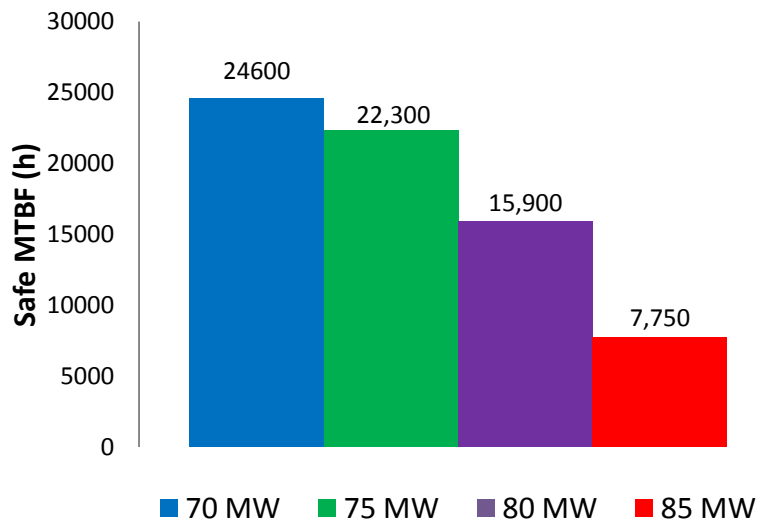
Figure 57: Power requirement versus safe life of engine

Again, PDF distributions can be created for each power setting to deduce the likelihood of failure and chart the pattern of risk. The graph in Figure 58 shows that the distributions change between power settings for the Frame 7EA gas turbine. It can be seen that increasing power demands not only means a lower life, as expected, but also means less uncertainty. This results is justified because increased temperature effects exaggerate the occurrence of failure and the higher the temperature the lower the variation in life. The variation for the 85MW variant is very low and the failure is very much defined at around 7,700 hours. Interestingly, the lower power trends have a lot of variation respectively. The operator can use these results to make decisions about how to run the engine and how much uncertainty there will be, though there is a lifetime saving to be made by running at lower firing temperatures, it is harder to predict with confidence the range of times between which failure will occur.
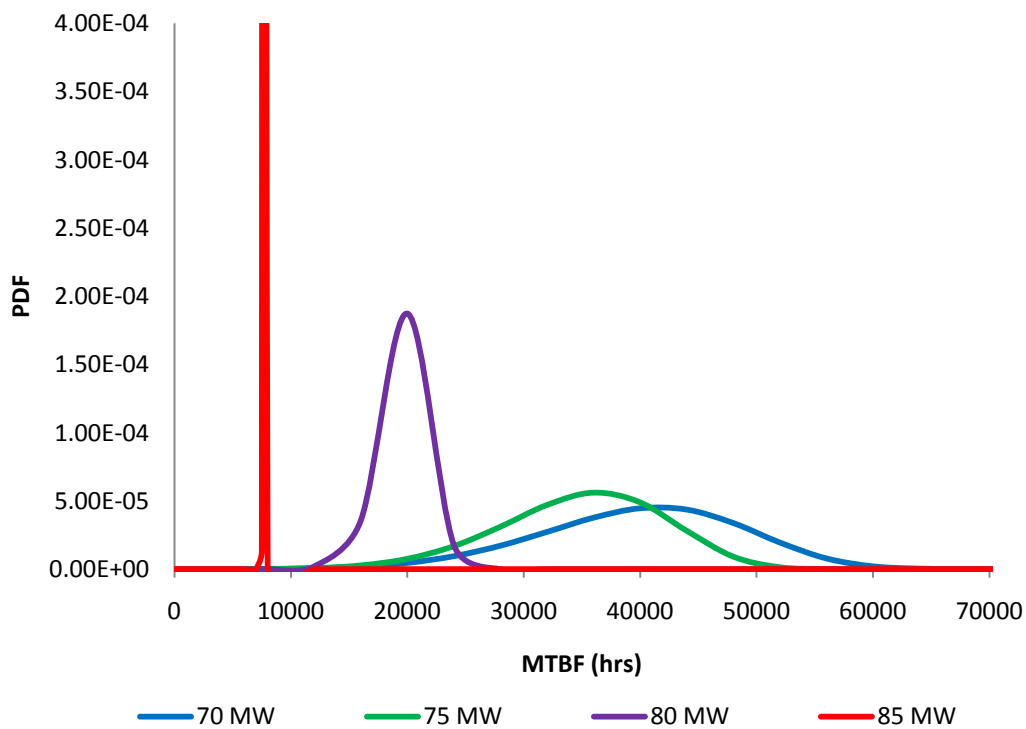
Figure 58: Failure distributions for the entire engine at different power demands

8.1.3   Baseline Engine: Maintenance and Economics

The maintenance and economics findings give further insight to the behaviour of the GT. The trend in Figure 59 shows how the maintenance cost varies with time both on a year by year basis as well as a cumulative maintenance cost. These costs are accumulated for both engines

126

in a single train and whilst the costs for the first engine are lower; the overall costs follow the same trend. The total maintenance costs over a 20 year period come to around $16 million. These costs are expected to change for varying production and later, comparisons will be made between other engines with larger production capacities.
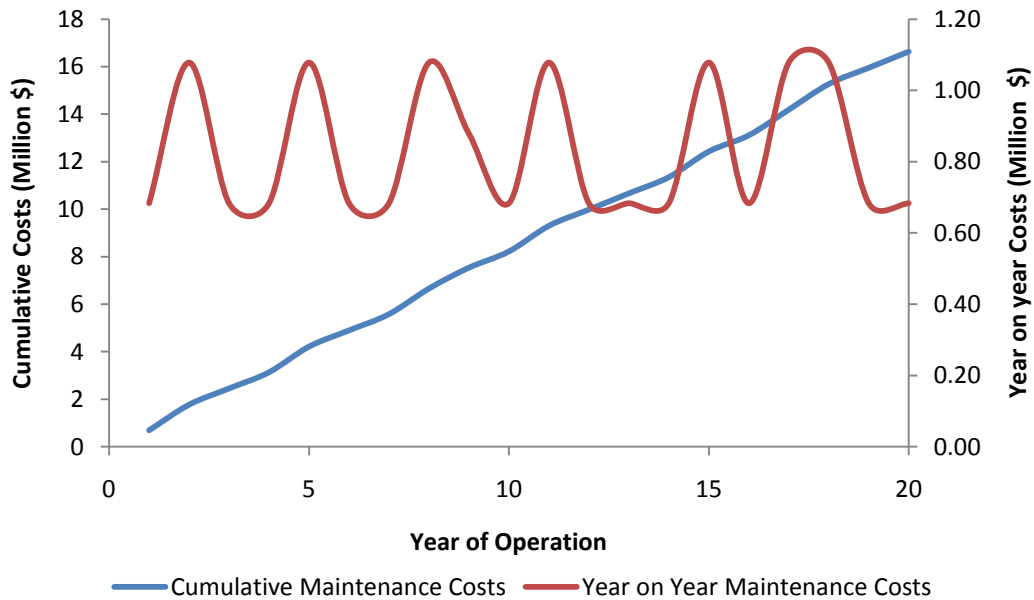
Figure 59: Year on year maintenance costs and cumulative costs for the Frame7EA

Further, Figure 59 shows the total cost of operation for this set up of train and a target production of 4.53mmtpa. It is interesting to see that the ratio of fuel cost to total cost is very high, which means that the majority of costs are due to fuel. In fact, for this train, the fuel accounts for 86% of the costs. This may be higher than expected because the study is looking at the isolated engine and not the infrastructure and auxiliary components around the engine. Indeed no attempt is made to calculate total plant costs since this is outside the scope of the project and requires further modelling of other components which and not under the branch of rotating equipment. Hence the study should be considered a comparison and not a final overall appraisal.
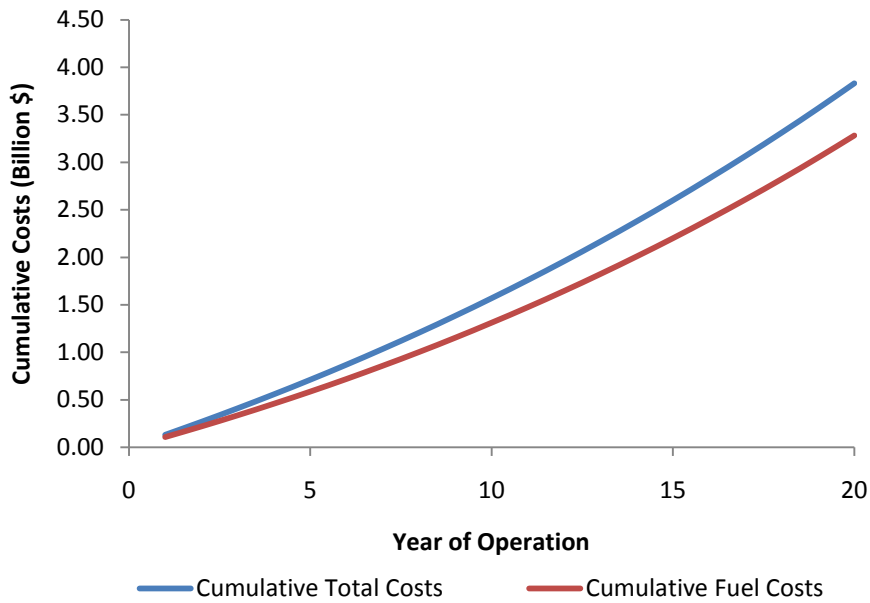
Figure 60: Comparison of Frame7EA total cost of operation and fuel costs

Further, the economics of plant operation have been quantified in terms on NPV in Figure 61. The NPV technique normalises the value of investments in years to come and one can see how the NPV varies for a given engine versus the discount rate and fuel price. It must be noted that the discount rate is used as a measure of risk in finance. An increase in discount rate means a project with greater risk. The discount rate can be expected to change geographically from region to region depending on the varied risks that the operator takes on to produce the oil or gas.

The trend in Figure 61 shows that as the discount rate increases, i.e. one is taking on more risk, the NPV value drops in an inversely proportional relationship, as expected. It also shows that there is a drop in NPV for a reduction in gas price. If one is to reduce the price of gas then it can be expected of course that there will be a decrease in NPV as revenues are reduced. What is interesting to see is that the reduction in gas price is not as imposing on the trend as is the change in discount rate. This is an important consideration for designing plant and selecting equipment because the value of the associated financial risk, in other words the discount rate, seems to have a far greater effect on the projected profits than does the price of fuel gas used to run the plant. This will impact decisions on where the plant is located, and will also inform greater business decisions as to whether the operator should invest in a

certain resource or project based on what an acceptable level of risk is. Certainly, for projects with higher associated risks, the operator will be looking for greater returns and this can be used as a bargaining chip when negotiating with the owner of the resource.
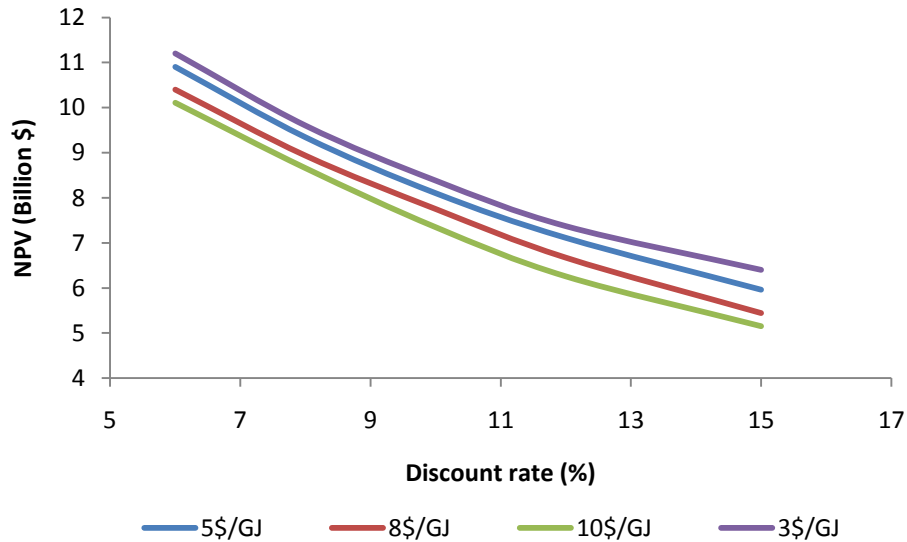
Figure 61: Change in NPV versus discount rate and fuel price

Figure 62 shows how the designed plant life can affect the NPV. This can be used this to find the optimum plant life given a discount rate. Note that the plant life is more varied for low discount rates and as the plant life is increased there is a lesser difference between NPV values. This may be due to the fact that the plant has entered a phase where the failure rate has picked up and thus its worth lesser to keep maintaining as opposed to revamping the plant and that the maintenance aspects are coming to a normalised average value which is similar regardless the discount rate.

At lower discount rate there is much worth in selecting the right plant design life according to Figure 62. It shows that for example, for a discount rate of 6%, there is worth in designing for a longer plant life. However, with increasing plant life, the return seems to be diminishing.
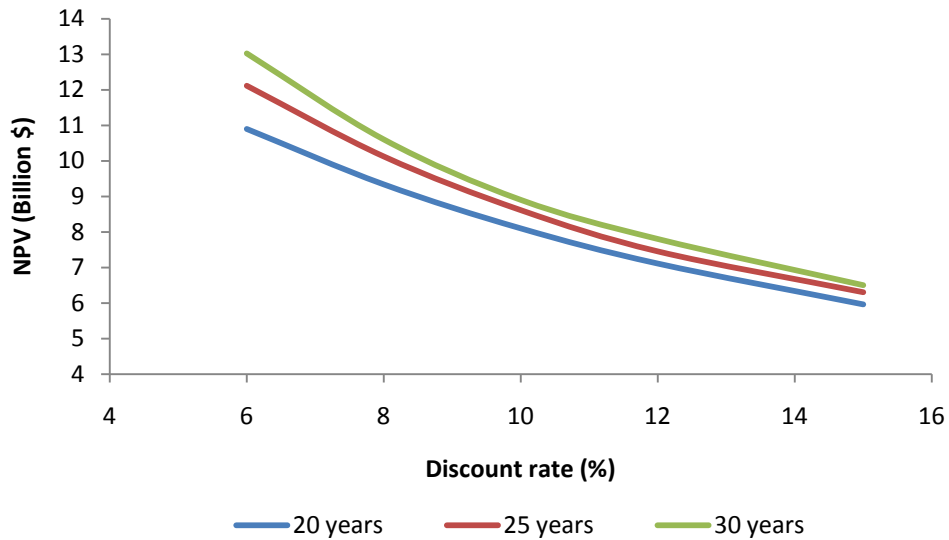
Figure 62: Change in NPV versus discount rate for different panned plant life, can help to optimise design plant life

8.1.4 Quantifying Risk

There is however another dimension to the analysis. Whilst all previous results have taken some mean value of life to do the risk analysis and thus the maintenance and economics results have been generated, Figure 63 and Figure 64 show how changing the operating philosophy can affect the maintenance requirements. This technique will help bring the effects of risk into the overall analysis. Operators are interested in knowing what will happen if they ran to failure, or ran the engine beyond OEM prescribed maintenance schedules. The TERA allows the user to investigate this, though this concept was not fully developed. Instead of taking a mean life form the lifing and risk, one can restrict the TERA to select values of life for the Monte Carlo simulation from a particular region of the distribution to reflect a level of risk taken on by the user. For example, the user may say that though the OEM recommends 20k hours for replacement, it will run to 25k hours. This is an increased risk the operator takes on, but it has rewards in that less downtime will occur and more revenues will be generated. In Figure 63 the high risk strategy is played out using TERA, running with less maintenance actions. The downtime due to corrective actions is 6516 hours whilst for the low risk strategy; components are replaced even when not necessary, resulting in 6756 hours of downtime (Figure 64), thus increasing corrective maintenance actions by 250 hours in a plant life time.

Figure 63: Maintenance results for Frame 7EA in high risk maintenance strategy

Figure 64: Maintenance results for Frame 7EA in low risk maintenance strategy

Based on the maintenance and economics of risk levels based analysis discussed above, the results for changing the risk level for a Frame 7EA are presented in Table 8. It shows the relative risk taken on by prolonging the time between maintenance in the first column; the second column shows the likelihood of achieving the projected production given the level of risk taken on, consequent columns summarise the economics analysis and the final two columns give the profit-risk index and the normalised index respectively. The index is arrived at by multiplying the risk, the probability of achieving said projection of LNG production and finally the profit that is expected to result from this. The normalising is done by dividing all values by the 50% level of relative risk. The results show that the median value of risk is the best option, with extremes of low and high risk not being good options.

However, there is a clear limitation here which is that the modelling only looks at creep, and since creep is a phenomenon which does not undergo a large amount of variation, especially at higher power setting and temperatures, it can be seen that swinging the risk drastically does not produce critical changes in the revenues and downtimes. This process is indicated here to show that potentially a scaling system can be created based on normalising the revenues generated and swinging the risk levels by selecting from different parts of the distribution to mimic risk.

Further, the author expected the optimum risk level to lie at higher values of risk, perhaps the 60-70% range. The downtime difference is not exaggerated enough by the changing in levels of risk (see Figure 63 and Figure 64). The initial difference is large in terms of numbers of components that fail but later in the aggregated schedule, the difference is dampened out. This damping of the risk level is due to the fact that many component maintenance actions are adjoined; the rules for which are built into the maintenance module. Thus, the total number of downtimes during the plant life reduces, and so does the total time for maintenance.

Table 8: Profit-Risk Analysis for Frame 7EA engine

Risk	Probability	Production (TPA)	Revenue ($)	Cost ($)	Profit ($)	Profit-risk Index	Relative Index
0.1	0.9	4.141E+06	2.035E+10	1.651E+09	1.870E+10	1.683E+09	0.36
0.2	0.8	4.141E+06	2.036E+10	1.657E+09	1.871E+10	2.993E+09	0.64
0.3	0.7	4.144E+06	2.037E+10	1.660E+09	1.871E+10	3.930E+09	0.84
0.4	0.6	4.144E+06	2.038E+10	1.700E+09	1.868E+10	4.483E+09	0.96
0.5	0.5	4.145E+06	2.038E+10	1.700E+09	1.868E+10	4.671E+09	1.00
0.6	0.4	4.250E+06	2.090E+10	1.700E+09	1.920E+10	4.608E+09	0.99
0.7	0.3	4.251E+06	2.090E+10	1.657E+09	1.925E+10	4.042E+09	0.87
0.8	0.2	4.254E+06	2.092E+10	1.657E+09	1.926E+10	3.082E+09	0.66
0.9	0.1	4.258E+06	2.094E+10	1.661E+09	1.928E+10	1.735E+09	0.37

8.1.5 1D Lifing

The lifing improvements have meant the results are further affected. The initial lifing (0D) and 1D lifing will now be compared. The main difference is that temperature and stress profiles have been introduced. The rest of the methodology is similar in the sense that it is the

same parametric LMP system. The maximum value for temperature is assumed at 75% of the blade height.

The lifing analysis was conducted by Ramaswamy (2011) as an off-shoot to the present research. The sizing methodology was one in common use and can be found in various texts such as Mattingly (2005) and Ramsden (2011). This methodology allows the blade sizes to be calculated and further a detailed analysis to be conducted accounting for axial stresses, bending moment and thermal stresses. The method is well charted by Abdul Ghafir (2011). The sizing algorithms allow the path to be mapped out using thermodynamic performance data and then the Zweifel coefficient methodology can be used to calculate the dimensions in 3D of the blades, and hence accurate stress and thermal models can be generated.

Only some selected results are presented here because the methods were not the focus of the current research but rather a necessity when blade dimensions data was not at hand, however, the 1D lifing system does make far more realistic predictions than the 0D system. The 0D system works on the basis of using life safety factors or confidence intervals to bring the estimations of life into a realistic level whist the 1D is predicting reasonably without too much correction; this is down to the detail of the algorithms built into the modelling.
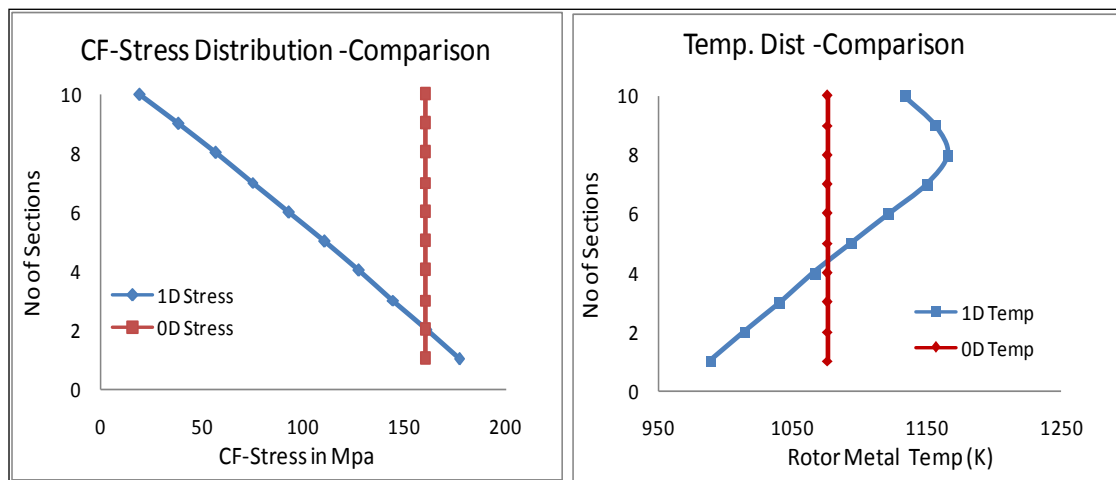
Figure 65: Stress and temperature profiles versus single values for the 1D and 0D lifing models (Ramaswamy, 2011)

The graphs in Figure 66 and Figure 67 show how the life changes between 0D and 1D lifing analysis. The 1D analysis is comparable to real values from GE publications for the engine. In

the distribution for the 1D lifing shows a lower life and a sharper distribution which is due to the fact that thermal affects dominate the creep calculations in 1D lifing; the mean is lower, and the variation is also lower because variation is due to location of stress on LMP curves, and it is those very curves which are used to determine the variation or the beta value of the distribution. Thus, the risk analysis methodology is sensitive to the accuracy with which the initial values of life are predicted at the lifing stage of the analysis.
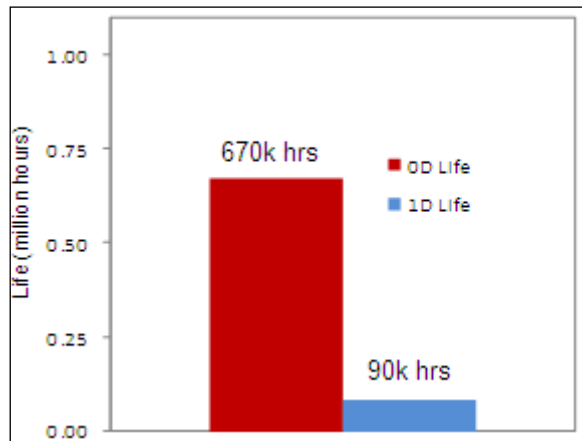
Figure 66: Life comparison between 1D and 0D lifing at 85 MW constant power demand (Ramaswamy, 2011)
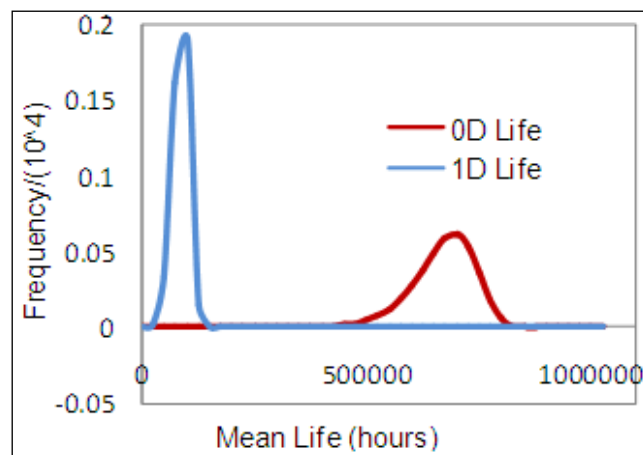
Figure 67: Weibull failure distributions for 1D and 0D lifing (Ramaswamy, 2011)
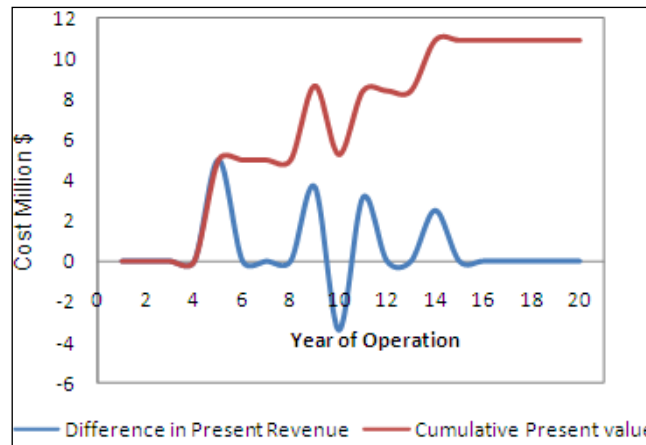
Figure 68: Difference in NPV for 1D and 0D lifing (Ramaswamy, 2011)

The change in lifing analysis can also affect the economics as can be seen in Figure 68. The cumulative difference in NPV is around $10million per train per plant life given the same engine and same operating conditions.

However, it must be mentioned that this model was only used to the extent of sizing the engine blades since this was the only missing piece of information. The rest of the analysis and scenarios in this thesis utilise the 0D lifing method since it was deemed more robust and in spirit of the TERA philosophy. Further, in a tool such as TERA, the operator cannot be expected to do preliminary design exercises to run the tool, hence it was deemed impractical but has been presented here to give a comparison and is a candidate for further work if it can be incorporated in the future. Since the selection aim is to look at comparisons between engines as opposed to achieving highly accurate life estimates the 0D modelling was deemed more suitable.

8.1.6   Emissions Taxation

The emissions taxation has already been built into the results and the economics analysis seen thus far and in later scenarios is using what is called a baseline case for emissions which reflects the current emissions legislation. However, given the changes being made currently and future plans, it is perhaps important to also analyse other alternative scenarios for the emissions predictions.

136

Scenarios are presented as two different possibilities which will be based on legislation passed with respect to emissions. Countries such as Sweden, Finland and Canada have some measures in place and it is possible that other countries will follow in step in the future.

The emissions scenarios are based on allowable emissions in parts per million (ppm). The two figures used here are 450ppm and 550ppm; the former a more stringent legislation than the later. So essentially, they can be described as a stringent and non stringent scenario. The scenarios were selected thus because of the US led investigation into current and future levels. The current levels are at around 385 ppm whilst taking into account the carbon equivalent total of all emissions the figure is likely to be around 415 ppm. Now, for the future, the forerunners of energy production especially in the west want to limit the figure that will be reached by 2020, hence the two scenarios of 450 ppm and 550 ppm, with 450 ppm being the harder target to achieve and thus requiring more stringent taxation to motivate countries and companies worldwide to reduce emissions and to incentivise the process of emissions reduction and use of better technologies which contribute to environmental benefits.

In line with these ideas, Figure 69 shows how the baseline Frame 7 will behave in such scenarios. The figure is essentially a breakdown of costs for different aspects of the project and, as expected, the fuel costs are considerably high. In the first instance, without any change from status quo, it is clear that the fuel cost is by far the most considerable cost of all. However, as the different emissions scenarios are played out, it is also evident that emissions can begin to form a significant portion of the costs and hence can influence business and technology decisions and perhaps force the operators to use more efficient machines. By the time a 450 ppm scenario has been run out, the fuel cost proportion has dropped from a staggering 85.7% down to 67.4% whilst the emissions tax has increased from 8.6% to 28.1%. Further comparisons will be made when the emissions of other engines are presented.
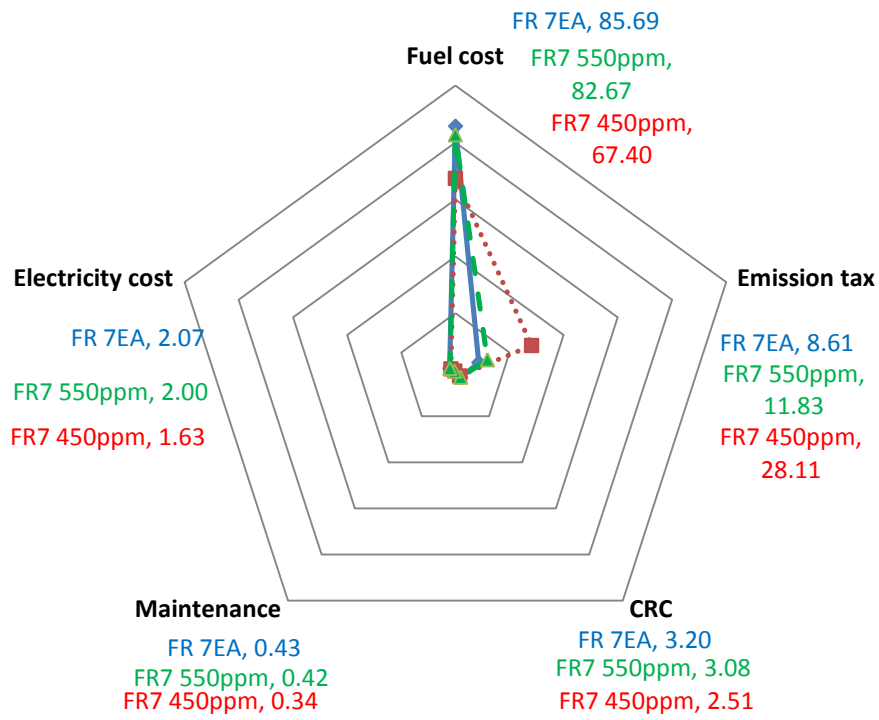
Figure 69: Costs breakdown in the FR7EA engine for the three different emissions scenarios

8.2 Case Study 2: Economies of Scale: Frame 9E

This scenario is based on the larger GE Frame 9E machine which belongs to the same family of engines as the Frame 7EA. The size is larger, as detailed earlier in the thesis where the engines were explained fully, and materials technology is also similar. Hence, the scenario results here will focus on looking at the economic argument for having larger engines as opposed to looking at the lifing and risk, though in a final section, all engines and scenario comparisons will be given.

8.2.1 Frame 9E: Economics Comparison

The results in Figure 70 and Figure 71 compare two potential trains, one with two frame 7 EA engines (target production circa 4.53mmtpa) and another with two Frame 9E engines (target production circa 6.57MPTA), both powering the same Shell DMR liquefaction process, but of course with different rates of LNG production and different size of starter motors and compression and cooling equipments. The engines are very similar technologies and so failure trends are also similar, one engine is a scaled up version of the other and the combustor technology is also the same though there will be slight differences in absolute value of firing temperature and the number of cans in the combustor. The firing temperature for the larger Frame 9E is lower at circa 1400K whereas the Frame 7EA is fired at 1418K.

Figure 70 shows benefits from the economies of scale in that the revenues of the larger Frame 9E are \$35.9 billion, some 45.3% greater than the Frame 7EA at \$24.7 billion. Operating the Frame 9E based train incurs 20 year cumulative costs of \$5.35 billion whereas the Frame 7EA incurs costs of around \$3.83 billion per annum. This is percentage difference of around 39.6%.
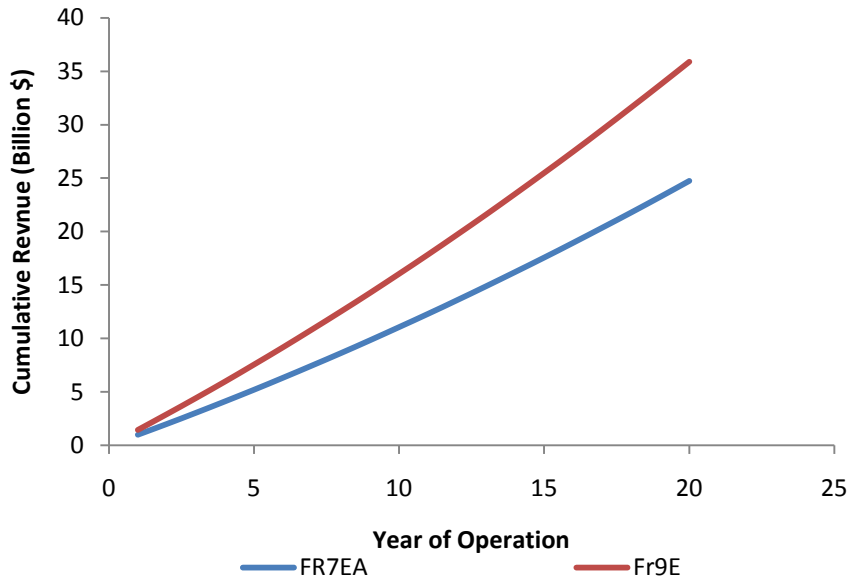
Figure 70: Frame 7EA and Frame 9E comparison of revenues
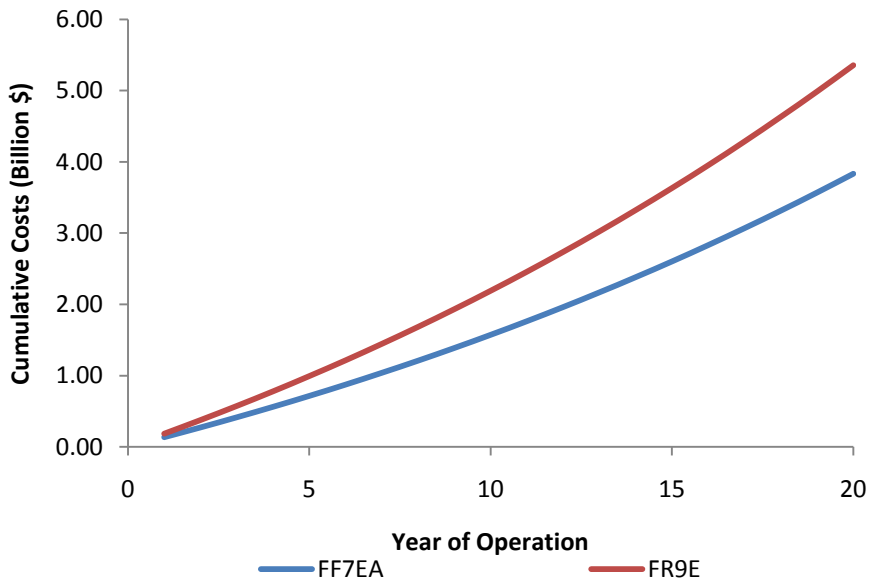
Figure 71: Frame 7EA and Frame 9E comparison of total cumulative costs

These results show that the larger machine is beneficial when compared on a single unit basis since the economies of scale mean that whilst the machines are very similar in build up, the

costs and revenues support having the larger machine. Again, it must be noted that there are slight differences in the respective downtimes and maintenance since the machines operate at slightly different temperatures and perhaps more importantly, different rotational speeds. This means there will be a different stress component affecting the life of the rotating components between the two engines as well as slight advantage to coating and combustor liner on the Frame 9E machine.

8.2.2 Frame 9E: Maintenance Comparisons

The maintenance results show that the downtime for the frame 9E is actually slightly greater than that for the frame 7EA (Figure 72). Over a 20 year period, the Frame 9E is expected to generate 300 more hours or 2.6% more downtime in absolute terms. However, it must be noted that these downtimes are in the context of operating conditions in the field and not the basic capabilities of the engines. Indeed, the Frame 9E is run at a different percentage of its design point power compared to frame 7EA and this in turn depends on target productions. It is perhaps better to look at relative downtime with respect the production or the power of the engine.
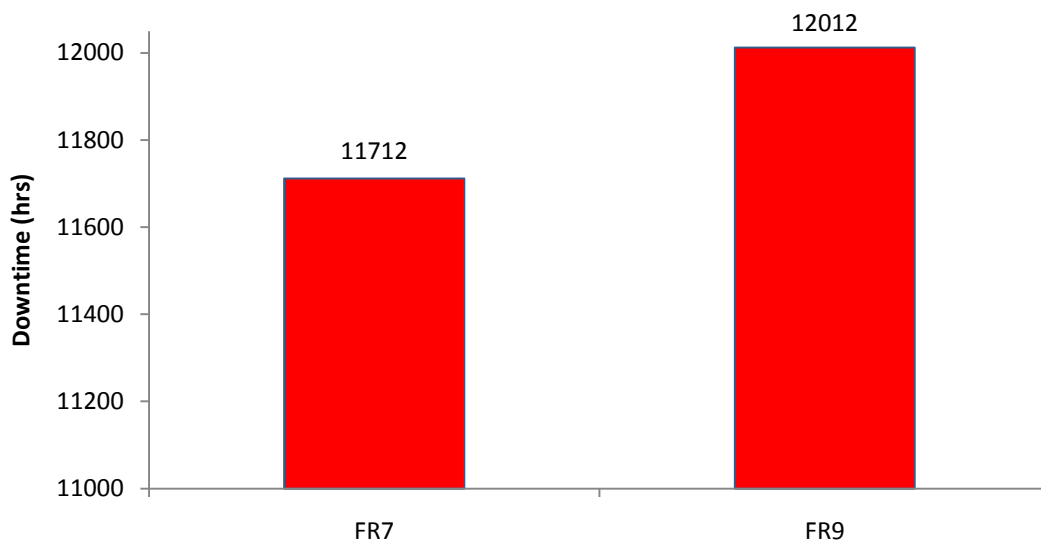
Figure 72: Comparing SBM downtime for FR7EA and FR 9E

On a relative basis, the cost of production per tonne of LNG produced is used as a measure to compare realistically the economic worth of each option. The Frame 7EA gives a value of 9,762 $/MW/year. This is a pseudo metric to bring the costs into perspective. It is calculated

141

by dividing the total maintenance cost by the power rating of the engine and the number of years after which the cost was incurred. The same ratio for the Frame 9E is 8,121 $/MW/yr. Hence, in relative terms the Frame 9E is cheaper and this is of course because the maintenance costs have been normalised with respect the power output.

Another metric can be the cost normalised to power and production. This value is calculated to be 0.043 $/MW/tonne of LNG produced for the Frame 7EA and for the Frame 9E it is 0.025 043 $/MW/tonne of LNG produced. Again, the Frame 9E is far cheaper to operate over longer periods of time when normalised to the power and production of the train which it constitutes.

8.2.3   Frame 9E: Emissions Comparison

The empirical correlation based emissions model yields that the emissions once again follow a similar trend to the frame 7 baseline engine. The slight difference s may be due to the fact the firing temperatures between the frame 7 and Frame 9 are slightly different and that the engines are not exact replicas of each other with difference only in size. However, broadly the trend on percentage terms is very similar to that which was presented in Figure 69.
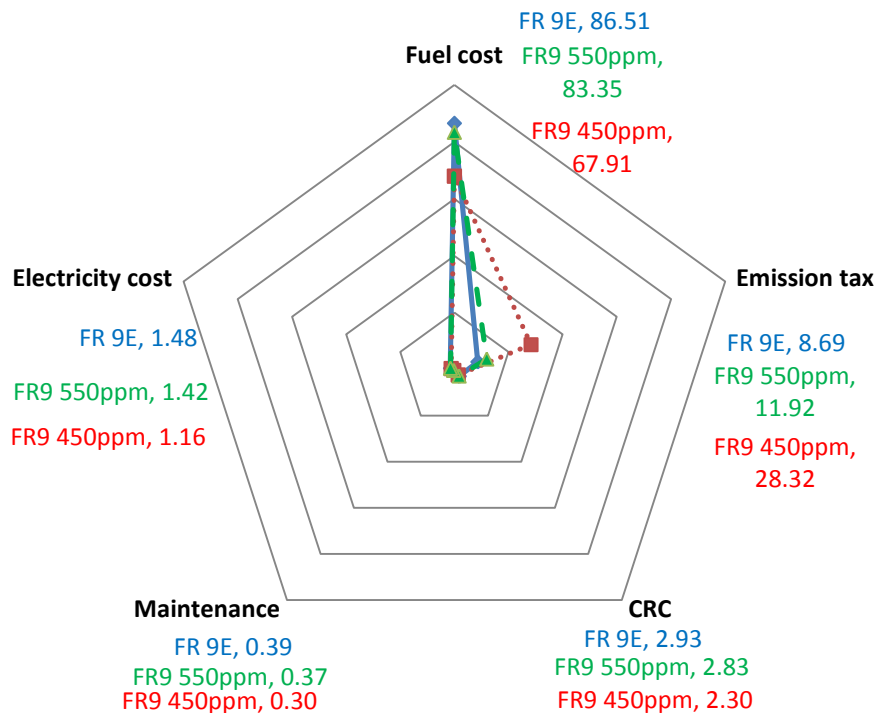
Figure 73: Cost breakdown for the FR9E engine for the three different emissions scenarios

8.3 Case Study 3: High Efficiency Aero-derivative Cycles

8.3.1   Aero-derivatives: Thermodynamic Performance Comparisons

It is worth charting the economics of both the aero-derivative engines analysed using the TERA tool and compare with the baseline. The graph in Figure 74 shows the relative performance of the aero-derivative engines versus the baseline Frame 7EA.
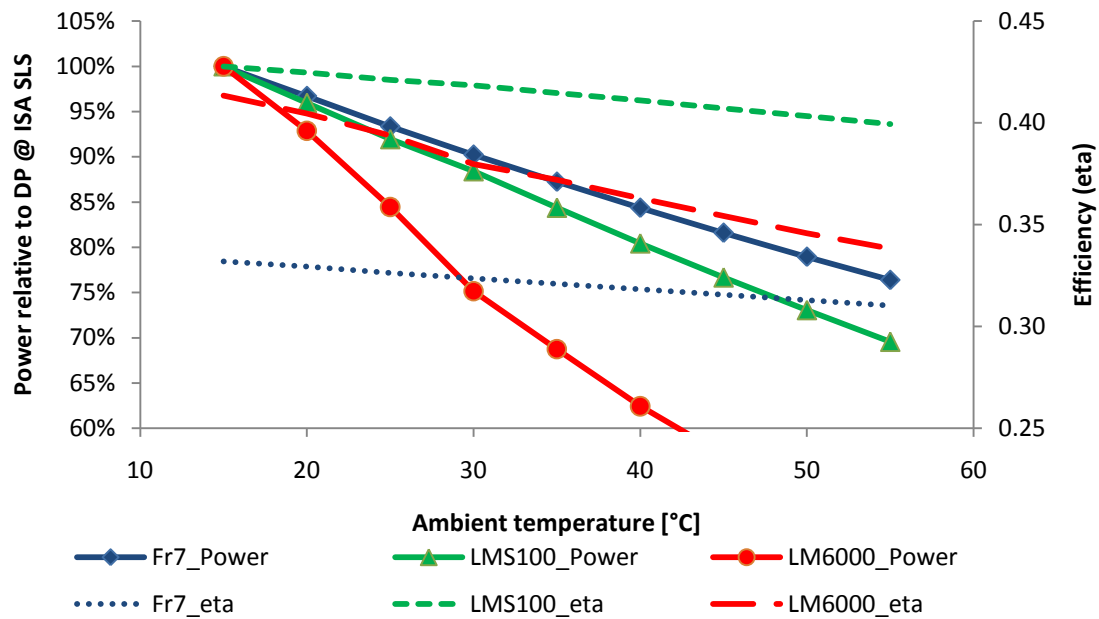
Figure 74: Power and efficiency variation of the aero-derivative engines (LMS100 and LM6000)

It can be seen clearly that the aero-derivative engines have far greater efficiencies than the industrial frame engine and this is a reflection on the level of technology and age of the engine designs. Further, the frame engine holds its efficiency better in off design as does the LMS100 whilst relatively; the efficiency of the LM6000 drops faster with increasing ambient temperature. This effect is magnified when looking at the power in off design, Once again, all three engines show a drop in power which is expected with an increase in ambient temperatures, but the LM6000 shows a far more drastic decrease.

143

The drop in power of the LM6000 can be attributed to its design and operation. The engine was simulated with TET control whilst in reality a more complex control system made up of both TET and IGV control is in order. The engine can be simulated in isolation using both types of control, but the automated TERA LNG was used to simulate this system directly, so for ease of use of the tool TET control was used.

The graphs of the isolated component efficiencies (Appendix B: Performance Data & Results) show how the component efficiencies vary in off design. This is further supporting evidence for the drop in power of the LM6000. For more details please refer to B.3Performance Charts.

8.3.2 Aero-derivatives: Lifing and Risk Analysis

The extreme conditions created in the hot gas path for the aero-derivative engines means that one expects losses in terms of expected lifetimes of hot gas path components. The graph in Figure 75 shows the relative life of different components in the aero-derivatives versus the baseline frame engine.
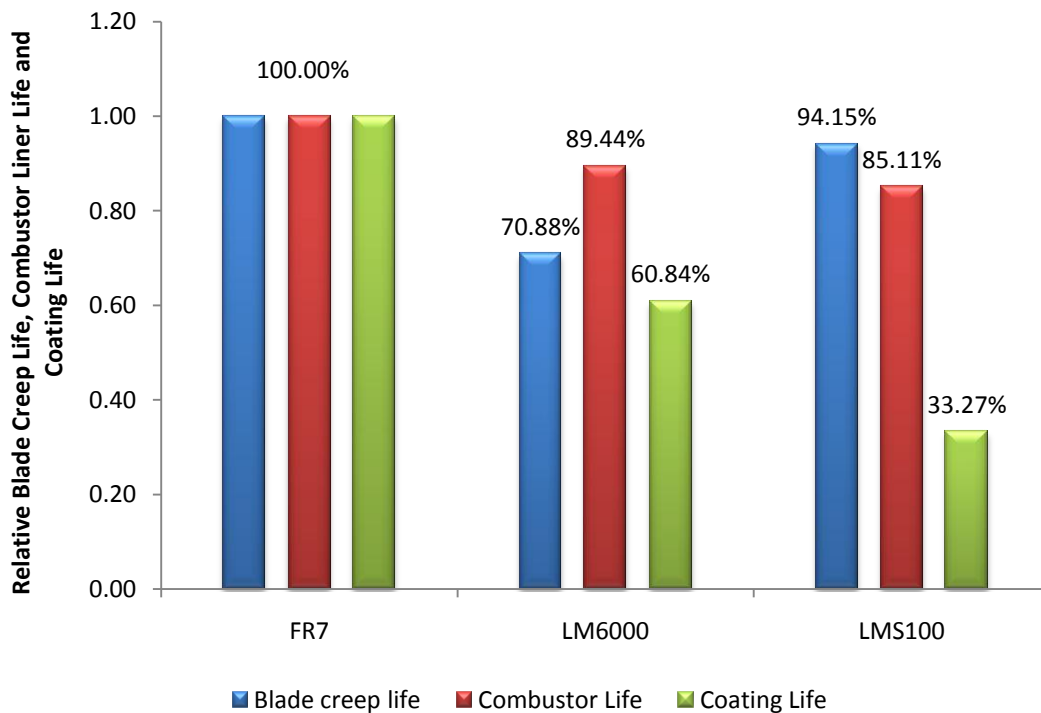
Figure 75: Relative life of hot gas path components for the aero-derivative engines

144

It can be seen that the relative life expectancy of the both the aero-derivative engines is considerably lower than that of the baseline engine. This would initially indicate a greater downtime, but of course downtime is a function of both the life of the component and the time taken to repair or replace it.

The figure shows that the combustor liner life is some 10.5% lower for the LM6000 and 15% lower for the LMS100 compared to the Frame 7EA. This is in line with expectation since these results are proportional to the respective temperatures generated in the core of each engine, with firing temperatures of 1650K, 1580K and 1418K for the LMS100, LM6000 and FR7EA respectively.

The coating also follows a trend which follows in line with increasing firing temperature with the worst coating life attributed to the LMS100. The blade creep life follows a different trend however, and this is because of the blade materials used in each engine. The worst result in this case is the LM6000 which has circa 31% less life than the baseline, but remarkably the LMS100, though fired at 1650K has only some 6% lower blade creep life than the baseline. This is mostly due to the materials and cooling technology deployed in the LMS100.

It must be noted again that the ultimate failure of the blade material may be something which was incurred at the cost of the coating cracks hence leading to hot spots being created and thus ultimately failure in creep, though the initial mode of failure may be attributed as coating failure. To amalgamate the two is beyond this research, though much work has been done on this recently, there are not many models which can be unanimously agreed upon for creep-coating interactions and thus providing realistic estimates for the interaction of the two. This sort of study is best done using tools such as CFD; the TERA tool models the coating and blade metal creep lives as two separate components and compares on the basis of which one occurs first.

The isolated lifing and risk of the aero-derivative engines can be misleading and cannot alone be used to draw conclusions, except conclusions about materials capability of the engines, but in order to select technology, the life of the components must be put into perspective of the maintenance and the downtime generated. Indeed it is believed that though the aero-derivative engines will incur failures at a faster rate than industrial machines, the aero-derivative machines, due to their modular structure, can be fixed and made online at a faster rate than industrial machines. Essentially this means there is lower reliability but higher availability

and maintainability. Hence, the argument is that the effective total downtime is lower for the aero-derivatives machines than the industrial frame engines.
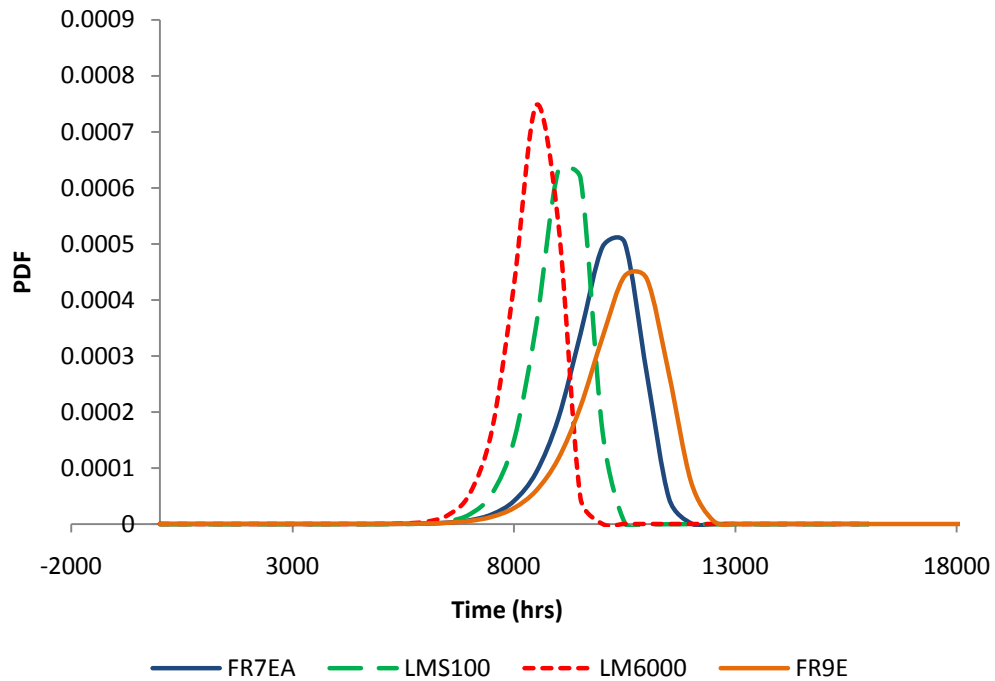
Figure 76: Whole engine Weibull curves for FR7EA, LMS100 and LM6000

The trends in Figure 76 show that indeed the aero-derivatives have the lowest time to failure, thus a higher failure rate than the industrial engine. It is interesting to note however that the phenomenon of failure is a far more defined occurrence with the aero-derivatives. This means that for the aero-derivatives, though they fail at a faster rate than the industrial engines, it can be said with greater confidence **when** they will fail, since their failure distributions are narrower, hence occupying a smaller range of possible occurrence, whilst there is greater uncertainty with the frame engine. Indeed the beta parameter of the Weibull is a good indicator of this uncertainty and this has values of 14.82, 18.11 and 17.50 for the Frame 7EA, LM6000 and LMS100 respectively. This value indicates the spread of data across the distribution and is a quantitative way of mapping the variation. It is clear that the Frame 7EA has a better average life, but it has a lower β value which gives it more uncertainty. The better of the two aero-derivatives in terms of mean life is the LMS100 with 9284 hours before expected failure, whilst the LM6000 gives a mean life of 8654 hours. However, it can be seen again that the spread of the LM6000 is better in the sense that there is a lower β value which

146

makes the occurrences associated with the LM6000 less varied. The PDF of the FR9 has been shown for comparison and it is clear how the lower fired conditions given this engine some benefit over the baseline FR7 engine.

Table 9: Weibull parameters for the Frame 7EA and Aero-derivative engines

Engine	η	β
FR 7EA	10324	14.82
FR 9E	10806	13.51
LM6000	8654	18.11
LMS100	9284	17.50
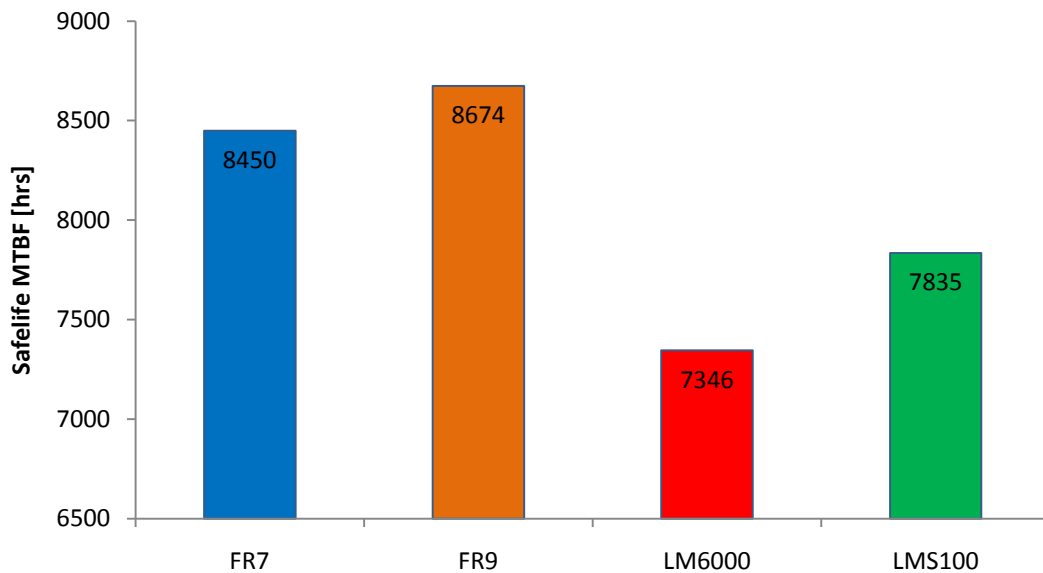
Figure 77: MTBF based on safe-life calculations

The graph in Figure 77 shows that the safe life of the aero-derivatives is lower than the industrial frame engines. This safe life is worked out from the overall engine Weibull curve and is based on a 95% confidence level that said life will be achieved. This safe life is calculated before the maintenance grouping algorithm has run.

Another way of looking at the risk is to turn the Weibull data into reliability curves as seen in Figure 78. This paints a similar picture to previous results but also allows the operator to map the maintenance based on reliability with respect to time, which is more useful for maintenance planning. For example, the operator can see the reliability, a percentage, at a given point in time; an operator can set the reliability limit after which maintenance might become mandatory.
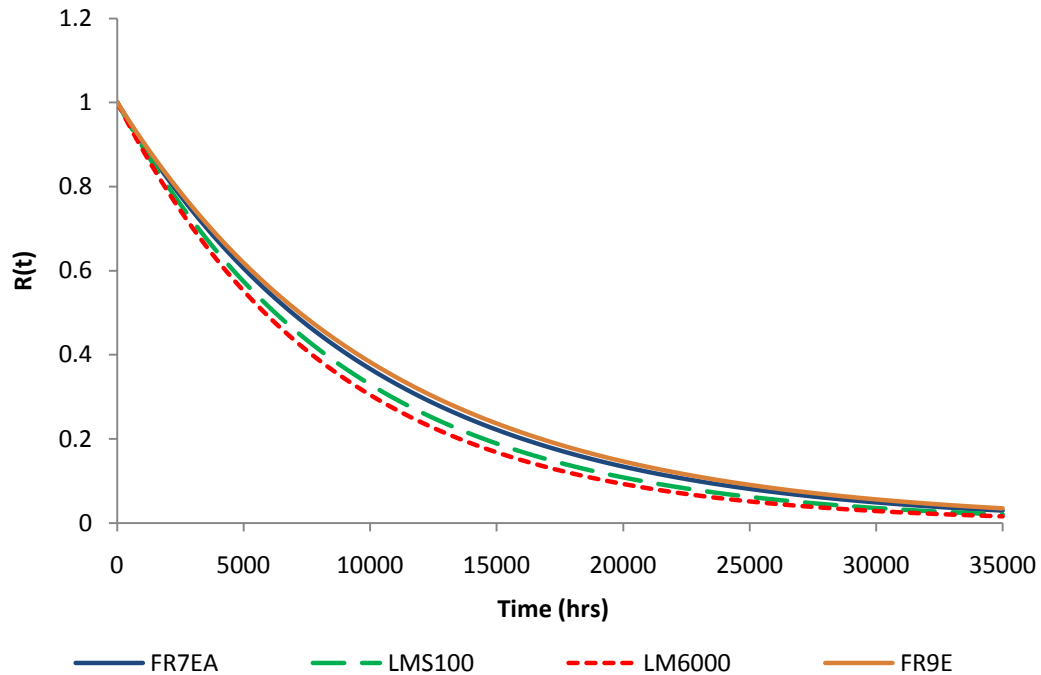
Figure 78: Chart detailing the reliability curves for the aero-derivative and frame engines

8.3.3 Aero-derivatives: Maintenance and Economics Results

Further, it is important to put the operation of the engine into context of the maintenance as was done in previous sections. The algorithms contained within the maintenance group the individual failures into maintenance actions based on planned and unplanned actions as well as routine and corrective actions.
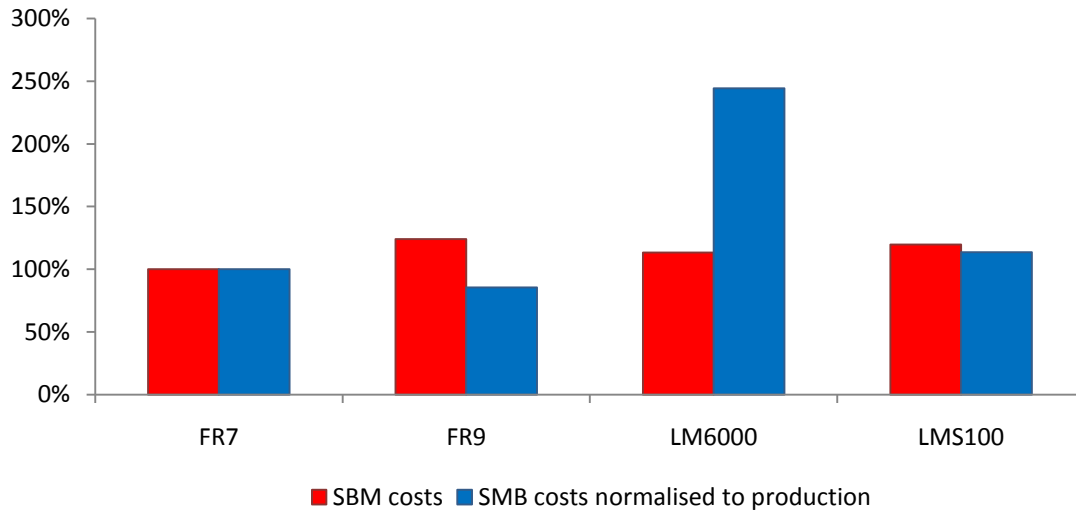
Figure 79: Simulation based maintenance costs of the industrial and aero-derivative engines

The chart in shows that the simulation based cost for the LMS100 aero-derivative are not so much higher than the industrial frame engines but for the LM6000 the costs are relatively very high at more than 250% the cost of the baseline frame engine. It must be noted that these values for each engine are scaled with respect to cost per tonne of production and then made relative to the baseline frame engine. Hence the values for the Frame 7EA are 100% and then everything is relative to this. The raw maintenance costs are similar for these engines, but when scaled to production the costs show another picture. In this case, the LMS100 would be a very clear winner over the other aero-derivative; however, given production, the costs of the LMS100 are slightly higher than the baseline frame engine.
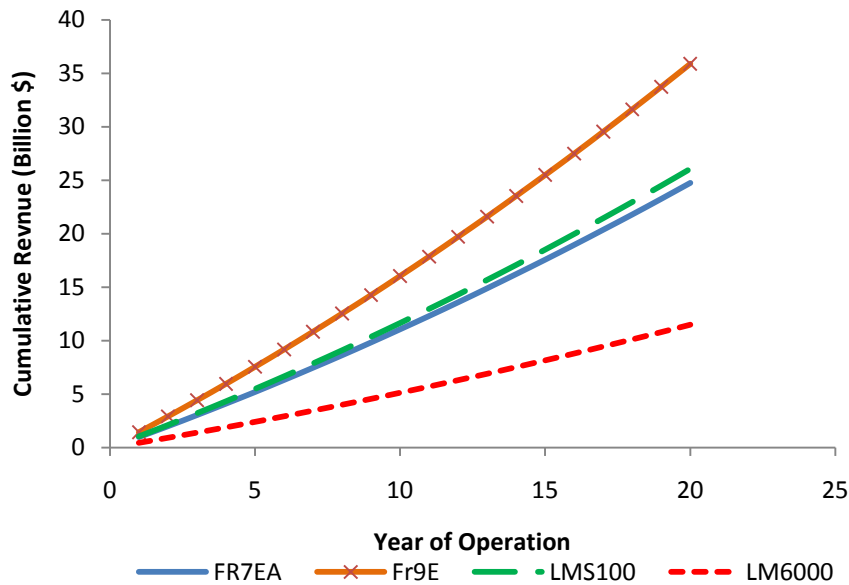
Figure 80: Cumulative revenues for the industrial and aero-derivative engines

The graph in Figure 80 shows the cumulative revenues for the four engines. The LMS100 generates similar revenue to the Frame 7EA though it is rated at moiré than 10MW higher. It must be remembered however that the Frame 7EA uses a starter motor for start up and supplementary power which is circa 7MW which brings its total plant capacity close to the LMS100. The capacity of the LM6000 is of course a lot lower and the revenue follows this trend since the scenarios here are restricted to a two engine, single train comparison. Of course, one could utilise more LM6000 in a single train to boost production, but for the purposes of comparison, the picture is as shown.

It is perhaps better to compare on a cost basis and look at relative cost of production. The graph in Figure 81 shows the relative costs of production where costs have been normalised to production and then again normalised also to the benchmark engine. So this is the total annual costs divided by the annual production of LNG in tonnes.
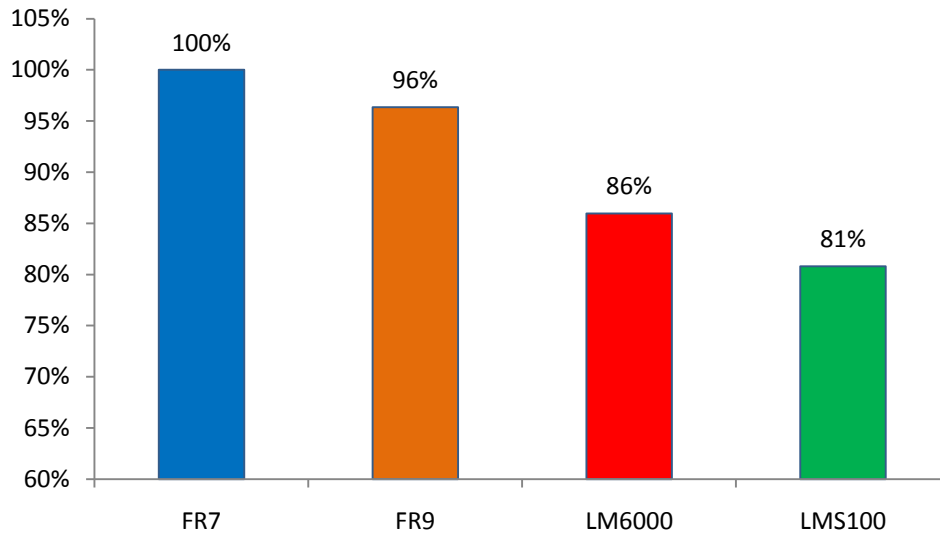
Figure 81: Total costs for aero-derivatives normalised to production and bench mark engine

The graph in Figure 81 shows clearly that on a total costs basis the aero-derivative engines are far better than the industrial frame engines. The Frame 9E is slightly better than the Frame 7EA since the larger engine is making use of the economy of scale argument. However, the large difference between the frame engines and the aero-derivatives is seen when one looks at the costs breakdown. The largest portion of costs is contributed by the fuel usage and maintenance is a far smaller portion of total costs. Since the aero-derivatives have better thermal efficiencies they perform better in the overall scheme of things.

Also, interestingly, though the lifing calculations of the LM6000 show that the life deterioration is fastest amongst all engines given the thermal conditions and the materials technology used compared to the other engines, the LM6000 still performs significantly better than the industrial frame engines and a whole 10% better than the Frame 9E, whilst 14% better than the Frame 7EA.
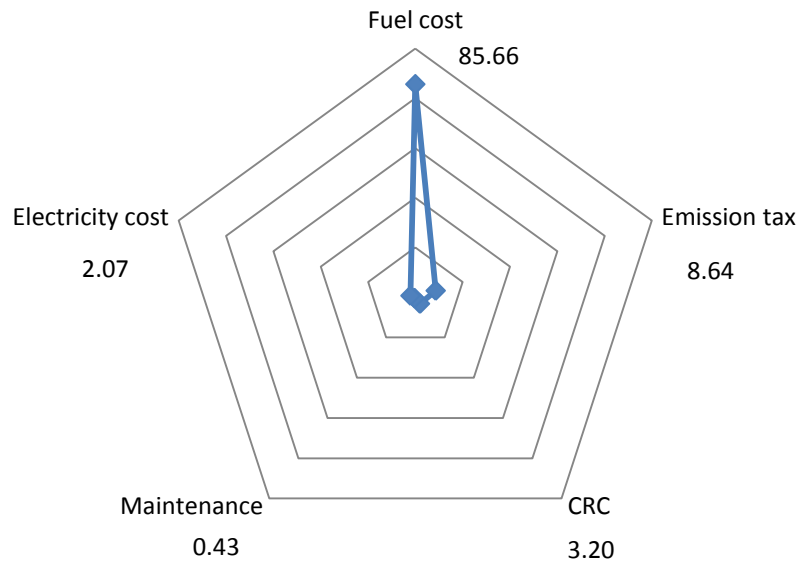
Figure 82: Relative weight of different costs for the Frame 7EA engine

The diagram in Figure 82 shows the relative weight of costs that make up the total costs. It shows a clear skew towards the fuel costs, which account for 85.66% of the total costs. It must be noted that these percentages have again been normalised to production of LNG. Similar diagrams for the other engines will show that again the fuel cost is the main contributor to the overall costs. Further, it can be seen that the maintenance cost is the smallest contributor.

Here it must be made clear that this does not mean the maintenance is not simulating appropriately the costs, but rather, cost of maintenance is not the whole story. There is a cost in lost production due to maintenance requirements which the basic costs do not capture. Such a cost is only captured by looking at the overall pattern of uptime and downtime and accounting for the entire period and then calculating the costs and profits. This has been done in the form of the final NPV analysis which takes into account the lost production.
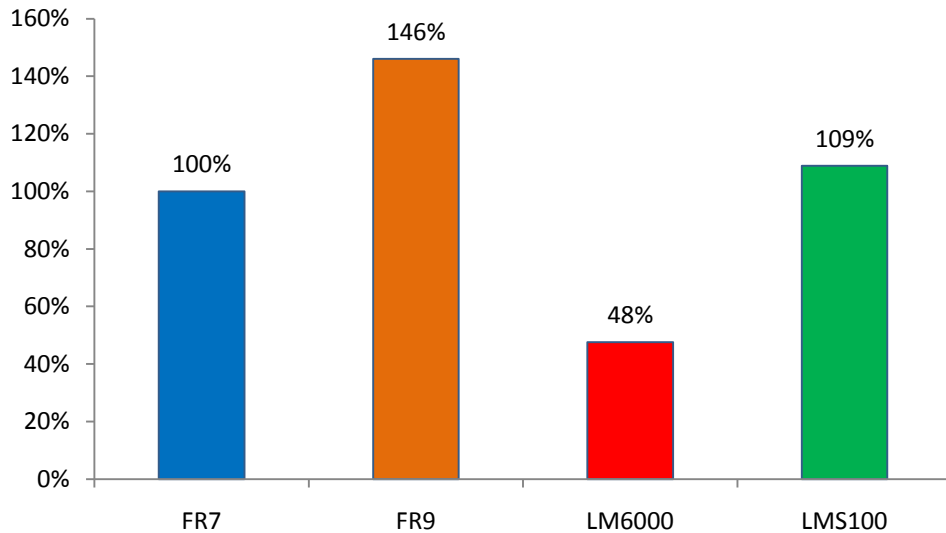
Figure 83: Non-normalised NPV of aero-derivative engines

This first picture, as seen in Figure 83, can be misleading since though it is the NPV values of each engine and take into account the entire modelling of the TERA tool, it is simply the trend as a function of train size. This is NPV based on train capacity and hence the larger engines win out. However, when normalised to production the trend in Figure 84 shows that the aero-derivative engines have a better relative performance overall. This trend is one based on dividing the total NPV by the total production, but of course the NPV is restricted to the costing that was selected and indeed does not account for the entire plant set up and equipments.
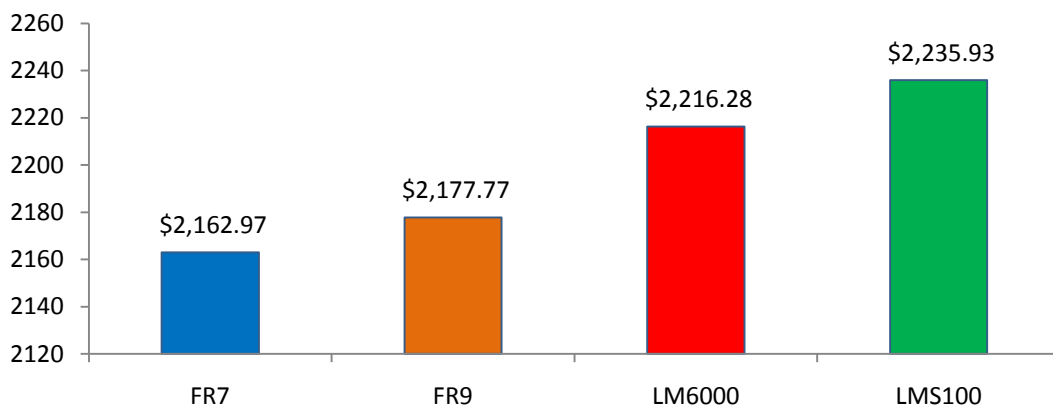
Figure 84: NPV per tonne of LNG produced for aero-derivative engines

153

Further then, the trend in and Figure 85 can be seen as something more useful for comparison purposes since it is a normalised NPV comparison based on percentage difference in NPV of the engines. Again, only to be taken in light of the fact that the whole plant was not considered but rather the key equipment in a train has been isolated.
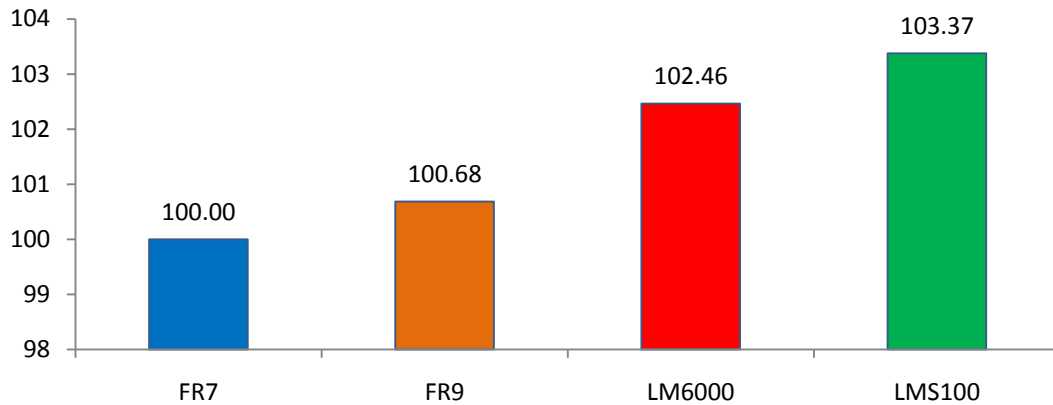
Figure 85: Normalised NPV per tonne of LNG produced for aero-derivative engines

The graphs in Figure 84 and Figure 85 show that the trend according to production is very different and that Figure 83 does not tell the whole story. Hence, it can be seen that the large aero-derivative LMS100 fares better than the other engines and that taking production into account one can see that the Frame 9E is not necessarily the best option. However, the fact is that one unit of Frame 9E produces the most LNG, so it is down to plant designers to choose different combinations depending on target productions. Permutations and combinations of these engines can lead to an endless variation in plant set up and that is not the subject of this thesis.

8.3.4   Aero-derivatives: Emissions Comparisons

The emissions prediction of the aero-derivative engines throws much light on the argument of whether aero derivative engines are in fact better than industrial frame engines. Here, the LM6000 and LMS100 are presented.

It is evident from Figure 86 and Figure 87 that the two aero-derivative engines behave in much the same way with respect the different emissions scenarios they are put through. Once

again, it must be mentioned that the formulations which derive the emissions for these engines are empirical correlations and as such there is little difference between aero-derivative combustors that can be modelled with such a modelling tool. However, in this case it is perhaps better to look at the results when normalised to production or tonnes of LNG produced since in basic percentage terms the results don't differ too much
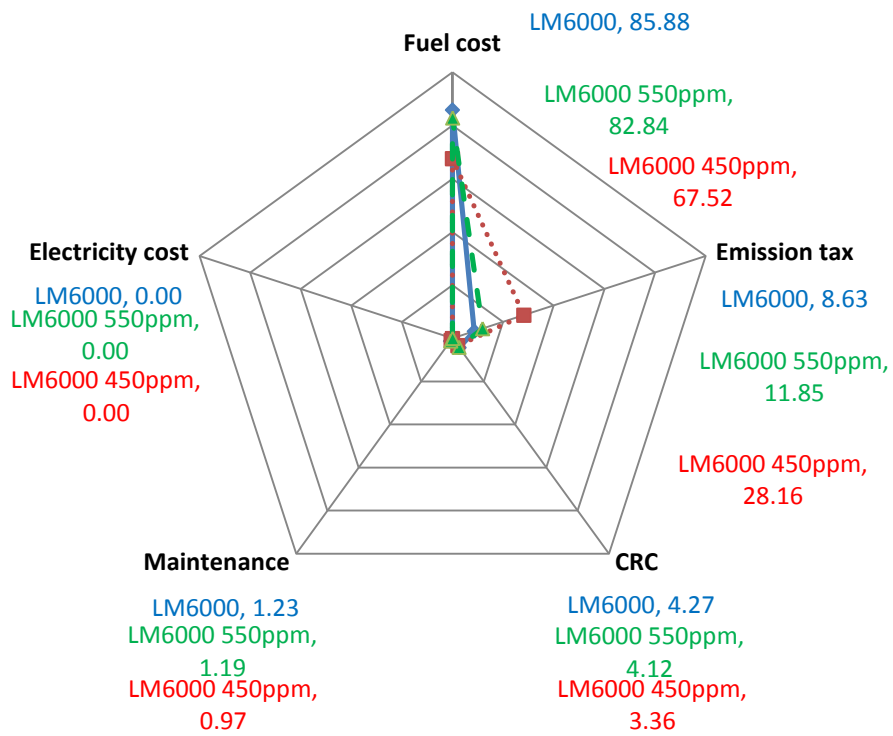
Figure 86: Cost breakdown for the LM6000 engine for the three different emissions scenarios
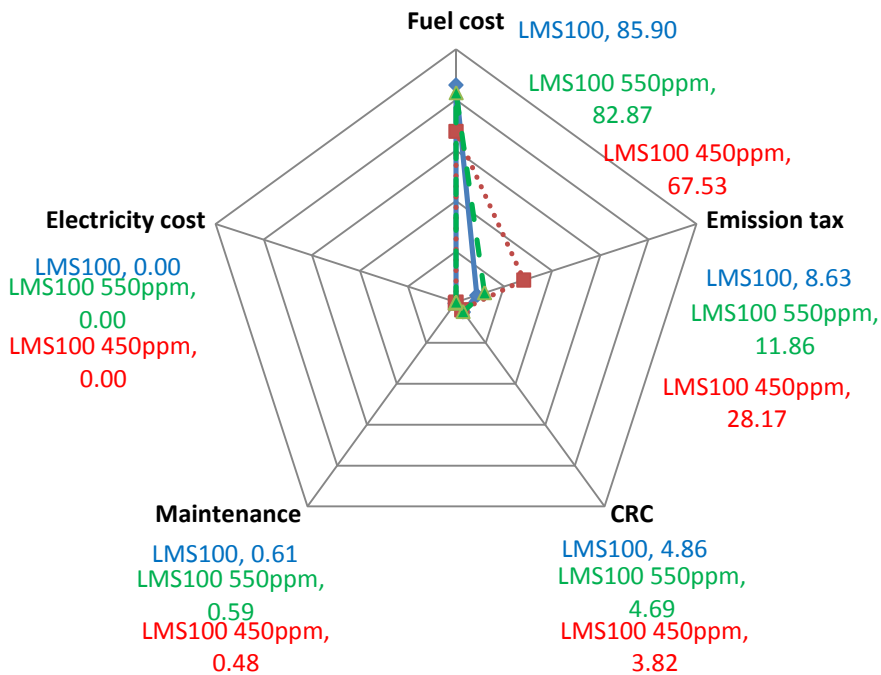
Figure 87: Cost breakdown for the LMS100 engine for the three different emissions scenarios

It is perhaps better to show only the very significant costs and how they change for all the engines analysed so far. Since the characteristic of the aero-derivatives and industrials are similar in their own families a percentage breakdown of costs is perhaps not signifying the difference enough. The graphs in Figure 88 and Figure 89 shows the results when normalised to production or rated power show once again that the engines are all quiet different in their emissions signature. Again, it is clear that the aero-derivative engines are by far better with respect the emissions production per tonne of LNG produced and also per MW hour the engine is utilised. The latter is deduced by dividing the emissions costs by the number of hours in a year and the power of the engine at design point. This is a slight approximation since the engines don't operate continuously throughout the year but it does give a relative comparison for the engines.
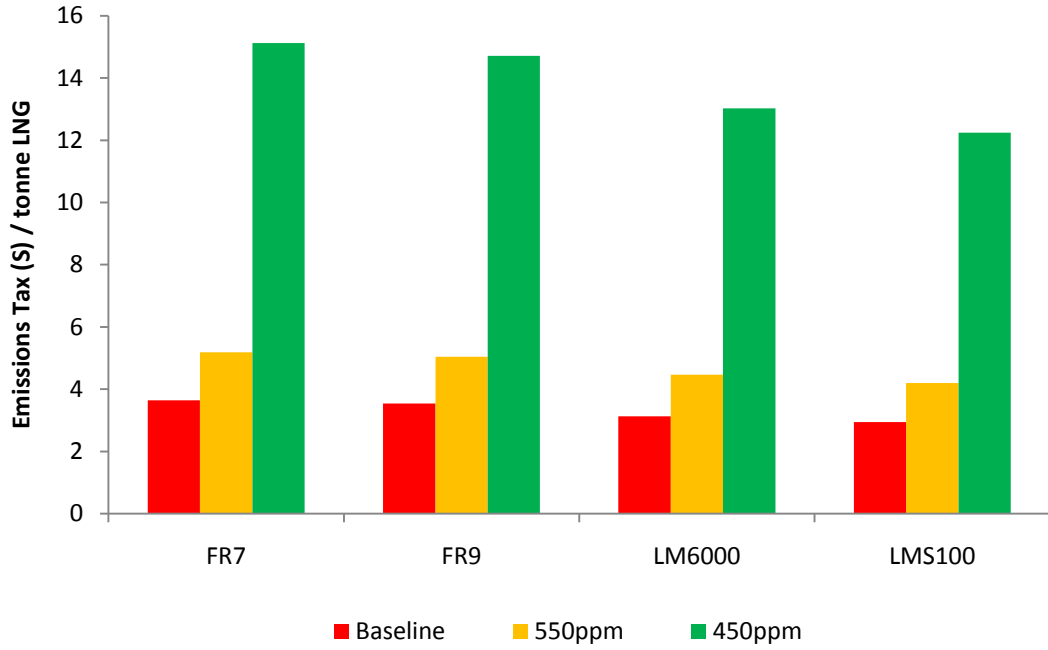
Figure 88: Emissions tax for aero-derivative engines normalised to production

Also, the graph in Figure 89 shows a very similar trend, but is this time normalised to rated power.
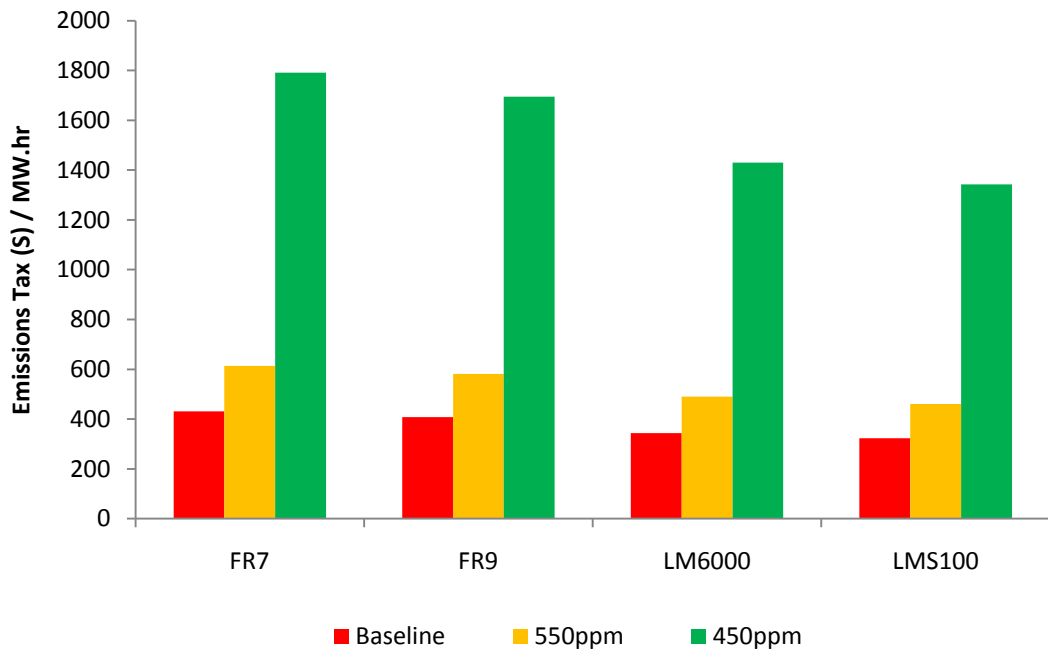
Figure 89: Emissions tax for aero-derivative engines normalised to rated power

8.4 Case Study 4: Innovative Cycles: The Pseudo Engines

A further analysis has been done as part of this project by a number of researchers (the author, Maccapani, 2011 and Laganà, 2007) which looks at the idea of coming up with what are called 'pseudo' engines in order to enhance the already existing engines which are available to the operator off the shelf. The idea here is that though some typical machines in LNG are dated, they can be enhanced in terms of changes in design and materials technology in order to increase the capability in terms of capacity or indeed improve core performance and efficiency. Such an option will allow the use of existing designs with modifications and this can be of much interest to operators if at all feasible, The aim of these studies was not to create entirely new engines or to validate the use of such pseudo engines but rather to start a basic feasibility into the use of upgraded engines.

To this end, the author worked closely with Laganà and Maccapani to create basic models of the pseudo engines in simulation and later in preliminary design phase to generate a first set of results which could highlight the usefulness or shortcomings of such engines. To this end, the engines that were modelled were based on the Frame 7EA and the LM6000.

Two variants of the Frame 7EA were studied namely a zero staged version (designated FR7-ZS) and a highly fired version (designated Fr7-TET). The LMS6000 variant was a zero staged version of the LM6000 designated LM6000-ZS.

8.4.1 Pseudo Engines: Thermodynamic Performance Comparison
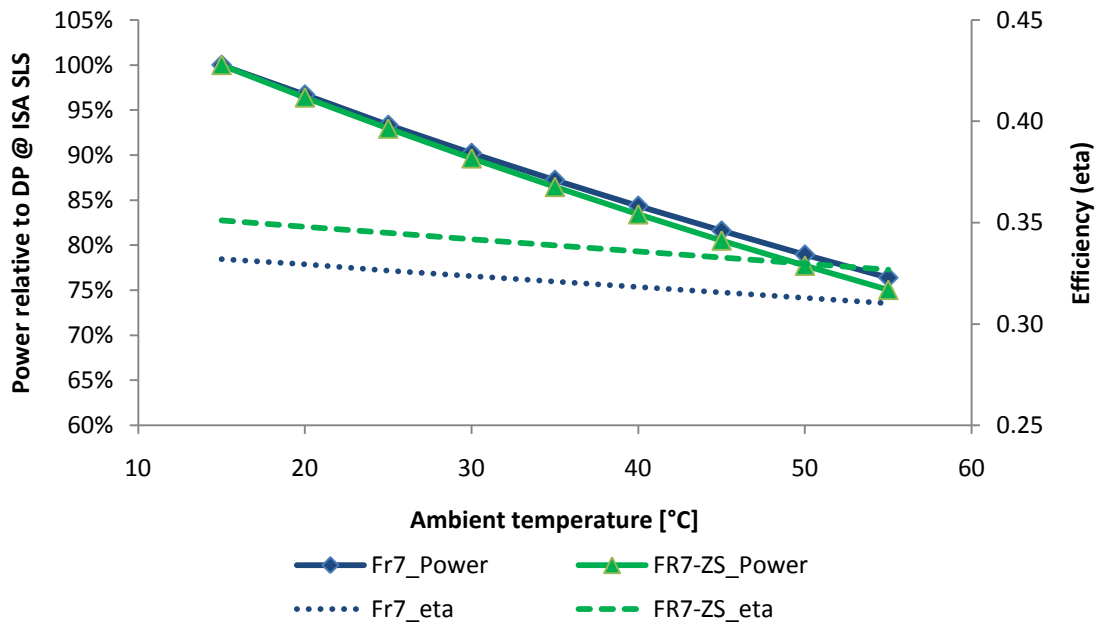
Figure 90: Ambient capability of the pseudo Frame 7EA engine with zero staged compressor

The graph in Figure 90 shows that there is a marked improvement in the efficiency of the zero staged variant of the frame 7EA. A mean improvement of 2% in efficiency continues throughout the charted of-design shown in the picture and this is a substantial gain which will be qualified with further analysis at a later stage. Further, the power trend is somewhat similar though it can be said that at higher ambient temperature of greater than 35°C to 40°C the power of the pseudo engine drops with respect the original engine. This can be attributed to the preliminary nature of this design; indeed the design is not optimised for the new configuration so that when the new compressor configuration was added the rest of the machine was not optimised to meet this change.

It must also be mentioned that the other Frame 7EA variant analysed is the highly fired version for which the basic performance is the same, hence not charted here, but of course allows the engine to reach higher firing temperatures. This change is represented in the simulation as an improvement in materials technology and hence allows the engine to be fired

higher; with respect the core performance and geometry the original Frame 7EA and Frame 7-TET version are the same.

Similarly a picture of the ambient capability is charted for the pseudo engine with respect the LM6000 which is again a zero staged engine as seen in Figure 91.
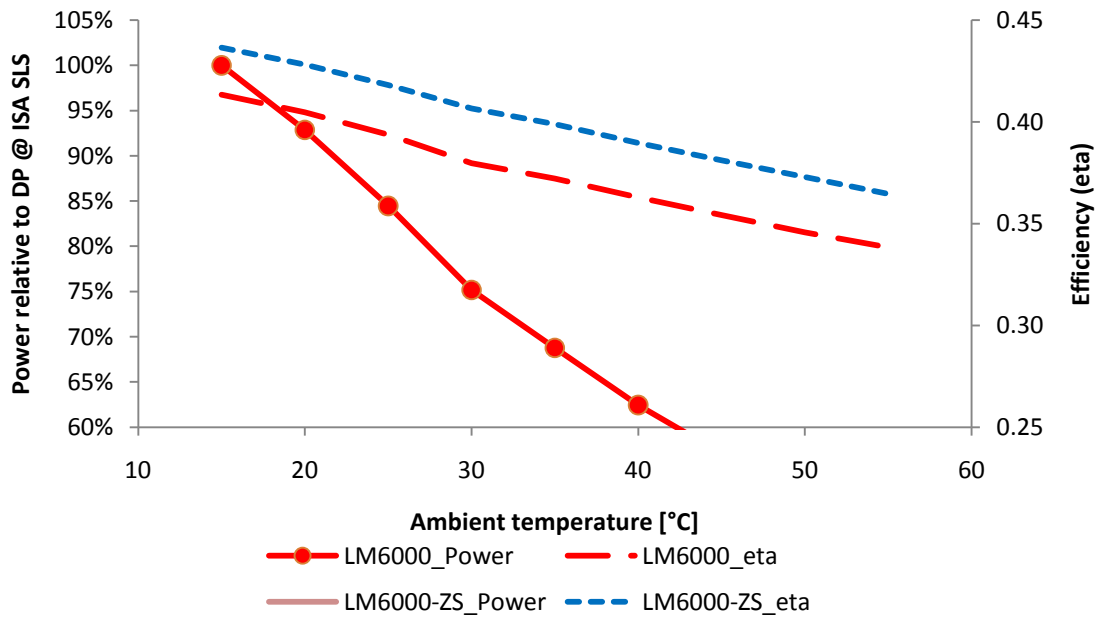
Figure 91: Relative improvement in efficiency for the zero staged LM6000

This graph shows that there is again a marked improvement in the efficiency. Approximately, 3% greater efficiency is maintained throughout the off-design performance of the engine whilst the power is not changed very much. In fact the power curve for the variant engine is superimposed by the power curve for the original engine and cannot be seen. Once again, the gains in power and efficiency will be quantified when the engine simulation is carried through the TERA tool.

8.4.2   Pseudo Engines: Lifing and Risk Analysis

This section will look at the consequent changes in the life expectancy of the hot gas path components given changes made in the core cycle of the engines. One expects lower life form the highly fired version of the Frame 7EA though this will be off-set by some degree due to the fact that the TERA assumes a better material technology usage.

160

Table 10 summarises the materials and coatings technology employed for the engines in these scenarios. Some of this information has been provided in earlier sections in more details. It can be seen that the FR7-ZS in terms of materials was the same as the original engine, whilst the FR7-TET version was modelled with a different material, though the coating was unchanged, whilst with the LM6000-ZS the coating and the turbine blade material were changed. These changes were picked so as to be able to investigate the different changes and look at the factors affecting life of components. These are not particularly optimised solutions, nor does the author suggest that any one is the best option, they are simply scenarios which help show how the LNG TERA tool can be utilised to look at options.

Table 10: A summary of the turbine blade and coating technology for the pseudo engines

Engine	Turbine Blade Material	Material Type	Coating Technology
FR 7EA/ FR7-ZS/ FR9E	GTD111	Directionally Solidified (DS) Nickel based super-alloy	73
FR7-TET	CM 186 LC	Single crystal, DS, Nickel /Hafnium based super-alloy	73
LM6000	Rene 142	DS, Rhenium / Nickel super-alloy	130
LM6000-ZS	CMSX-4	DS, Rhenium / Nickel super-alloy	140

The graph in Figure 92 shows the variation of the blade metal creep life for the different engines given their operating conditions. Here, all engines from all scenarios mentioned thus far have been amalgamated. The graph shows that, as expected, the blade creep life of the zero staged and highly fired variants of the Frame 7EA are indeed lower. However, it is interesting to note that the life expectancy of the FR7-ZS is far lower compared to the FR7-TET version. The possible explanation for this can be the fact that due to the change in turbomachinery at the front end and the addition of stages to incorporate the zero stage design, it has meant that the relative temperature at inlet to the combustor is higher, and

161

indeed this means that relatively the temperatures experienced at the turbine inlet will be far greater. This, and the fact that the materials technology was not changed, indicate that the engine is running hotter with the same materials technology and hence is suffering the consequence, hence a drastic decrease of life expectancy. The highly fired FR7-TET version however, does not see a change in turbomachinery but rather only a change in firing temperature, and hence the materials were changed. It is the example of improvement in materials technology for the same basic turbomachinery design. Hence the lowering of the life expectancy of the FR7-TET is less drastic and it loses some 30% life compared to the original frame 7EA. There are numerous possibilities with pseudo engines and this study is limited to a basic preliminary design and feasibility. However, the zero staging of the LM6000 does not affect the life of the blades so much relatively to the zero staging of the frame 7EA. This is because the materials technology already in use with the LM6000 is of far better capability than the industrial engines.

Further, comparisons with the aero-derivatives and the pseudo engines show that apart from the zero-staged Frame 7EA, the other two pseudo engines rank up well with the aero-derivatives. It must be noted that all pseudo engines were redesigned in order to give substantial power boosts, yet their life expectancy is comparable to the aero-derivatives and so this makes them strong contenders.

The LM6000-ZS does relatively better than the original LM6000 and this is because the material was yet again changed to accommodate the changes in the core of the engine. Here it must be noted that the LM6000-ZS would be the most drastic option perhaps in terms of changes made since both its coating and blade material technology are proposed to be changed.
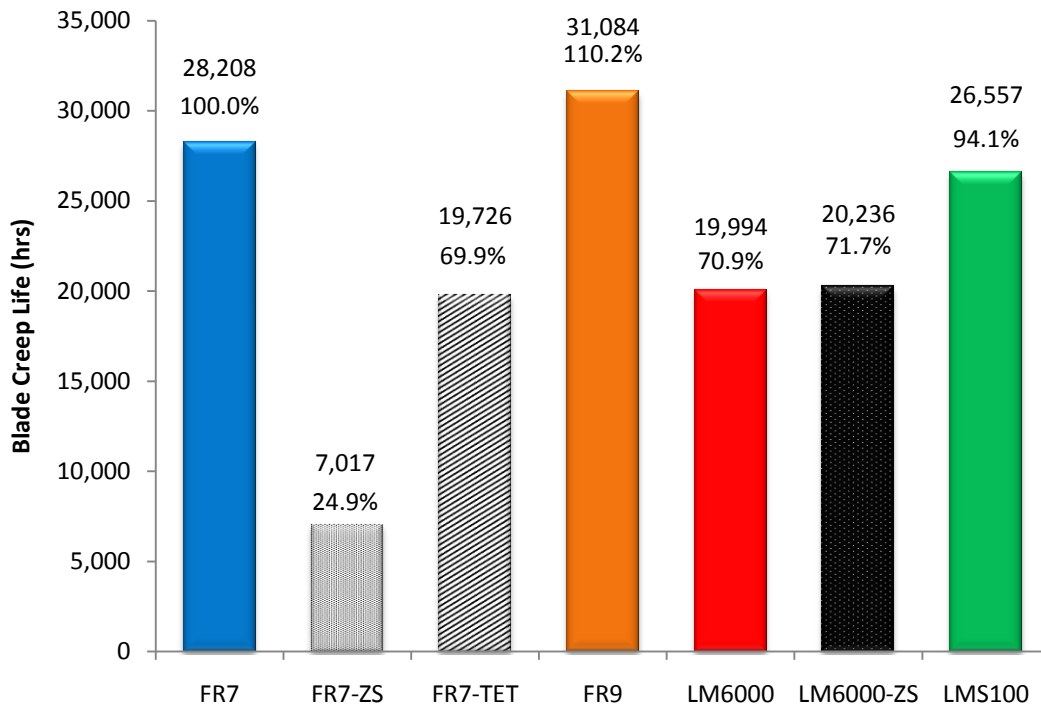
Figure 92: Relative life expectation of all engines for turbine first stage blade creep life

Further, the graph in Figure 93 shows turbine blade coating life comparisons. This is a somewhat different picture since the two frame 7 variants show less change from the parent engine. In fact, the graph shows that for the zero staged Frame 7, the coating life is lower than the original, as expected; since there are higher firing temperatures generated which in turn negatively impact the coating life. However, for the FR7-TET version, the coating actually does better than the parent engine, which is a slight surprise, however, the life of the coating is in the context of operation and so, in the operating conditions of the engine, different thermodynamic regimes are created. Hence, the FR7-TET does better since it does not operate in a regime as critically close to its design point as the other two Frame 7 based engines. This is due to the way each engine is utilised and is a function of the plant set up than the actual technology. If the FR7-TET was run as hard as the other two engines, the coating life would also show a decrease.

Further, it can be seen that the aero-derivatives in general do worse than the frame engines, as expected, however, even within the LM6000 and LM6000-ZS there is a reduction in coating life. The coating for the LM6000-ZS is changed and the relative delta T can be seen in Table

10. However, the major change in life between the two LM6000 variants is due to blade material change.
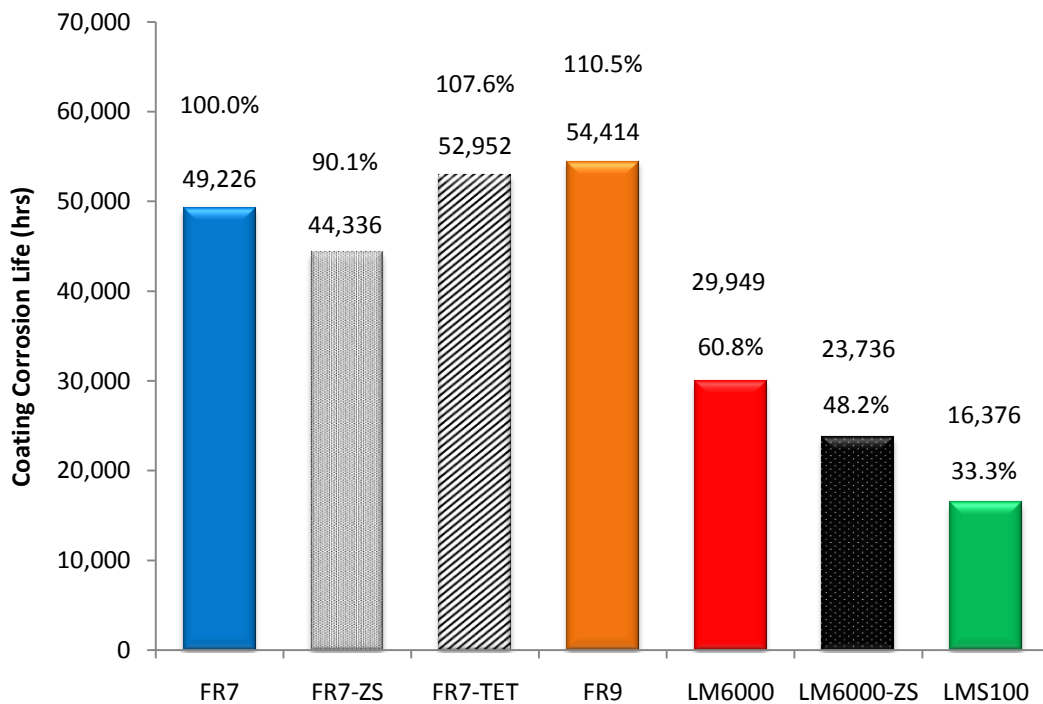
Figure 93: Relative life expectation of all engines for turbine blade coating

Finally, the chart in Figure 94 shows the change in combustor liner life expectancy with changes in engine technology. Here, it must be noted that the materials technology played a lesser part and similar engines carried similar combustor materials technology. Investigation on this front was limited due to lack of combustor materials information. In light of this, the changes seen in the life expectancy of the liner material are based more on the thermal effect than materials or vibrations effects. Hence, the engine which suffers most, relatively, is the FR7-TET version since the same combustor material is taking on a whole lot more thermal stress compared to the parent engine.
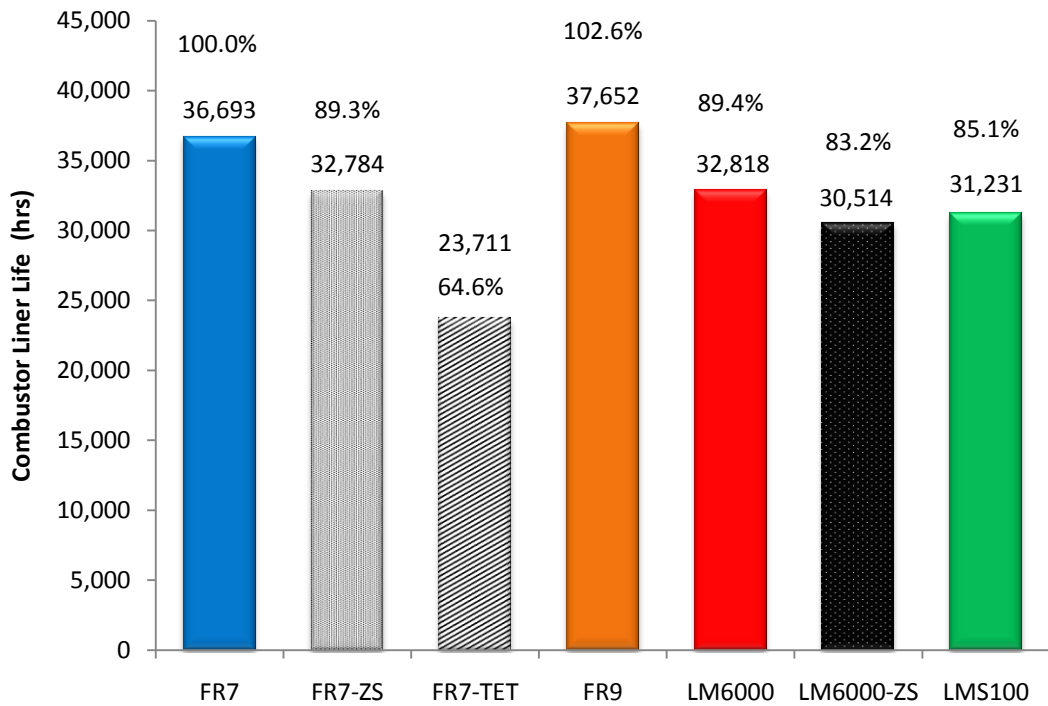
Figure 94: Relative life expectation of all engines for combustor liner material

Once again, the entire perspective can be seen in light of a set of Weibull PDF curves (Figure 95) or reliability curves (Figure 96). These pictures are similar to those presented for the original aero-derivative comparisons. Notably, the FR7 ZS shows the worst trend in terms of life expectancy but has the narrowest distribution which means its failure at said hours is more certain than the other engines.
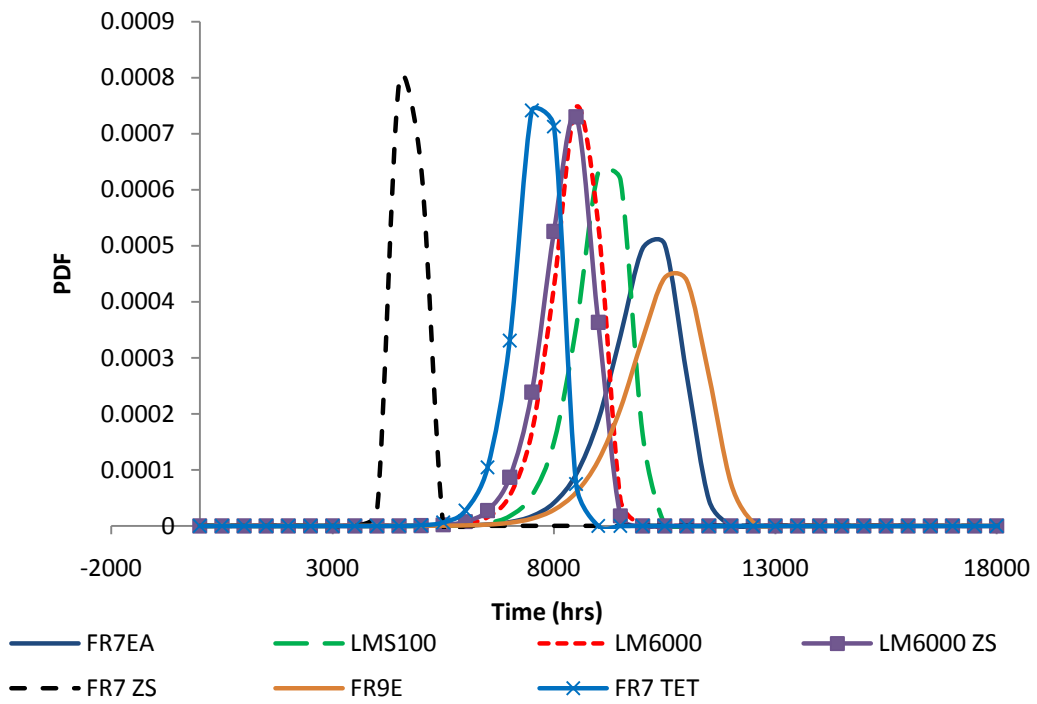
Figure 95: Whole engine Weibull curves for all engines investigated
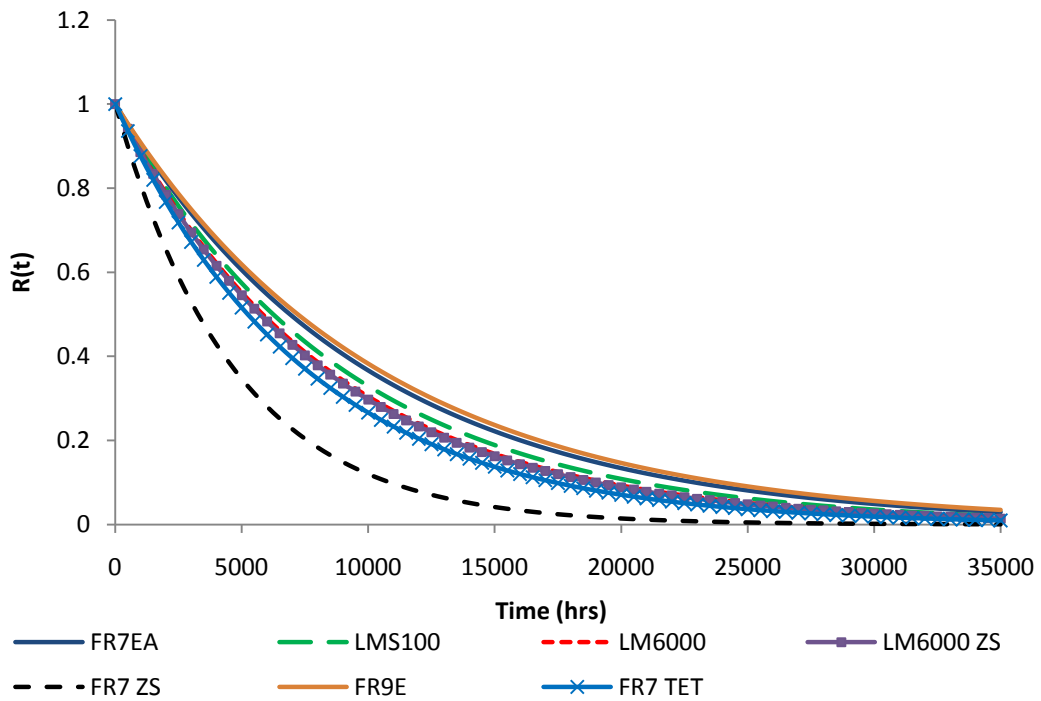
Figure 96: Chart detailing the reliability curves of all engines investigated

166

8.4.3 Pseudo Engines: Economics and Maintenance Results

Once again, it is important to look at the results in the context of the maintenance and financial calculations. This will help conclude whether the production boosts that have been attained for the pseudo engines by changing the materials or turbomachinery have an associated positive financial implication.
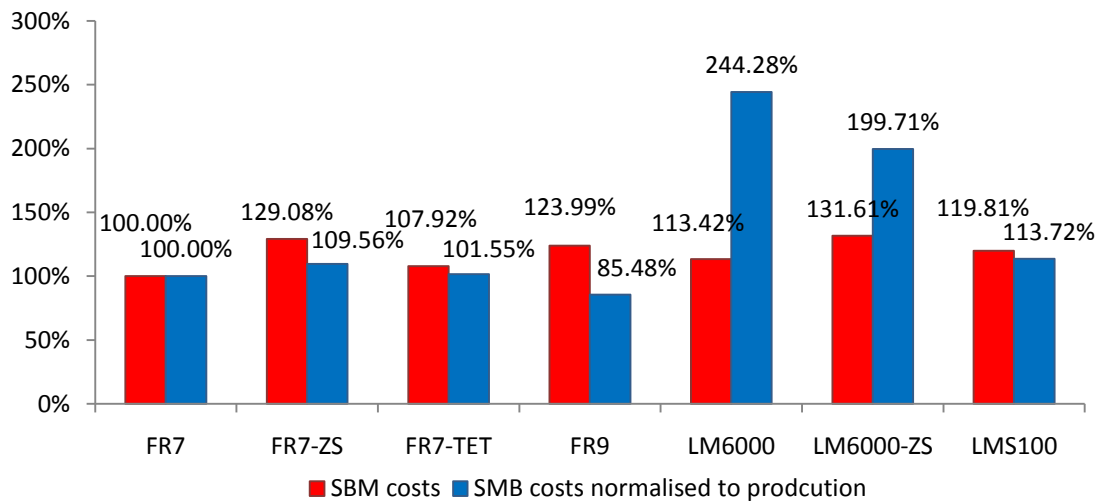
Figure 97: Simulation based maintenance costs of the pseudo engines compared to the original parent engines

The graph in Figure 97 shows the costs of maintenance for the pseudo engines compared to the original parent engines and contains all engines from all scenarios. Here, one can see the original values of the maintenance cost denoted as SBM cost and this is a percentage relative to the original baseline engine. Also, one can see the normalised value of the SBM costs when production is taken into account. This is similar to previous results presented and allows one to make a judgement based on production in tonnes of LNG since all train sizes in these scenarios are different.

The frame 7EA variants show that whilst the raw value of SBM costs is far higher than the baseline engine, the normalised values according to production are not so drastically different for the highly fired version (FR7-TET). There is only a 1.55% increase in normalised SBM costs between the parent and FR7-TET engine, which, given the production boosts is perhaps

167

negligible. The FR7-ZS however, shows a 9.56% rise in normalised costs of maintenance as compared to the parent engine and over 29% increase in absolute maintenance costs. This may be significant depending on the exact plant setup.

The pseudo engine LM6000-ZS does far better compared to its parent engine and there is a marked reduction in maintenance costs. The absolute difference in maintenance costs between LM6000-ZS and its parent engine is some 20% in favour of the parent engine, but interestingly, when normalised for production, the parent engine has higher costs accumulating to about 44.6% higher than the respective pseudo engine. This is a very substantial difference and is expected perhaps since the most significant changes were made to this pseudo engine in terms of coating and blade materials technology. However, on maintenance alone it would seem that the LM6000-ZS is lacking in the sense that it is still very much more expensive to run compared to the frame engines with respect its maintenance requirements. However, as discussed in earlier sections, the maintenance is such a small part of the overall economics balance that it may not affect the overall suitability of the aero-derivatives significantly enough.
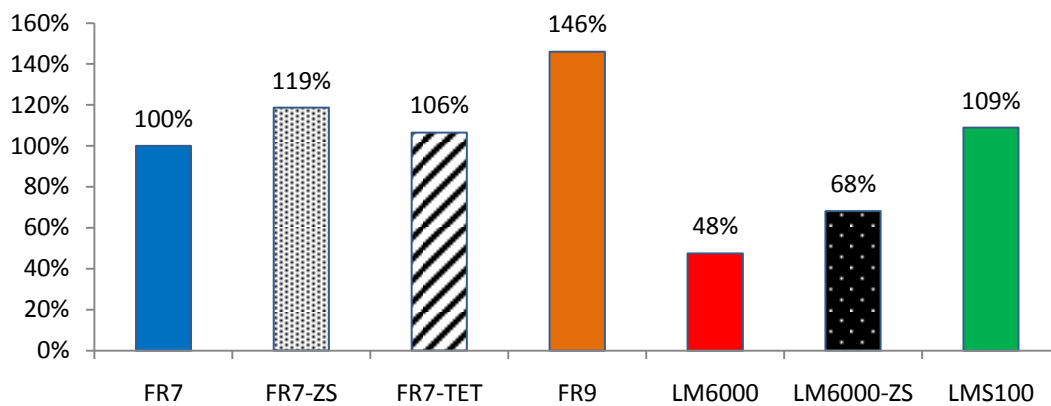
Figure 98: Non-normalised NPV of all engines

Once again, the absolute values of NPV are represented as percentage deviation from the baseline engine in Figure 98. These results show that the larger engines are favoured given the higher production. Hence, it is useful to look at the normalised NPV which is normalised to production (Figure 99). The results can be further developed to give percentage differences as seen in Figure 100. One can now see the more accurate picture when production is taken account of and is very interesting because it now begins to suggest that the FR7-ZS is indeed

a better option compared to the FR7-TET version. The NPV takes into account the entire analysis and hence is a better basis for comparison. Note also that the FR7-ZS has a relative NPV which is very similar to the Frame 9E engine. This can be expected since the FR7-ZS is a blown up version of the FR7EA and no materials changes were made, which makes it somewhat similar to the Frame 9E. In absolute terms the FR7-ZS is going to have less production, but per tonne of LNG it will be similar to the Frame 9E, hence giving the operator another option (103MW) in between the FR7 (87MW) and FR9 (130MW). However, for the turbomachinery design change which is required, and the fact that on an NPV per tonne of LNG basis there is no benefit, it may be very difficult to justify such an engine.
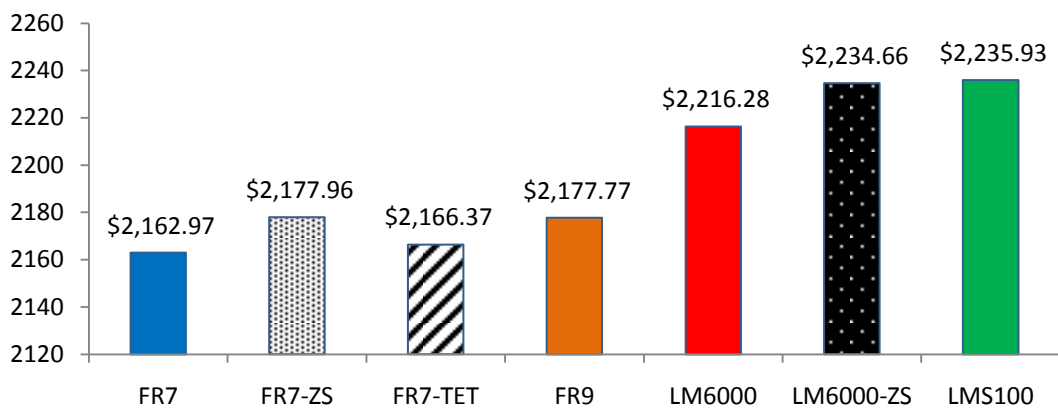
Figure 99: Normalised NPV per tonne of LNG produced of engines
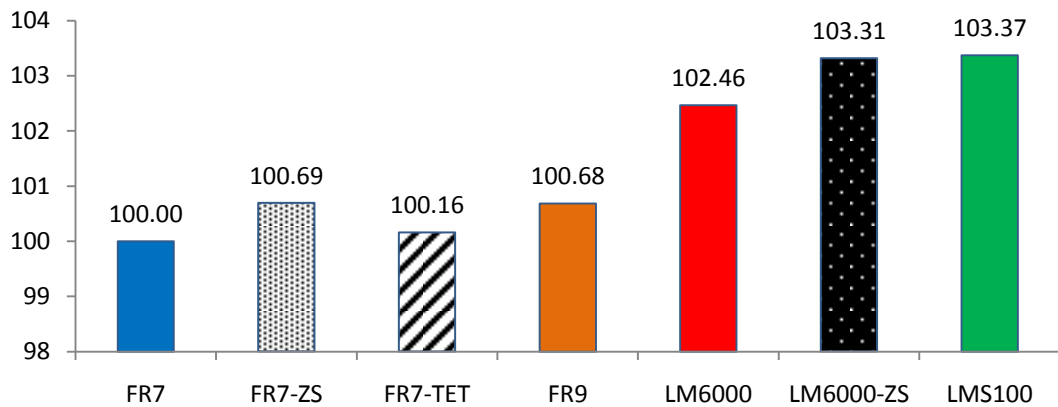
Figure 100: Normalised NPV per tonne of LNG produced of all engines as a percentage difference from the baseline engine

8.5 Case Study 5: Alternative Applications: Power Generation

It was envisaged that the LNG TERA tool could easily be extended to other applications and this was successfully achieved with the application of the modelling to the power generation scenario. Within this scenario, similar engines to the ones before were used to look at LNG.

The scenario is based on work by Noureddin Azhari (2011) under the supervision of the author. The LNG TERA code required minimal change to the code structure and no change in the algorithms apart from profit calculations which took into account electricity generation and profits thereof instead of amount of LNG produced.

8.5.1   Scenario Definition

This scenario involves a plant where a number of different engines are investigated including the GE Frame 6B, Frame 7EA, Frame 9E, LMS100, LM6000 and the Rolls Royce Trent 60 engines. The various engines used are detailed in Table 11. The Frame 6B is introduced as the new baseline since for power generation applications this engine was deemed the basic comparison point. Further, the Rolls Royce Trent 60 has also been modelled due to its significant application in this field.

Table 11: Engine ratings for Power Generation scenario

Engine	Design Point Power (MW)
Frame 6	42.1
Frame 7EA	87.3
Frame 9E	130.1
LM6000	42.7
LMS100	99.2
Trent 60	58.0

These engines are used in a six engine configuration so that each plant has six of each type of engine and they run in a 4 by 6 configuration. This means that there are 6 engines running at part load producing the power that 4 engines would do so at full load. This means that if an engine goes out, the other 5 engines should easily be able to continue at due capacity and there won't be loss in production.

170

8.5.2   Lifing Analysis: Power Generation Engines

The engines are running at part load compared to LNG operation and are thus expected to have far higher component lives. Figure 101shows how the blade creep life varies for the different engines involved. It can be seen that the frame engines follow a similar trend to that seen in earlier case studies where the engines which are fired less have a relatively higher creep life for the blade material. It is also worth mentioning that the Frame 6B has a higher firing temperature than the other two frame engines. The materials choice was again similar to the rest of the Frame family of engines.

The other notable results are linked to the aero-derivative engines. The Trent 60 engine shows the lowest creep life relative to the baseline engine. This is again expected as the creep modelling is sensitive to temperature and the firing temperature of the Trent engine is the highest given its design. There has however been a reversal between the LM6000 and the LMS100 as compared to the LNG scenarios. Here it can be seen that the LM6000 fairs better than the LMS by approximately 10%. The simple reason for this is the way the engines are being utilised; in power generation the engines were utilised close to design point firing temperatures whilst in the Power generation example they are being used in a part load of 6 engines providing the power of 4 engines at design point.
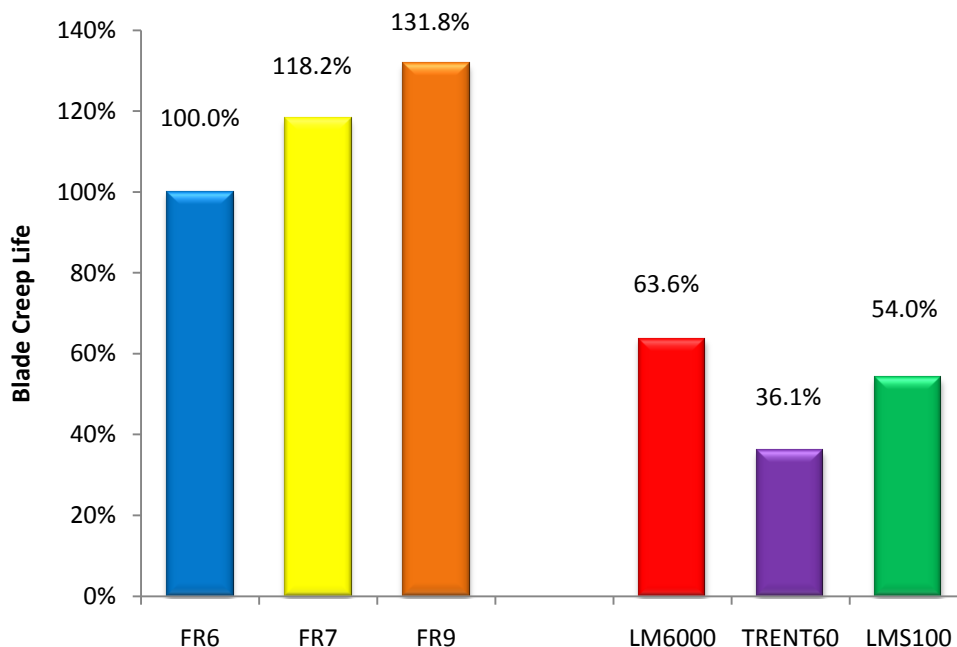
Figure 101: Relative blade creep life for power generation engines

171

Further, Figure 102 and Figure 103 show that the coating life and combustor liner life is again favouring the frame engines due to lower firing conditions. Notably for the combustor life, the aero-derivative engines are not far off from the baseline case for the Frame 6B engine. This is due to superior materials technology which nullifies the effect of the increased firing temperature to some extent.
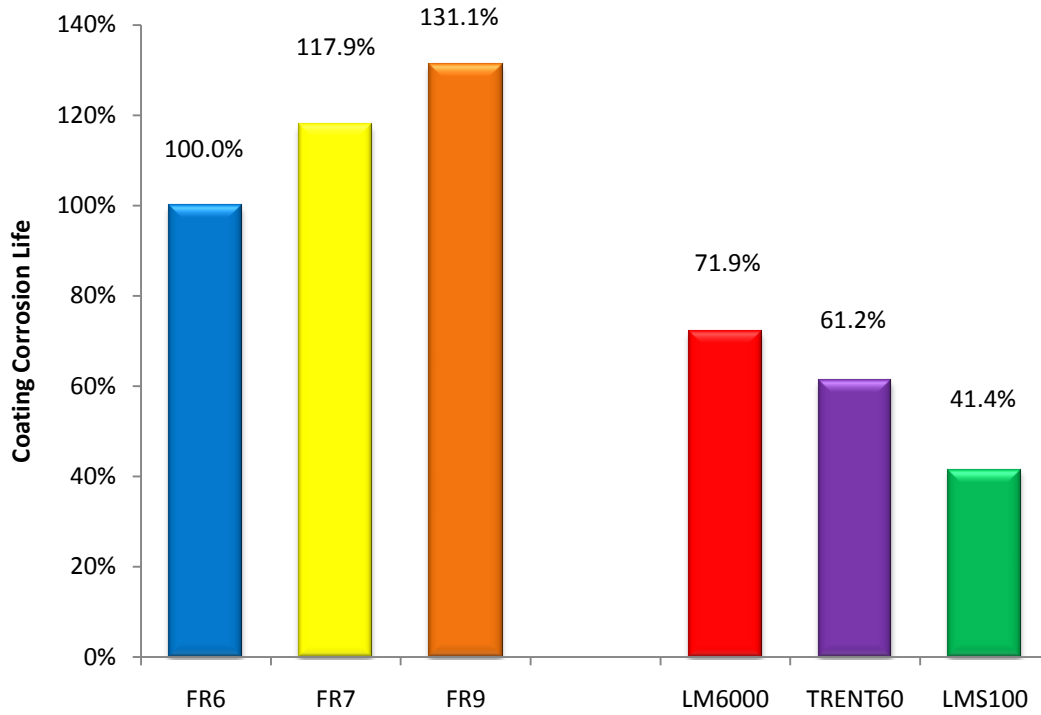
Figure 102: Relative coating corrosion life for power generation engines
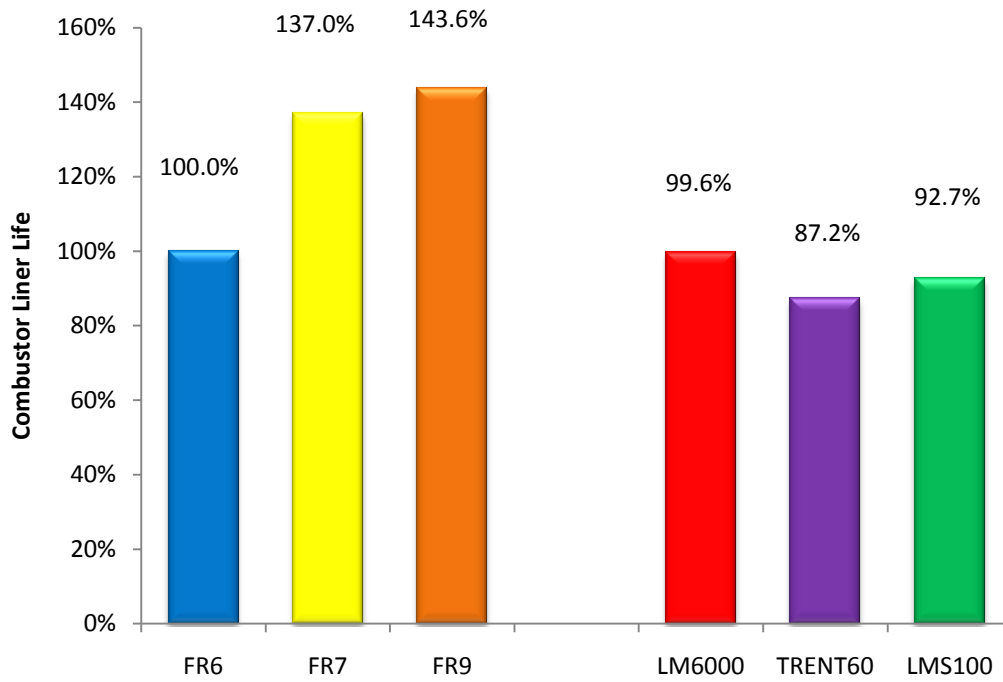
Figure 103: Relative combustor liner life for power generation engines

Further it can be seen in Figure 104 that the engines exhibit once again a slightly different failure distribution trend to the LNG case in the sense that the Frame 7EA engine shows a greater life than the Frame 9E. This has to be read in the view of the fact that the greater life also comes with a greater spread of failure possibilities and hence a higher uncertainty of when the engine will fail. The LMS100 shows the lowest amalgamated life as an engine. The η and β Weibull parameters are summarised in Table 12.
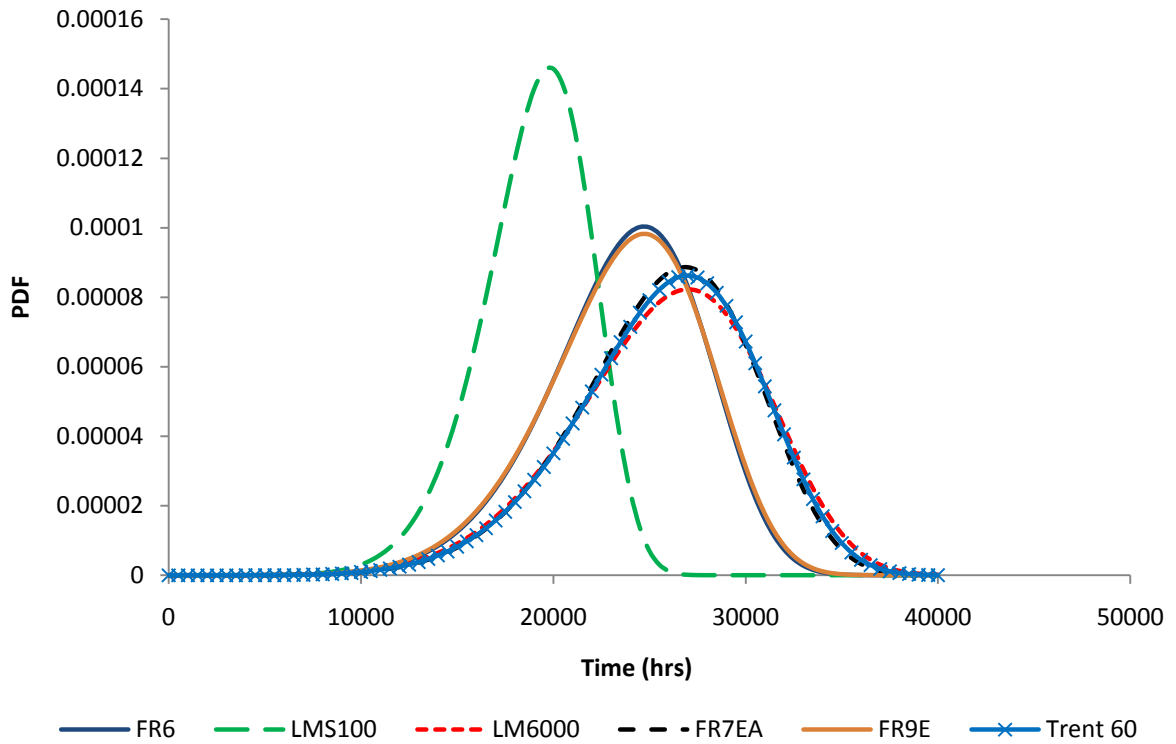
Figure 104: Distribution of failure for power generation engines

Table 12: Summary of Weibull parameters for power generation engines

Engine	η	β	R(t) @ 50%
FR 6B	25,300	6.82	16,000
FR 7EA	27,545	6.56	18,500
FR 9E	25,340	6.69	17,500
LM6000	27,810	6.13	16,000
LMS100	20,155	7.94	17,500
Trent 60	27,700	6.41	13,000

The reliability curves show the same results from a slightly different perspective (Figure 105). It can be seen that the Frame 7EA engine has the best reliability for any given time to failure. The operator can look at this curve and decide a critical reliability value after which maintenance can become advisable or mandatory. An example taken here is the time required

174

to reach 50% reliability. These values are tabulated in Table 12. It means that the reliability with respect to time falls to 50% for the Frame 7EA at 18,500 hours whilst the worst performance is by the Frame 6B and LM6000 engines which are reduced to 50% reliability after only 16,000 hours. So, it is clear that the beta parameter alone does not affect the trend of times to failure but rather is an indicator of most of the spread of data. The reliability with respect to time takes into account both the eta and beta Weibull parameters and hence is a good overall indicator of likelihood of failure.
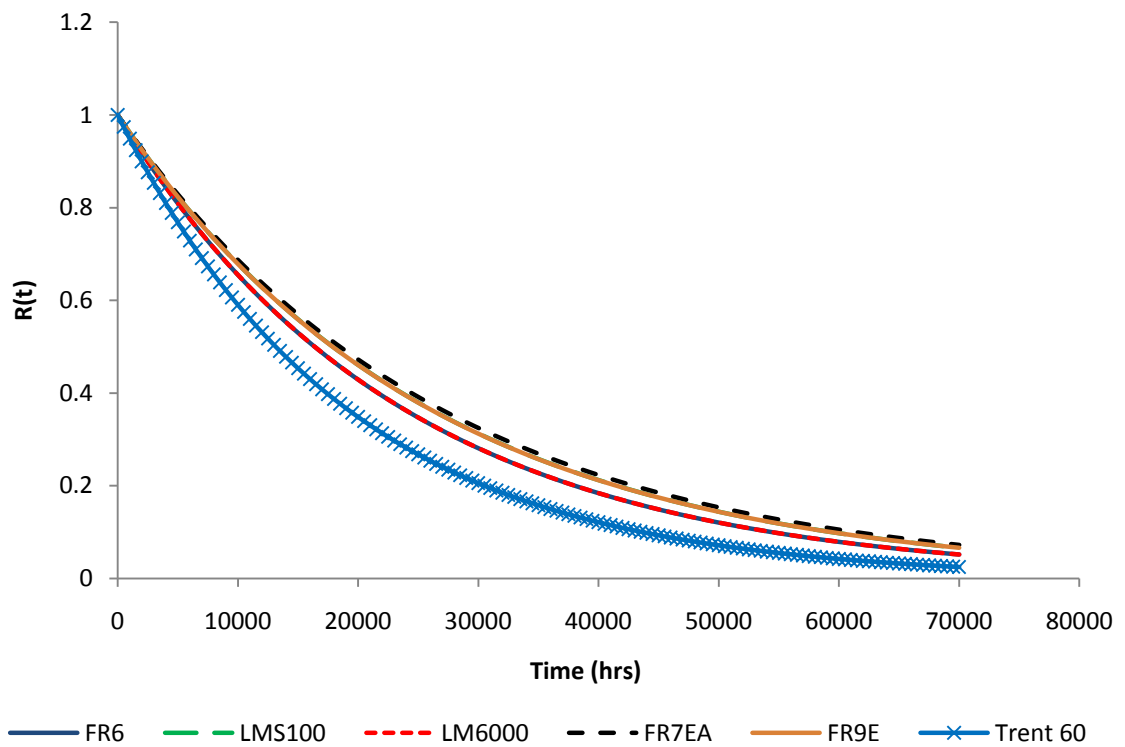
Figure 105: Reliability curves for the power generation engines

8.1.1   Maintenance and Costs Breakdown: Power Generation Engines
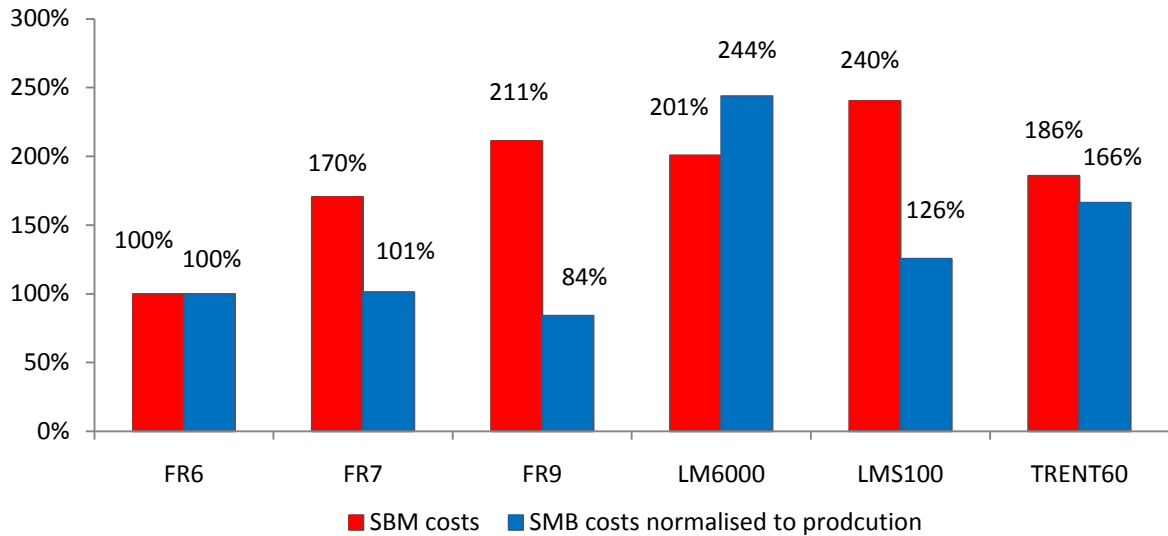
Figure 106: Maintenance costs normalised to production for the power generation engines

The maintenance results show that as expected, the absolute maintenance costs are relatively similar for the larger machines though the LM6000 shows very high costs, however, the normalised maintenance to production of electricity is a better picture because it shows that the frame engines have a better specific maintenance cost. Again, for the LM6000 even the normalised cost is high because as a smaller engine it has accrued greater absolute costs so on a relative basis this engine shows up as the worst case.

The total costs relative to the baseline engine can be seen in Figure 107. Total costs, as seen in the LNG scenarios are largely and function of engine size in terms of power and mass flows, and hence fuel consumption and thus will be biased towards the larger engines. For all engines explored in the power generation case, the costs are fairly similar in a relative sense, however, it is perhaps more useful to convert costs to net present values to look at the time value of money and also to normalise the results to production in terms of kilowatt hours delivered. Figure 108 shows the trend of NPV relative to the baseline engine and clearly the larger engines are seen to perform better; since the Frame 6B and LM6000 produce less power it follows that they suffer in terms of NPV.
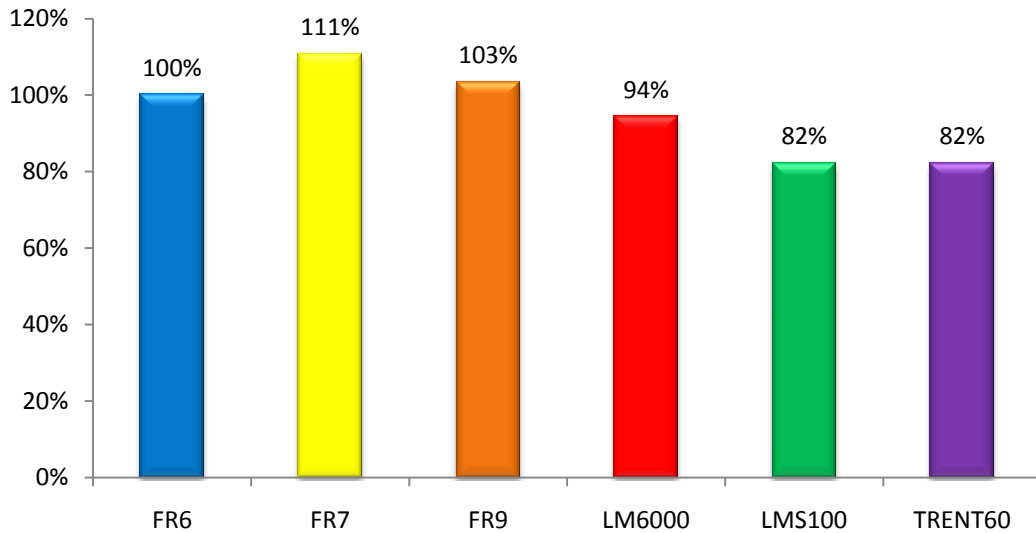
Figure 107: Total Cost relative to baseline engine
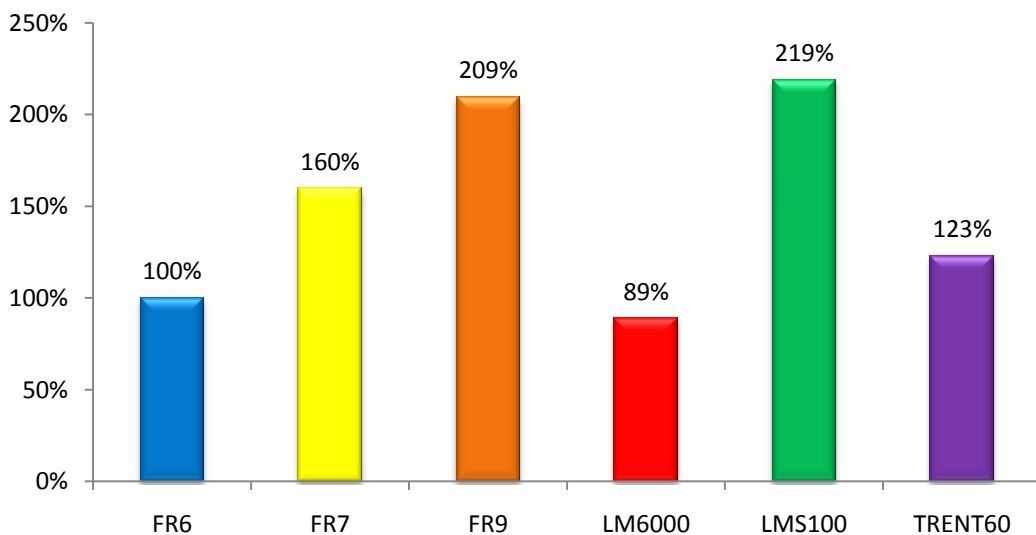
Figure 108: NPV relative to baseline engine

Further, Figure 109 shows the NPV normalised to production (NPV/MWhr) and Figure 110 shows the NPV normalised to rated engine power (NPV/MW). These two results are to be analysed in conjunction. The first result relative to power delivered (NPV/MWhr) is the true picture since it takes into account the NPV relative to the actual energy produced and thus is accounting for downtime whilst the second result (NPV/MW) is simply look at the engine *capacity* or *capability*. The later is a measure of what the engine can deliver depending on its

177

rated power. Engines can be selected based on the rated power they can deliver. This work highlights the importance of looking at the plant in context because for a specific plant the relationship between costs and net gains will change based on how the operator utilises the engine and thus plant design and set up. The ratio between these two figures can be loosely expressed as a measure of engine utilisation or how much the operator *'sweats the asset'*.

The first result (Figure 109) shows that the aero-derivative engines have a higher specific NPV with respect MWhr of energy produced. This value is highest for the LMS100 and Trent 60 engines. The second result (Figure 110) would mean that Frame 9E was worst off because it has the lowest NPV per MW of rated engine power. This effect is amplified for said engine because of the 130.1 MW rating it has.
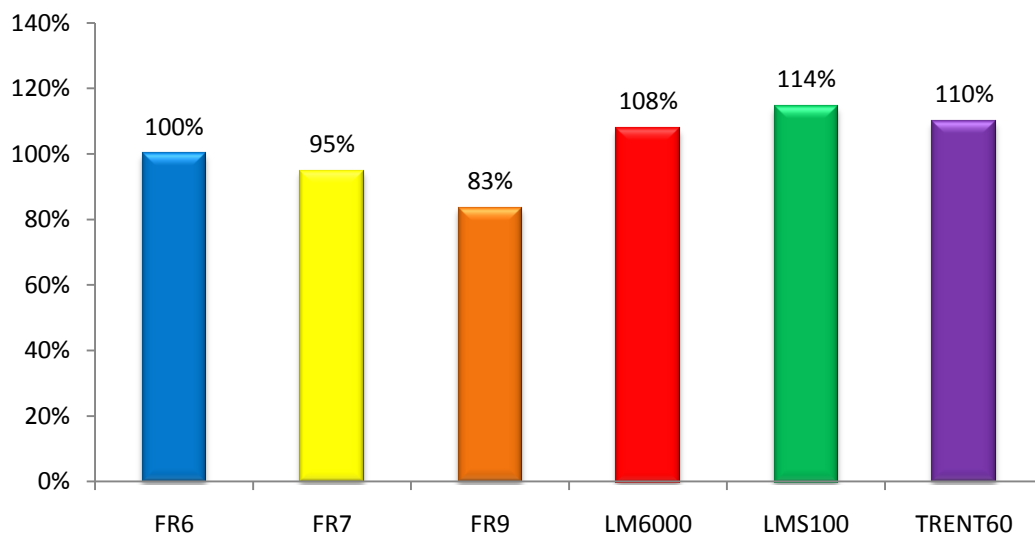
Figure 109: NPV normalised to electricity production (NPV/MWhr)

178
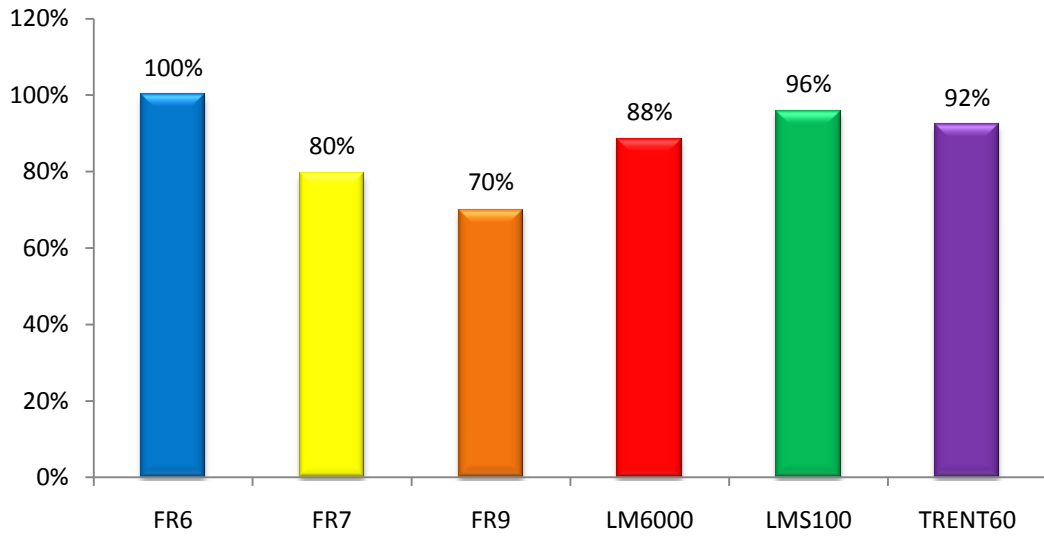
Figure 110: NPV normalised to engine power rating (NPV/MW)

9. Conclusions

This section summarises the key methods and results of the research and highlights the further works that provide a natural continuation of this research. The positive aspects and limitations of the LNG TERA tool are also discussed.

9.1 Summary of methods

The LNG TERA equipment selection tool is based on a multidisciplinary philosophy incorporating techno-economic, environmental and risk aspects as well as other unique considerations such as lifing, maintenance and technical risk assessments for the LNG version of the TERA.

The LNG TERA tool uses a gas turbine thermodynamic performance code at its centre called Turbomatch. Turbomatch simulates engines at design point and off design and relays the performance parameters at each core component to the other modules. The lifing module receives core gas temperature, pressures and mass flow data from the performance and calculates the blade creep life (Larson-Miller parametric), blade coating life (probabilistic) and combustor liner life (kinetic of destruction). Stochastic methods (Monte Carlo) allow the TERA to look at the expected value of life for selected components as well as looking at the uncertainty of the expected value using Weibull statistics. This forms the risk analysis module. The results of the risk analysis are fed into a maintenance planning algorithm which looks at the failure of the entire engine as opposed to isolated components and prepares a maintenance schedule. Emissions are calculated using empirical correlations based on known combustor characteristics. Based on the performance results (fuel flow), maintenance schedule and emissions, the economics module finally calculates the worth of each option or scenario of engine selected using the net present valuation methodology. This makes the TERA a multidisciplinary tool for analysing the problem of equipment selection.

9.2 Summary of Key Results

The discussion and results compare various different scenarios of engines that could potentially be used as drivers in a liquefaction process. The baseline frame 7EA engine was compared to a number of other options on a single train, dual engine configuration basis.

The key results from the first scenario show that the frame 9E is at an advantage compared to the frame 7EA due to the economies of scale argument in that the larger Frame 9E can be used to constitute a far larger train and boost production. Though the engines belong to the same family there are slight differences in the thermodynamic conditions created within the engines and the Frame 9E is fired slightly lower. There are hence some life benefits for the combustor liner, coatings and turbine blade material. This gives the Frame 9E a slight overall advantage. In absolute terms the Frame 9E can produce more LNG from a given train, but when compared in specific terms for example production per MW of power at which the engine is rated or production is normalised to costs then the picture is not so drastically different and this is expected since the engines are of the same family.

The second scenario looked at comparing the aero-derivatives engines to the baseline frame 7EA engine. This scenario shows that for some isolated aspects, the aero engines perform worse than the industrial frame engines, for example, the life expectancy of the hot gas path components for the aero engines is far lower than the industrial frame engines. Also, the emissions can be expected to be higher, though the emissions are not reaching critical levels. The outstanding quality of the aero-derivative engines is their supremacy in thermal efficiency and overall quality of the cycle. Given that the aero-derivatives are an amalgamation of the best parts of previously used aviation power plants and use materials and cooling technology which is advanced compared to the industrial frame engines, this means that the aero-derivative engines use far less fuel. The swing in the fuel economy direction outweighs any other costs associated with the aero engines. Indeed the life estimates of the aero-derivative engines are a fraction of the industrial engines, and the maintenance requirements are higher but the underlying fact is that due to the modular design on the aero-derivative engines, they can be changed out far faster than the industrial frame engines.

Further, the third scenario looks at the idea that pseudo engines could be utilised which could be a less drastic move away from currently utilised industrial frame engines. Some changes would be incorporated in the form of new materials and coatings whilst others will be redesign of existing turbomachinery. These scenarios show that a significant boost can be had if the original frame 7EA engine is zero staged or if fired at a higher temperature. The fired version would perhaps be less demanding in terms of redesign since the zero stage means geometric change to the current configuration, essentially producing a new engine. However, the life expectancy of the highly fired version will again come into contention. the other

pseudo engine was based on the LM6000 and was again a zero staged version making the engine larger and thus creating a train with higher production capacities.

The overall analysis shows that the zero staged version of the FR7 is better than the highly fired version on a normalised scale correct to production in tonnes of LNG. However, it is still not better than the original engine, so one might ask why bother with such redesigns. However, the redesign of the LM6000 produces a zero staged pseudo engine which is far better than the parent engine and this owes to drastic changes in blade materials technology and coating technology employed in the critical gas path components.

The modelling was extended to an alternative application to exemplify the flexibility and diversify the use of the TERA tool. The power generation application shows that the life of the aero-derivative engines diminishes a lot faster than the industrial frame engines and there are also high maintenance costs associated with the more highly fired engines. However, once again the economics argument is in favour of the aero-derivative engines and due to lower fuel consumption. The new engine added was based on the Rolls Royce Trent 60 engine as well as changing the baseline to a GE Frame 6. The final metric used for the economics analysis is the NPV per MWh of power actually generated and this shows that the best Frame engine is the baseline rated at 100% for nominal comparisons, whilst the aero-derived engines are 8% (LM6000), 14% (LMS100) and 10% (Trent 60) better than this baseline. It must be said once again that these are engines based on the original cycles and not entirely or exactly reflective of the original engines. Further, the NPV is expressed for the engine only as opposed to greater plant and hence comparisons are difficult and not sensible at this stage.

This study was carried out assuming a given ratio of load split between the engines and hence is sensitive to the way an operator demands power of the engine as opposed to LNG application where the operator tries to drive the engine as hard as possible to get the most production out of the train.

9.3 Further works

It must be noted that the entire analysis is done in line with isolated trains and the economic worth of each scenario and consequent comparisons are based on this isolation. Hence, the costs that come with each scenario are not all accounted for and this costing and detailed plant design would be outside the scope of this project.

A number of challenges are yet to be solved within this framework and this denotes further work and potential continuation of the research project. The main challenges are:

1. The economics analysis is not very sensitive to the changes in levels of risk. An attempt was made to look at variation in risk by statistically controlling the region of the failure distribution from whence the values for life of a component are generated via a Monte Carlo simulation. However, given that creep is a phenomenon with relatively low variation compared to fatigue for example, the simulated changes have been small. This may be due to nature of creep and reduced variability. It may be an idea to introduce the fatigue routines for the wheel and spools. Fatigue tends to produce far higher variation and this is a way forwards for the components which were not in the lifing regime of the present TERA. For this reason, the current modelling was not extended to the creation of a novel comparison/scaling system like the TRL/TCL scale suggested earlier.

2. Preventive Maintenance is a flat prediction and does not change within the context of this simulation, hence comparisons between PM and SBM are not very illustrative of the benefits of SBM. In reality even PM schedules vary with operational experience. This is hard to simulate but needs to be incorporated in further studies if direct comparisons are to be made. Further comparison should be made to maintenance schedules form the operators as they are presently used and compare these to SBM. PM was included in the study because it was the remnants of the first maintenance module. However, in the context of this thesis it is not the best method for comparing with SBM. Further, SBM maintenance is to be compared between engines as opposed to PM directly. The expectation was that SBM would always be the best solution but this does not necessarily mean it will have the lowest downtime, it simply means that it is the right thing to do given the way the engine is being operated.

3. The emissions analysis was restricted to empirical correlations which is not the best method for estimations since variable combustor types would have needed, ideally, a physics based model. The possibilities of using a physics based model with dissociation and other effects was investigated but was not taken up due to the complexity of the modelling and the time required to carry out the modelling and analysis. This is important since the scenarios looked at here had varying combustor designs and perhaps the empirical correlations were not best to bring out those

differences. Further, empirical correlations are dependent on trends for the combustor already established which makes the modelling limited to the user having those trends whilst the physics based approach would do the calculations from basic principles and build up the picture of the chemistry inside each individual combustor type.

4. The greater plant needs to be simulated and a detailed look at other equipment (gas compressors and electric motor failures) needs to be incorporated to allow comparisons to published results.

5. Further work can be done after the preliminary nature of the pseudo engines was investigated. The scope of this research did not allow detailed investigation and hence a clear further work would be to look at the optimisation of pseudo engines for the LNG application. It was clear that the Frame 7 pseudo engine with zero staging is a viable option but would need further materials technology considerations before further conclusions could be drawn, as yet, without a change in materials technology, it is unjustified to conclude it is not a good option. The challenge was to look at materials changes in light of the turbomachinery alterations proposed (refer to case study 4 comments).

10.   Management Report

This brief report will highlight the management aspects of this thesis and describe how the guidelines of the EngD requirements were followed. Broadly, it describes the content of the thesis which pertains to commercial applicability of the LNG TERA equipment selection tool, management knowledge learned and applied to the research and the planning and approach to the research.

The requirements for approximately 20% of the thesis to be based on the management aspects such as looking at:

1. Business and commercial aspects of the research, justification thereof
2. Management knowledge and usage
3. Weaknesses of current alternatives
4. Planning and Management (time, resource, knowledge transfer) of the research

10.1   Commercial Applicability

The commercial applicability of the research was discussed at the beginning of the thesis and it was highlighted how this research is useful to the sponsor company. The key benefits to the sponsor are that the tool developed could potentially help reduce costs of selecting and operating machinery in a plant and hence is also a strategic tool.

The commercial benefits of the research to Shell can be summarised in three parts:

1. Selection: The current work exemplifies how the LNG TERA tool can be used as a basis for selection of machinery. Emphasis is placed on the idea that this is another method of highlighting technology which can fit the purpose and is not envisaged to be the only tool for selection purposes. It can work in compliment to detailed existing framework for selection and provide another view. If anything, it will raise questions about selection which can prompt a more detailed study. The whole point of TERA is to find the solution area and narrow the design space which this tool is capable of doing. From there onwards, it would require a detailed analysis of engines and the process to get a decision. This tool is a decision making aid.

2. Operations: The main purpose with respect operations is that LNG TERA was envisaged as a tool which will provide a link between performance and operation of the engines and the failure of components and maintenance aspects. Three attempts were made which gradually made this happen, starting with a risk framework which was not linked to the performance, but allowed the methods to be developed in isolation. Stage two involved linking the performance of the engine to scaled Weibull parameters and finally the mapping of performance directly to risk took place. This aimed to quantify risk in operation and aid in decision making. This will also help the operator to make decisions about repair and replace of components.

3. Sensitivity Analysis: By sensitivity it is meant that the tool is capable of exploring a range of different situations where key parameters such as gas price, discount rate, price of commodity sold (whether electricity or LNG) and various other performance based and econometric parameters can be varied to get a picture of how the modelling is sensitive to these parameters. This aspect is explored in great details by Maccapani (2011) whilst the focus of this thesis was core results of the scenarios. Some sensitivity to the creep curves was mentioned by Burgmann (2010).

Further, the tool can be extended to other pant types and operations, and the research provides a framework which shows how such modelling can be of financial benefit to the operator.

10.2   Management Knowledge and its Application

The requirement of the research to take aspects of the taught element of the management side is also met since 25% of the traditional TERA philosophy is rooted in financial and economic considerations of utilising plant machinery. Hence, a very significant portion of the technical works and modelling was attributed to the financial calculations and worth of using such a tool. Indeed, the entire technical analysis is concluded using the Net Present Value technique that was learned in the management (MBA) studies. Those techniques were brought in to help evaluate the project and provided a strong basis for total plant evaluation. Financial management as a taught course was greatly helpful in educating the author as to what techniques are available and applied currently to evaluate projects.

10.3   Alternative Methods

It cannot be concluded that alternatives to this equipment selection tool are necessarily weak in their approach since plant operations and optimisation thereof is a deep and subjective subject and different companies will utilise different techniques and philosophies to improve plant performance. However, it must be said that the sponsor company bought into this research so as to benefit from an independent method of looking at maintenance and plant machinery selection. This was done so that different ideas than those presently used at the company could be explored thoroughly and without taking traditional routes.

10.4   Planning and Management of the Research

10.4.1 Planning

The planning of the research was done using typical techniques such as breaking the tasks down into work packages and putting them on a timeline. This plan, or Gantt, went under much change as needed and as and when the project definition grew, however, the key dates were adhered to and the modelling was delivered more or less on time and in the format the sponsor company had required.

The final plan that was executed is presented in Figure 111. It shows the discretisation of the tasks into work packages and shows which tasks had additional resource attached to them. Key dates, milestones and review dates are also given.

The first year tasks are colour coded blue and the emphasis was to look at the performance of the key engines and create thermodynamic performance simulation models. Another objective was to put forward a method for the risk analysis (isolated risk analysis).

The second year tasks are in red. This year involved doing the MBA so the resource was limited hence grater external resource made up of three masters level researchers. Here the emphasis was to further develop the risk which was now at stage two (scaling risk to performance) as well as looking at emissions and maintenance modelling.

The third year is coded in green and was the stage where most of the modelling was completed and tested. The integration of the models happened at this stage as well as

finalising the engine library, performance inputs and outputs, and the TERA was run from end to end for the first time.

Year four is coloured purple and was a phase where the TERA was made robust so that it could run with various engine types. This meant finding information for materials, creep curves, blade sizes and emissions information for different combustor types. This was more of a validation stage rather than development.

There were a number of publications during the second and third years (2 conference papers and 1 journal paper) and some are planned post viva. At the time of writing the thesis a further 7 papers were planned with 4 completed and in the pipeline for publication.

This plan was changed at various stages during the project since there was lack of definition in the first stages of the research. As the project went on the plan developed according to the way the modules were developed and also depending on the feedback from the sponsor company. However, the majority of the key dates remained unchanged and the project submission was only delayed due to external reasons. All development was complete in early 2011 and results had been generated for the majority of scenarios by August/September 2011.

10.4.2 Management of Resources & Knowledge Transfer

The research was unique in that there was a large utilisation of Masters level researchers whose role it was to aid in modelling and running of results and scenarios and testing the robustness of the algorithms that were programmed.

The procedure/relationship:

1. EngD researcher writes a brief for the research project which they intend for the masters researcher to conduct
2. Brief shown/presented to many researchers and interested parties are recruited onto the project
3. Knowledge Transfer 1: The Masters researcher spends circa 3 months learning from the researcher: Can be in terms of
   a. Already established code and how it works
   b. Learning a programming language

       c. Learning about adjacent algorithms to the ones they will work on within greater TERA architecture

       d. EngD provides framework for input, output required

       e. EngD dictates the models to be utilised in black box

       f. Masters researcher designs the black box

4. The work packages and deliverables are agreed at Cranfield

5. The work packages and deliverables are presented to the sponsor and approved

6. Work begins, under supervision of an academic and the EngD researcher

7. Mid-term presentations to academics and sponsor

8. Adjustments to the project deliverables if need be

9. Knowledge Transfer 2 (reverse): Final deliverables achieved and knowledge transferred back from masters researcher to research owner (EngD researcher)

10. Final integration of new modelling to main LNG TERA tool if applicable and approved by sponsor

The entire procedure is a closely knit relationship between the EngD and the Masters researchers and the models are worked on interchangeably and the entire team consisted of as many as 8 to 10 people at a time that interchangeably used models, developed parts and passed onto other researchers. In this way the whole procedure and its management was down to the EngD researcher.

10.4.3 Relationship with Researchers

Without the help of the additional resource due to the researchers working on this project, not nearly as many objectives could have been set and covered. It also meant that the author got the experience of managing researchers in a closely knit team and to delegate research tasks and also bring the research together. This increased the value of the experience for the author.

Further, the relationship between the masters researchers and the author was such that there was continuous communication on a daily basis. The approach involved the author setting up meetings between the researchers, himself, and academics and specialists in key subject areas. The whole process was managed by the author. The author acted as a bridge between the researchers also, since they were all contributing to different parts of the modelling and it was the role of the author to bring together and integrate the works as well as bridge the efforts of the researchers so as to form seamless continuation of the models.

This also involved meticulous planning so as to be able to manage the time and form and shape of the modelling. By this it is meant that the author was ultimately responsible for delivering the modelling at each check point and had to encourage and support the researchers to deliver their respective work packages. By form and shape of modelling it is meant that the input and output of consecutive models had to come together smoothly so as produce a chain of modules which exchanged data without causing the algorithms to crash.

Forms of learning and communication employed between author and rest of team were:

1. **Gantt charts for planning**: The author showed each member of the team where their work package fitted into the project Gantt chart and helped the members to develop their own Gantt charts to compliment this greater plan

2. **Progress presentations to sponsor**: This became a common routine and involved all members presenting updates to the sponsor regularly. This system was entirely supervised by the author and involved checking, correcting, and collating presentations. Typically the sponsor would visit for an entire day and listen to progress reports and discuss further actions. This was a key team event here all members had to complement each other and build up the progress in conjunction with each other and show how it all fitted together. This process was managed by the author as the research lead.

3. **Telecons**: These were interim meetings over the phone (some of which have been minuted in the appendices) for times when the sponsor could not come and visit or when a pressing issue had to be discussed.

4. **Knowledge transfer sessions**: As mentioned earlier, there was an initial phase of transfer of knowledge between author of this report and the rest of the researchers. This was vital to bring the researchers up to date with progress to date so they could contribute constructively. This event could take the form of sessions over days or even weeks where the members of the team would be educated about theory, background, methods and tools used in this research. Typically it was sessions on tool familiarisation and programming and looking inside the algorithms to see how the modules and models were built up. This also had the effect of further integrating the research.

5. **Typical dialogue in meetings between the author and team members involved**:
    a. What progress have you made – check list of previous tasks and targets
    b. Where are we/ should we be on the Gantt chart?
    c. What skills/knowledge has been acquired or is needed?
    d. Presentations to each other and rest of group
    e. Contacts made / share contacts
    f. Brainstorming sessions – post it note method to get everyone involved
    g. Decisions on which models to utilise and methods – round table meetings
    h. Tasks and targets for next meeting

The emphasis of the team meetings was to motivate the team and to share knowledge so as to progress faster. Typically one team member could help another with either skills they had or knowledge they had gained from reading or finding information for their own tasks. This is the main benefit of research in small teams.

Typically help was sought from academics outside the direct project team, without contaminating them with sensitive information, so as to be able to take full advantage of experience of academics in the institution.

10.4.4   Work Package Split

It is also important to say what credit is worth to different people who worked on the project. This will be done module by module:

1. **Performance Module**: Here the entire programming, building of the wrapper code which controls all the modelling and interface between modules was done almost entirely by the author.
    a. This was the appropriate thing to do because the author is the architect of the research and the only person who sees's all the modules come together.
    b. The master's researchers throughout the four years did help with modelling the engines in Turbomatch, but the majority of this work was also done by the author. The modelling of the GT in Turbomatch involves preparing an input file to instruct the Turbomatch tool, it does not involve programming as such.

2. **Risk and Lifing Modules**: This was done in a number of stages so is slightly more complicated:

a. As explained earlier, there were 3 stages to the risk module development; initially the modelling was not connected to the performance. This was during the first year when master's researchers Maria Lagana and Javier Barreiro worked on the risk. This modelling was not used in the final version and served as a learning curve, though much of the theory was later applied to new modelling.

b. The second phase involved Andrea Baioni (2009) and this was also not used in the final version again since it was not fully representative. It was an attempt to scale the performance to risk parameters, which was again useful learning curve but not part of the final modelling.

c. The final phase was a direct link between risk and performance via lifing. The lifing algorithms were selected by the author and developed in conjunction with Paul Burgmann. Burgmann (2010) did most of the programming in FORTRAN language under the direct instruction of the author. In this way, the author is architect of the models whilst Burgmann is the programmer. Burgmann was instrumental in trouble shooting the working and interface of the models, but it must be understood that the models were first developed and selected by the author before Burgmann joined the project. This included LMP method, the novel risk method with multiple creep curves and selecting the probabilistic coating model. Burgmann did however contribute the Liner lifing model which again was only made part of the modelling after the author selected it as a method.

d. An additional work, the 1D lifing model was coded by Ramaswamy (2011). However, the preparation work for this and the bulk of information finding and research into models and methods was done entirely by the author. Some time before Ramaswamy joined the project, the sizing and blade profiling in MS Excel had already been established by the author, Ramaswamy came in to code this to FORTRAN to make it work with the rest of the TERA. However, Ramaswamy was instrumental in trouble shooting the workings of the methods and also to create blade profiles and detailed stress and thermal calculations.

3. **Maintenance and Economics Modules**:
   a. The first maintenance module was developed again by the author and researcher (Joseph Ekanem, 2009) in conjunction. Ekanem worked on this

during the second year of research. This involved a costing and economics mixed module which would later be changed for separate modules. The author had limited input in this since focus was on the risk methods.

b. Later during the third year of research the author revisited and totally revamped the maintenance module and with the aid of Adin Mba, added a separate economics module. The algorithms which created the maintenance schedule were entirely programmed by the author and the entire economics module was developed together with Mba sitting at the same computer and producing and editing the code together.

4. **Emissions Module**:

   a. This was a model initially developed by someone outside this project working on aero engines. It was later adapted by the author.

   b. There were two stages to this also; in the first year an aero emissions code was used but it was felt the algorithms therein did not represent the industrial turbines well

   c. During the third year a second aero model was used created by Aristo Courtinho (not part of this project) and major changes were made by the author. The researcher helping on this (Uwakwe, 2011) did *no* code improvements though he was supposed to. He fell behind so the author of this report had to take up the modelling. The input of the masters researchers was very useful since he did the trending (which was done in MS Excel) which was then hard coded into the FORTRAN based code. This trending was based on established trends published by GE.

   d. During the final year, the work of further trends were added to the hard coded into the modelling based on the work of Maccapani (2011). Again, the modelling was not changed by the researcher, only a hard coded trend for aero-derivative engines was added.

5. **Power generation TERA**:

   a. The final scenario looked at utilising the LNG TERA for power generation applications.

   b. This work was done in conjunction with Nur Azhari (2012). It must be noted that the changes to the programming and LNG TERA tool were very minimal

(100 lines of code change) which were again designed by the author of this thesis.

    c. Azhari helped to generate the results of the modelling and ran a large number of scenarios, the results of which were used directly by the author in case study 5.

6. **Overall Techno-economic analysis**:

    a. The final analysis could not be done till the entire TERA was complete and integrated

    b. This was made possible during the beginning of the fourth year

    c. Maccapani (2011) was instrumental in running prolonged scenarios under the supervision of the author. The results presented by Maccapani and the author will be similar because Maccapani was used to run the planned scenarios since his role as a developer was limited

    d. Azhari (2012) was used in a similar capacity to generate results for the power gen TERA.

7. One further note is that a lot of this modelling was developed together and at the same time by the researchers and the author.

    a. This involved sitting down together, using one computer and developing the programming and models together.

    b. First the researcher would go away and plan the modelling; the structure of the code and then the researcher would sit with the author and programme the modelling together.

    c. In some cases this took 2 continuous weeks of programming at a stretch working together continuously, but it was deemed the best way of getting both parties to understand the final code that would be produced.

    d. The author experimented with this process and initially let the researchers go away and do the work package, but it was felt that a programmed code is a very personalised thing and without good comments or notes in the code it was difficult to understand what had been done, especially because most of the researchers were first time programmers and were learning.

    e. A lot of the time was spent around making sure that the structure the researcher proposed will fit into the rest of the modelling, so this was project integration. Much time was spent trouble shooting the programming and

making a robust code which will work seamlessly for all different engine types and different scenario configurations.
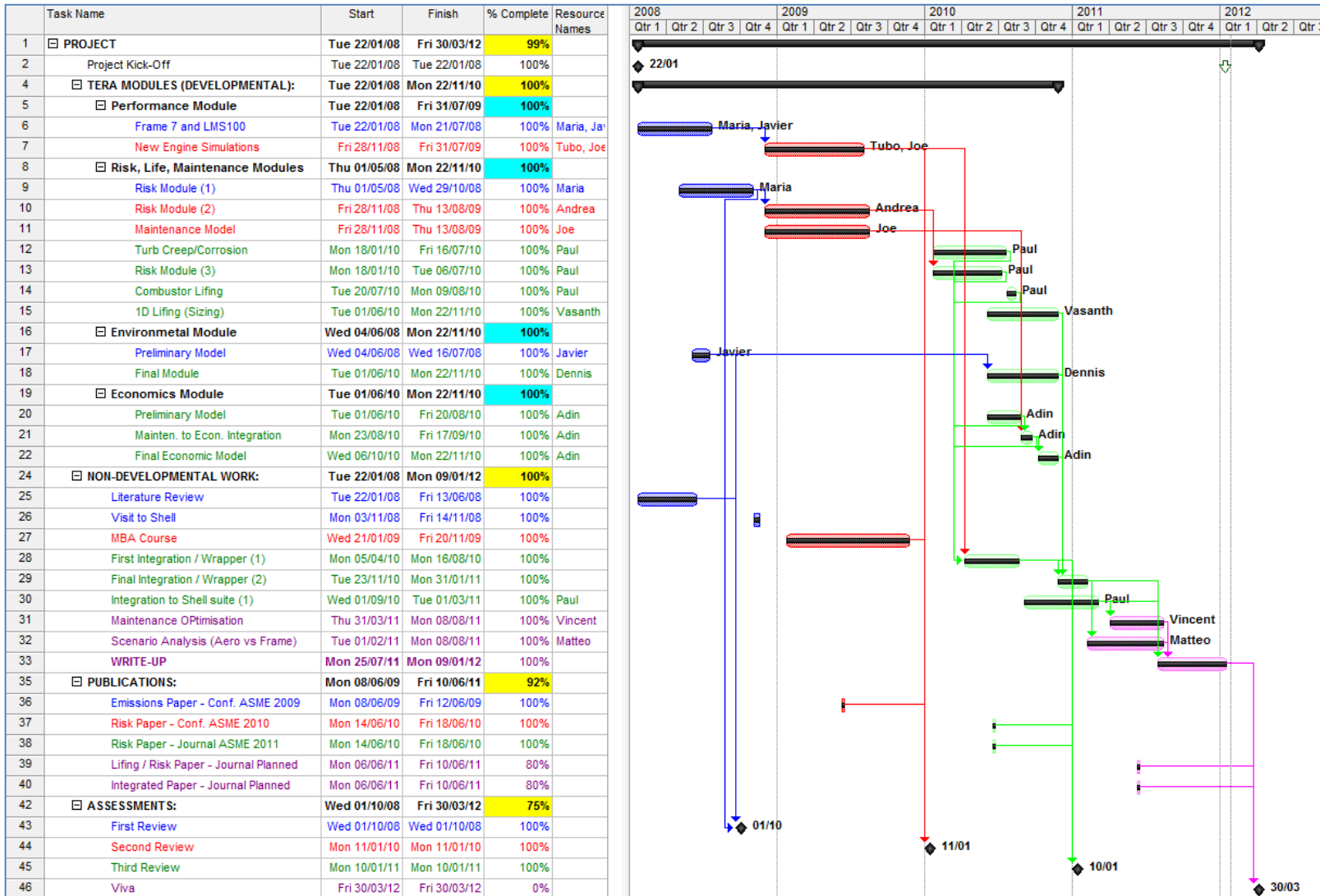
Figure 111: Gantt chart projecting the timeline for completing modules and also highlighting key dates such as reviews

196

References

[1] Abdul Ghafir, M.F., *'Performance Based Creep Life Estimation for Gas Turbines Application,'* PhD Thesis, School of Engineering, Cranfield University, UK (2011)

[2] Abernathy, R.B., *'The New Weibull Handbook, Reliability and Statistical Analysis for Predicting Life, Safety, Survivability, Risk, Cost and Warranty Claims'* Fourth Edition, (2000)

[3] Akhtar, S., *'Driver Selection for LNG Compressors'* MSE Consultants Ltd, Carshalton, Surrey, UK (2004)

[4] Al-Saadoon, F.T., and Nsa, A.U., *'Economics of LNG Projects,'* Production and Operations Symposium, Oklahoma City, Oklahoma, USA, 4-8 April, (2009)

[5] Anderson, R.E., and Hoffman, L.C., and Viteri. F., *'Integration of clean energy systems' technology with air separation units, gas turbines, and steam turbines into zero-emission power plants'* Natural Gas Technologies Conference II, Arizona (2004)

[6] Andrade, E.N. da C., Proceedings of the Royal Society A, 84, pp.1 (1914)

[7] Arnold, G., *'Corporate Financial Management'* Third Edition, Pearson Education Ltd (2005)

[8] Assovskii, I. G. and Istratov, A. G. "*Effect of the Mode of Combustion on the Service Life of the Combustion Chamber Material*", Russian Journal of Physical Chemistry B, vol. 2, no. 4, pp. 589-594 (2008).

[9] Australian Bureau of Metrology. Accessed: May, 2008. http://www.bom.gov.au/

[10] Azhari, N., *'TERA for Turbo-Machinery Equipment Selection,'* MSc. Thesis, School of Engineering, Cranfield University, UK. (2012)

[11] Baioni, C.A., *'TERA for LNG – Risk Methodology for Gas Turbine Selection in LNG Application,'* MSc. Thesis, School of Engineering, Cranfield University, UK. (2009)

[12] Balevic, D., and Burger, R., and Forry, D., *'Heavy-Duty Gas Turbine Operating and Maintenance Considerations, GER-3620K,'* GE Power System, GE Energy Services, Atlanta, GA, USA, (2004)

[13] Barringer, H.P., and Weber, D.P., *'Where is my data for making Reliability Improvements?'* Fourth International Conference on Process Plant Reliability, Marriott Houston Westside, Houston, Texas, November 14-17, (1995)

[14] BBC., '*Timeline: LNG Plants in Wales,'* BBC News Report, available online (2009) Accessed: (05.07.2011) http://news.bbc.co.uk/1/hi/wales/south_west/7881826.stm

[15] Bloch, H.P., '*Improving Machinery Reliability, Practical Machinery Management for Process Plants,'* Gulf Publishing Company, Houston, Texas (1998)

[16]   Bloch, H.P., and Geitner, F.K., *'Machinery Failure Analysis and Troubleshooting, Practical Machinery Management for Process Plants',* Third Edition, Gulf Publishing Company (1998)

[17]   Bloch, H.P., and Soares. C., *'Process Plant Machinery,'* Second Edition. Butterworth Heinemann (1998)

[18]   Bloch, H.P., and Soares. C., *'Turboexpanders and Process Applications'* Elsevier, Gulf (2001)

[19]   Boyer, H.E., *'Atlas of Creep and Stress-Rupture Curves'* ASME International, Metals Park, Ohio (1988)

[20]   Boyce, M *'Gas Turbine Engineering Handbook'* Second Edition, Gulf Professional Publishing (2002)

[21]   Boussabaine, H., and Kirkham, R., *'Whole Life Cycle Costing: Risk and Risk Responses,'* Blackwell Publishing, (2004)

[22]   BP Annual Report (2011)

[23]   Buller, A.T., and Owren, G.A., and Pettersen, J., and Heiersted, R.S., and Fredheim. A.O., *'Liquefied Natural Gas, Snohvit Process and Plant,'* Research and Technology Memoir No. 6. Statoil (2004)

[24]   Burgmann, P.J., *'An Industrial Gas Turbine Life Analysis: Deterministic and Probabilistic Comparative Assessment'* School of Engineering, MSc Thesis, Cranfield University (2010)

[25]   Cho, S., and Cho, C., and Kim. C., *'Performance Characteristics of a Turboexpander Substituted for Expansion Valve on Air-Conditioning'* Experimental Thermal and Fluid Science 32, pp. 1655-1665, Elsevier (2008)

[26]   Corran, R.S.J., and Williams, S.J., *'Lifing methods and safety criteria in aero gas turbines,'* Engineering Failure Analysis 14, pp.518–528, (2007)

[27]   Courtinho, A., *'Preliminary Universal Emission Model,'* MSc. Thesis, School of Engineering, Cranfield University, UK. (2009)

[28]   Cruse, T.A., and Mahadevan, S., and Tryon, R.G., *'Fatigue Reliability of Gas Turbine Engine Structures,'* NASA/CR-97-206215, Lewis Research Centre (1997)

[29]   Davis L.B., and Washam. R.M., *'Development of a Dry Low NO_x Combustor'* American Society of Mechanical Engineers, paper 89-GT-255 (1989)

[30]   Desnos, V., '*Maintenance of Ageing Gas Turbines: A Techno-economic, Environmental and Risk Analysis Approach,*' MSc. Thesis, School of Engineering, Cranfield University, UK. (2011)

198

[31]   Devereux, B., and Singh, R., *'Use of computer simulation techniques to assess thrust rating as a means of reducing turbo-jet life cycle costs,'* International Gas-Turbine and Aero Engine Congress and Exposition, The Hague, Netherlands, June 13–16, (1994)

[32]   Dibbert, A., *'Extending Gas Turbine Life'* Turbomachinery International Magazine, Norwalk, USA (2006)

[33]   Dusa., D.J., *'Analytical Method for Designing Turbine Nozzle Partitions,'* Journal of Aircraft, vol. 1, no. 1, pp. 23-27 (1964)

[34]   Economides, M.J. and Mokhatab, S., *'Compressed Natural Gas: Monetizing Stranded Gas'* Energy Tribune, Online Website, www.energytribune.com (accessed: 18.07.2009) (2007)

[35]   Ekanem, J., *'An Approach to Industrial Gas Turbine Maintenance Cost Modelling'* School of Engineering, MSc Thesis, Cranfield University (2009)

[36]   Enright, M.P., and Hudak, S.J., and McClung, R.C., and Millwater, H.R., *'Probabilistic Based System for Prognosis of Fatigue in Aircraft Engine Components,'* 44th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference, 7-10 April 2003, Norfolk, Virginia, AIAA 2003-1660 (2003)

[37]   Gayraud, S., '*Technical and Economical Assessment for Industrial Gas Turbine Selection,'* MSc Thesis, Cranfield University, United Kingdom (1996)

[38]   General Electric, '*Liquefied Natural Gas, Enhanced Solutions for LNG Plants,'* GE Document, Nuovo Pignone, Document Number: LNG_A4_012306 (2006)

[39]   Ginter, T., and Bouvay T., *'Uprate Options for the MS7001 Heavy-Duty Gas Turbine, GER-3808C,'* GE Power System, GE Energy Services, Atlanta, GA, USA, (2006)

[40]   Ginter, T., *'Uprate Option for the MS9001 Heavy-Duty Gas Turbine, GER-3928C,'* GE Power System, GE Energy Services, Atlanta, GA, USA, (2008)

[41]   Golden, P.J., and Millwater, H.R., and X. Yang *'Probabilistic Sensitivity Analysis of Fretting Fatigue,'* 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Palm Springs, California, AIAA 2009-2304, 4 - 7 May (2009)

[42]   van de Graaf, J.M., and Pek. B., *'Large Capacity LNG Trains - The Shell Parallel Mixed Refrigerant Process,'* LNG Review, Shell Global Solutions International BV (2005)

[43]   Graham, A.D., and Mallinson, G.D., *'NERF-A Computer Program for the Numerical Evaluation of Reliability Functions-User Manual,'* DSTO, Structures Report 411, (1984)

[44]   Griffin, T., and Sundkvist, S.G., and Sen, K., and Bruun. T., *'Advanced Zero Emissions Gas Turbine Power Plant,'* Journal of Engineering for Gas Turbines and Power 127 (81) (2005)

[45]   Guevara Carazas, F. J., and Martha de Souza, G. F., *'Availability Analysis of Gas Turbines Used in Power Plants'* International Journal of Thermodynamics, Vol. 12, No. 1, pp. 28-37, (2009)

[46]   Haslam, A. S., and Cookson, R. A., '*Mechanical Design of Turbomachinery,'* MSc Lecture Notes, Cranfield University, Cranfield, UK. (2007)

[47]   Henley E.J., and Kumamoto. H., *'Reliability Engineering and Risk Assessment,'* Prentice Hall Inc., (1981)

[48]   Hoffelner, W., '*Creep Dominated Damage Processes in High Temperature Alloys for Gas Turbines and other Applications'*, Liege, Belgium, Reidel Publishing Company (1986)

[49]   Holland, L., *'Probabilistic Prediction of Failure Events in Gas Turbine Discs due to Material Anomalies'* School of Engineering, MSc Thesis, Cranfield University (2007)

[50]   International Civil Aviations Organization *'ICAO Engine Exhaust Emissions Data Bank,'* First Edition, Doc 9646-AN/943 (1995)

[51]   IEA, *'World Energy Outlook 2010,'* International Energy Agency (2010)

[52]   Jeong, S.J., and Kim, K.S., and Park, J.W., Lim, D.S., and Lee, S.M., *'Economic comparison between coal-fired and liquefied natural gas combined cycle power plants considering carbon tax: Korean case,'* Elsevier Energy Journal (2008)

[53]   Kappas, J., *'Review of Risk and Reliability Methods for Aircraft Gas Turbine Engines,'* Airframes and Engines Division, Aeronautical and Maritime Research Laboratory, Australia (2002)

[54]   Kappas, J., and Antoniou, R.A., *'Engine System Risk and DEFSTAN 00-971,'* DSTOTR, (2002)

[55]   Khan, R.S.R., and Barreiro, J., and Lagana, M.C., and Kyprianidis, K.G., and Pilidis, P., and Ogaji, S.O.T., and Bennett, I., *'An Assessment of the Emissions and Global Warming Potential of Gas turbines for LNG Applications'* Proceedings of the ASME TURBO EXPO 2009: Power for Land, Air and Sea, June 8-12, Florida, USA, Paper GT2009-59184, (2009)

[56]   Khan, R.S.R., and Lagana, M.C., and Pilidis, P., and Ogaji, S.O.T., and Bennett, I., *'Risk Analysis of Gas Turbines for Natural Gas Liquefaction'* Proceedings of the ASME TURBO EXPO 2010: Power for Land, Air and Sea, June 14-18, Glasgow, Scotland, Paper GT2010-23261, (2010)

[57]   Koff, B. L., *'Gas Turbine Technology Evolution-A Designer's Perspective,'* 14-17 July, Dayton, Ohio, (2003)

[58]   Kvamsdal, H.M., and Jordal, K., and Bolland. O., *'A Quantitative Comparison of Gas Turbine Cycles with CO2 Capture'* Energy Policy 32 (1), pp. 10-24, Elsevier (2007)

[59]   Kyprianidis, K.G., and Quintero, R.F.C., and Pascovici, D.S. and Ogaji, S.O.T., and Pilidis, P., and Kalfas. A.I., *'EVA - A Tool for Environmental Assessment of Novel Propulsion Cycles,'* ASME Paper GT2008-50602, Proceedings of the ASME TURBO EXPO 2008: Power for Land Sea and Air, June 9-13, Berlin, Germany (2008)

[60]   Lefebvre, A. H., '*Fuel Effects on Gas Turbine Combustion—Liner Temperature, Pattern Factor, and Pollutant Emissions,'* Journal of Aircraft, Vol. 21, No. 11, pp. 887–98, (1984)

[61]   Li, Y.G., *'Gas Turbine Diagnostics,'* MSc Course Notes, Cranfield University, UK (2008)

[62]   Lagana, M., *'TERA for LNG Applications,'* MSc thesis, Cranfield University, (2008)

[63]   Leonard, G., and Stegmaier. J., *'Development of an Aeroderivative Gas Turbine Dry Low Emissions Combustion System,'* American Society of Mechanical Engineers, paper 93-GT-288, (1993)

[64]   Lisdonk, S.V., and Rijmenam, C., and Tanaeva, I., and Di Nola, G., and Loon, M., and Nagelvoort, R.K., *'Next Generation On-shore LNG Plants Designs,'* Paper PS3-2, LNG 16 Conference, Oran, Algeria (2010)

[65]   Liu, Y.N., and Bronfrenbrenner, J.C., and Bower, R.W., *'Reducing LNG Costs by Better Capital Utilization,'* Paper PS5-4.3, LNG 13 Conference, Seoul, South Korea, (2001)

[66]   Lust, R.V., and Wu, Y.T.J., '*Probabilistic Structural Analysis-An introduction,'* Experimental Techniques, (1998)

[67]   Maccapani, M., *'A Techno-economic and Environmental Study of Stationary Gas Turbines for LNG Applications,'* MSc. Thesis, School of Engineering, Cranfield University, UK, (2011)

[68]   Mahorter, R., and London, G., and Fowler, S., and Salvino, J., *'Life Prediction Methodology for Aircraft Gas Turbine Engine Discs,'* Proceedings of the AIAA/SAE/ASME/ASEE 21st Joint Propulsion Conference, New York: American Institute of Aeronautics and Astronautics, pp 1-6, (1985)

[69]   Marshall, H.E., *'Technology Management Handbook,'* CRC Press, New York, (1999)

[70]   Mattingly, J.D., *'Elements of Gas Turbine Propulsion,'* AIAA, (2005)

[71]   Mba, A.P., *'Techno-Economic Analysis for Industrial Gas Turbine Selection in LNG Production,'* MSc thesis, Cranfield University, (2011)

[72]   Meher-Homji, C., B., Matthews, T., Pelagotti, A., Weyermann, H., P., *'Gas Turbines and Turbocompressors for LNG Service,'* Houston, USA, Proceedings of the 36th Turbomachinery Symposium, (2007)

[73]   Millwater, H., and Wu, Y.T., *'Structural Reliability Assessment (SRA) Capability in NESSUS,'* Southwest Research Institute, Advanced Earth to Orbit Propulsion Technology, NASA Conference Publication No.3174, Vol II, pp.511-521 (1992)

[74]   Mobley, R.K., '*An Introduction to Predictive Maintenance,'* 2nd Edition, Maryland Heights, MO, Elservier Science, (2002)

[75]   Mokhatab, S. and Economides, M. J., *'Onshore LNG Production Process Selection,'* Paper SPE 102160, (2006)

[76]   Moore, N.R., and Ebbeler, D.H., and Creager, M., *'A Methodology for Probabilistic Prediction of Structural Failures of Launch Vehicle Propulsion Systems,'* Paper No. 90-1140-CP, Proceedings of the AIAA 31st Annual Structures, Structural Dynamics and Materials Conference, pp 1092-1104, April (1990)

[77]   Moran, M.J., and Shapiro, H.N., and Munson, B.R., and DeWitt, D.P., *'Introduction to Thermal Systems Engineering: Thermodynamics, Fluid Mechanics and Heat Transfer,'* John Wiley and Sons, Inc. (2003)

[78]   National Institute for Materials Science (NIMS) (Japan) *'Creep Curve Database'* Accessed: Between March, 2010 and July 2011 http://mits.nims.go.jp/index_en.html

[79]   Neeraas, B.O., and Fredheim, A.O., and Aunan, B., *'Experimental Shell-side Heat Transfer and Pressure Drop in Gas Flow for Spiral-wound LNG Heat Exchanger'* International Journal of Heat and Mass Transfer 47, pp. 353-361 (2002)

[80]   NETL., *'Liquefied Natural Gas: Understanding the Basic facts,'* DOE/FE-0489, National Energy Technology Laboratory (NETL), Department of Energy (DOE), United States of America (2005)

[81]   Nibbelke, R., and Kauffmann, S., and Pek. B., *'Double Mixed Refrigerant LNG Process Provides Viable Alternative for Tropical Conditions,'* Oil and Gas Journal, pp. 64-66, Shell Global Solutions International BV, The Hague (2002)

[82]   Nicholls, J.R., '*A life Prediction Method for the Corrosion of Hot Components and Coatings,'* European Propulsion Forum, 16-18 June, London, RAES, pp.14.1 (1993)

[83]   Ogaji, S., and Pilidis, P. and Vishal, S., *'The TERA - Power Plant Selection in a Carbon Constrained World,'* Proceedings of 2nd (ISJPPE) International Symposium on Jet Propulsion and Power Engineering. Guilin, China, 22-26 September, (2008)

[84]   Pachidis, V.A., '*Gas Turbine Performance Simulation,'* Department of Power and Propulsion, Cranfield University, Cranfield, UK (2008)

[85]   Pascovici, D.S., *'Thermo Economics and Risk Analysis for Advanced Long Range Aero Engines'* School of Engineering, PhD Thesis, Cranfield University (2008)

[86]   Patel, B., *'Gas Monetisation: A Techno-economic Comparison of GTL and LNG,'* 7th World Congress of Chemical Engineering (2005)

[87]   Pavri, R., Moore, G., D. *'Gas Turbine Emissions and Control,'* Atlanta, US : GE Power Systems, GER-4211 (2003)

[88]   Piotrowski, J., '*Shaft Alignment handbook,'* New York, Marcel Dekker, (2006)

[89]   Ramsden, K.W., *'Design of Turbomachinery,'* Course Notes, Cranfield University, Cranfield, UK (2011)

[90]   Ransbarger, W., *'A Fresh Look at LNG Process Efficiency - Impacts of Process and Equipment Selection on LNG plant efficiency,'* LNG Industry (2007)

[91]   Reuters., *'First LNG Tanker Unloads at UK's Teeside,'* Reuters News Agency, available online (2009) Accessed: (03.12.2010)
http://uk.reuters.com/article/2009/04/14/britain-lng-imports-idUKLE16256420090414

[92]   Rink, K.K., and Lefebvre, A.H., *'Influence of Pressure and Equivalence Ratio on CO,'* International Journal of Turbo and Jet Engines, 6(2), pp.113–22, (1989)

[93]   Rizk, N. K., and Mongia, H. C., *'Emissions Predictions of Different Gas Turbine Combustors,'* AIAA Paper 94-0118, (1994)

[94]   Roth, B.A., and Graham, M.D., and Marvis, D.N., and Macsotai. N.I., *'Adaptive Selection of Aircraft Engine Technologies in the Presence of Risk,'* Journal of Engineering for Gas Turbines and Power 126 (40) (2004)

[95]   Salisbury, R., Rasmussen, P., Griffith, T., Fibbi, A., *'Design, Manufacture and Test Campaign of the World's Largest LNG Refrigeration String,'* Paper PS2-2, Barcelona, Spain, LNG15 Conference, (2007)

[96]   Singh. R., *'Managing Gas Turbine Availability, Performance and Life Usage via Advanced Diagnostics,'* Symposium for Turbomachinery Engineers, Institute of Diesel and Gas Turbine Engineers, Milton Keynes, United Kingdom (2001)

[97]   Singh, R., '*Gas Turbine Applications,'* Course Notes, Department of Power and Propulsion, Cranfield University (2007)

[98]   Singpurwalla, N.D., *'An Interactive PC-Based Procedure for Reliability Assessment Incorporating Expert Opinion and Survival Data,'* Journal of the American Statistical Association, Vol.83, No.401, March (1988)

[99]   Smith, D.J., *'Reliability, Maintainability and Risk, Practical Methods for Engineers'* Sixth Edition, Elsevier (2001)

[100]   Sourmail, T., *'Coatings for Turbine Blades*,' (accessed 2009, Jan). Available at:

http://www.msm.cam.ac.uk/phase-trans/2003/Superalloys/coatings/index.html

[101]   Spakovszky, Z.S., *'Thermal Energy, Course Notes,'* Massachusetts Institute of Technology, MIT OpenCourseWare (2002)

[102]   Stern. N., '*Stern Review: The Economics of Climate Change,'* Her Majesty's Treasury (2006)

[103]   Todinov, M.T., *'Risk Based Reliability Analysis and Generic Principles for Risk Reduction'* Elsevier (2007)

[104]   Uwakwe, D., *'Industrial Gas Turbine Emission Assessment and Modelling for LNG Application,'* MSc Thesis, School of Engineering, Cranfield University, UK. (2011)

[105]   Vigna-Suria, O., *'A Flexible Lifing Model for Gas Turbines: Creep and Low Cycle Fatigue Approach'* School of Engineering, MSc Thesis, Cranfield University (2006)

[106]   Vittal, S., Hajela, P., and Joshi, A., *'Review of Approaches to gas turbine life management,'* 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Albany, New York, AIAA 2004-4372, 30 August - 1 September (2004)

[107]   Vittal, S., and Phillips, R., *'Uncertainty Analysis of Weibull Estimators for Interval-Censored Data'* GE Energy, Annual Reliability and Maintainability Symposium, RAMS '07, IEEE (2007)

[108]   United Nations, *'The Kyoto Protocol,'* (1998)

[109]   Walz, G., and Riesch-Oppermann, H., *'Probabilistic fracture mechanics assessment of flaws in turbine disks including quality assurance procedures,'* Elsevier, Structural Safety 28, pp.273–288 (2005)

[110]   Whellens, M.W., and Singh. R., *'Propulsion System Optimisation for Minimum Global Warming Potential,'* Proceeding of the 23rd ICAS Congress, Toronto, Canada (2002)

[111]   Wilson, T. K., and Korakianitis, T., *'The Design of High Efficiency Turbomachinery and Gas Turbines,'* Section: *'The Design and Performance Prediction of Axial Flow Turbines,'* Second Edition, Prentice-Hall International Limited, London, pp. 283-297 (1998)

[112]   Wu, Y.T., and Enright, M.P., and Millwater, H.R., *'Probabilistic Methods for Design Assessment of Reliability with Inspection,'* AIAA Journal, Vol. 40, No. 5, (2002)

[113]   Yang, J.N., and Salivar, G.C., and Annis Jr, C.G., *'Statistical Modelling of Fatigue-Crack Growth in a Nickel-Base Superalloy,'* Engineering Fracture Mechanics Vol. 18, No.2, pp257-270, (1983)

[114]   Zaretsky, E.V., and Litt, J.S., and Hendricks, R.C., and Soditus, S.M., *'Determination of Turbine Blade Life From Engine Field Data,'* 49th AIAA/ASME/ASCE/AHS/ASC

Structures, Structural Dynamics, and Materials Conference, 7 - 10 April 2008, Schaumburg, IL, AIAA (2008)

[115]   Zhurkov, S.N., *'Kinetic Concept of the Strength of Solids,'* International Journal of Fracture Mechanics. Vol. 1, 4, pp. 311-322 (1965)

Appendices

Appendix A: Input Files

A.1 Wrapper Input Files

The wrapper input file is one which controls the entire TERA LNG code and provides most of the input data for every scenario investigated. There are only two input files which sit outside the wrapper, one which is the Turbomatch file and the second is the materials database. For ease of simulation/programming, those two files have not been included inside the wrapper input file. All other data and instructions, including switches for control of which analysis and to what depth is done, is controlled by the wrapper input file.

Frame 7EA Sample:

```
*****************************************************************************
```

PerforMarker[5]

```
*****************************************************************************
```

Frame7EA.dat[6]	Engine file name with .dat extension
	(Choose from: Frame5E, Frame7EA, Frame 6, Frame9E, Frame7EA_0stage, LM6000, Trent 60, Frame_7EA_TET, Frame_7EA_IGV, LM2500PLUS)
1[7]	GT Control Switch (1 = fuel flow/TET control, 2 = IGV control))
1[8]	Power Demand Switch (1 = constant power demand, 2 = variable power demand) Siemens_V84.2, Trent_60, LMS_100_ratio, LMS_100_constant_diff)
58.46[9]	Power demand (MW)
87.3	Design Point Power (MW)
15	minimum ambient temp at plant location (C)
40	maximum ambient temp at plant location (C)
5	T amb steps for calculation in off design (K)

---

[5] This is a code name for the FORTRAN code so that it can read from the right place in the input file, every main module and main data set has a unique code name

[6] This is a unique engine name which directs the code to go to a Turbomatch library and pick up the engine file with this engine designation

[7] This controls the algorithms for switching between IGV and TET turbine control and instructs the performance to control the Turbomatch accordingly

[8] This switch allows the gas turbine to be run at either a single or various power demand, it is useful when simulating power generation applications with the TERA tool

[9] This is the power demanded from the engine based on current scenario

1100	TET min (K)	
1650	TET max (K)	
10	TET step (K)	
-3	NGV_min (deg) w.r.t. design point	
20	NGV_max (deg) w.r.t. design point	
1	NGV_step(deg)	
3600	Rotational speed (RPM, rev/minute)	
1	no. of compressors	
1	no. of turbines	
1	bleed cooling ? - no. of spools	
0	intercooler? (1=yes, 0=no)	

****

AmbMarker[10]

****

!ambient temperature data at plant site and corresponding power demands

Time	Summer	Power_Demand[11]
0000	32.20	75
0200	30.25	75
0400	29.88	75
0600	29.58	75
0800	31.15	75
1000	32.95	75
1200	34.45	85
1400	34.90	85
1600	33.38	75
1800	32.40	75
2000	31.15	75
2200	30.43	75
Time	Mid-season	

---

[10] Gives site specific data for daytime ambient temperatures- not a module, just a data set for the performance module to utilise for off-design calculations

[11] This controls the power demand over the day and only works if the previous power demand switch was set to variable power, these numbers are to be ignored for constant power demand

0000	21.65	75
0200	20.90	75
0400	20.08	75
0600	19.93	75
0800	26.55	75
1000	30.10	75
1200	29.98	85
1400	30.78	85
1600	28.78	75
1800	27.13	75
2000	23.58	75
2200	21.68	75
Time	Winter	
0000	19.15	75
0200	18.65	75
0400	18.48	75
0600	17.95	75
0800	18.70	75
1000	21.43	75
1200	23.38	85
1400	23.18	85
1600	21.68	75
1800	20.25	75
2000	19.58	75
2200	19.40	75

****

LifeMarker[12]

****

!------------------Creep Calculations------------------------------

GTD111[13]   Put material specifier from the list: Rene80/IN738/GTD111/xxxx

---

[12] Data for the module which conducts blade thermal modelling and stress calculations

1   :Corrosion_selector (1=proceed to hot corrosion estimation, 2=No analysis)

1   :Blade_selector (1=proceed to creep calculations, 2=No analysis)

1   :Combustor_selector (1=proceed to burner life estimation, 2=No analysis)

36   :sum of number of segments into which the day has been split for all seasons

3600   :HPT rpm @ design point

1.   :blade stress selector (1 = stress unknown, a stress subroutine will calculate it; 2 = stress known)

1.   :cooling selector (1 = blade cooled; 2 = no cooling)

73.   :Delta of Temperature due to Termal Barrier Coating on the blade

1.   :blade Larson-Miller selector (1 = insert values to be interpolated; 2 = LMP known for each segment)

0.33   :cooling effectiveness

! if the stresses are known for each segment for the blade put below (SKIP A LINE AFTER THESE COMMENTS) all the stresses in MPa first for the
! blade and the same applies if the Larson-Miller parameter for each working is known. LAST CONDITION FOR DESIGN POINT VALUES!!!!!! First
! put all the stresses and then all the LMPs for the blade (SKIP A LINE BEFORE ENTERING LMP VALUES). LET AN EMPTY LINE BEFORE THE HOT CORROSION SECTION.

!-----------Hot corrosion estimation---
Do not use this module if the blade metal is poor in Cr and if the expected coating temperature is much higher than 1170 K, if PtAl coating the blade metal corrosion resistance must be close from the ones of the IN738 and the GTD111.

2   :blade coating material index. 1=PtAl diffused coating, 2=GT29 (normal, Plus and InPlus), 3=GT33 (In-Coat and InPlus)

!Average Sodium ion (Na+) concentration (in µg/m3) in the surrounded atmosphere
0.919   :in the summer
1.72   :mid-seasons

---

[13] The data specific to these materials is held in another file for ease of programming

2.98   :winter

0.5   :value at DP

0.5   :Mean value of the sodium contaminant concentration in the fuel (µg/m3)

0.780   :fuel density (kg/m3)

!-----------Blade Geometry---

1.   :geometry selector. 1=Geometry not known (you still need to give the inner
                    and outer radius),2=Geometry known

1.   :number of section the blade has been split into

0.71   :inner radius

0.89   :outer radius

0.00698   :inner cross area

0.00698   :outer cross area

!-----------Combustion process--

3   :Burner type. 1=annular, 2=tubo-annular, 3=Can

12   :Number of combustion chambers around the engine

1   :Staging: proportion of fuel injected at the first stage/Main injector of the burner
          (between 0 and 1, 1 if no staging)

1   :Combustion type: 1=lean combustion, 2=rich combustion

1   :Thermal Barrier Coating. 1=The liner is coated with TBC, 2=no coating

0.30   :liner inner diameter (m) (in the case of an annular chamber: tip diameter)

0.004   :liner thickness (m)

0.40   :combustor casing inner diameter (m)

****

RiskMarker[14]

----

[14] Data for module which conducts risk analysis using the lifing results

```
********************************************************************

!------------Risk Analysis-----------------------


1.                      :analytic selector. 1=use analytic calculations,2=use a default time between
                        failure (TBF)
1.                      :risk selector. 1=use life and risk 2=use only life no risk, 3=use field data for
                        the risk (no life),4=use literature data for the risk module


!If risk_selector = 3 or 4, to study the HPT blade coating separately from the base metal you
have to add it as an additional component (see below name, default tbf (not in the predefined
coating input), eta and beta) and put corrosion_selector =2 (life input section)


10000           :Number of MCS runs

500000          :Time period (in hours) for whom you want to build a maintenance schedule
                (integer number)

0.95            :Desired probability that the engine will fail before the safe engine mean time
                between failures (between 0 and 1)

7.              :number of components considered represented by a Weibull distribution


!Respect this order: if corrosion and/or blade selectors =1 then put first HPT (as a whole: base
metal+coating). If combustor selector=1 put it in 2nd position unless blade and corrosion
selectors=2 (both), in that case the position is 1. If you want to use default values for these
components, put them in the list after the one considered into the lifing module.


HPT                     :name of the 1st Weibull component (High Pressure Turbine) (less
                        than 18 characters, included spaces)
Combustor               :name of the 2nd Weibull (Combustor)
HPC                     :name of the 3rd Weibull(High Pressure Compressor)
Control_valves          :name of the 4th Weibull (control valves)
T_indicators            :temperature indicators
P_indicators            :pressure indicators
flow_instrument         :flow instrumentation
200000                  :DEFAULT tbf for the HPT BLADE COATING (integer). (Never
                        delete this line!!)
112000                  :DEFAULT tbf (OEM) for the 1st component (integer).
```

50000	:DEFAULT tbf for the 2nd component
222000	:DEFAULT tbf for the 3rd component
100000	:DEFAULT tbf for the 4th component
150000	:5th
116000	:6th
125000	:7th

!for each component put eta, beta then if the distribution must be scaled according to the TET (1=yes, 2=no) and the RPM (1=yes, 2=no)

125000 1.6 1 1	:default eta, default beta,TET_scaling selector, RPM_scaling selector for the 1st component
80000 1.5 1 2	:2nd component
250000 2.5 2 1	:3rd component
100000 1 2 2	:4th component
222000 1 2 2	:5th
125000 1.2 2 2	:6th
125000 1 2 2	:7th
2	:number of components for whom you want to use field data. CAUTION!!! Must fit to a Weibull distribution.
7	:max number of samples you want to study for a single component

!Repeat the process below (without skipping blank lines) for all the components you want the distribution to

2	:component number (related to the name you have inputted)
7	:number of samples you want to study for this components. Remove samples with extreme life values!!!!(samples must be taken for components working on the same conditions and possibly in the same plant and engine type).
17000	:1st sample life (no need to put it in a particular order)
17946	:2nd sample life
18946	:3rd sample life
21113	:4th sample life
20000	:5th sample life
22289	:6th sample life

23529	:7th sample life
4	:component number
6	:number of samples you want to study for this components. Remove samples with extreme life values!!!!(samples must be taken for components working on the same conditions and possibly in the same plant and engine type).
20000	:1st sample life (no need to put it in a particular order)
22289	:3rd sample life
23529	:2nd sample life
18946	:5th sample life
17946	:7th sample life
17000	:6th sample life

****

RiskLevelMarker[15]

****

0	:lower bound for corrosion	u boundary
0.5	:upper bound for corrosion	u boundary
0.025	:lower bound for blade creep	u boundary
0.975	:upper bound for blade creep	u boundary

****

EconomicsMarker[16]

****

8	!DISCOUNT RATES (%)
20	!DESIGN PLANT LIFE
8760	!ANNUAL OPERATING HOURS
43	!HEATING VALUE OF FUEL IN MJ
1	!CO2 marker (1=use emissions, 2=use default stoichiometrics)
1	!NOX marker (1=use emissions, 2=no NOX calculation)

---

[15] Allows user to control the simulation so as to pick data from selected parts of the distribution in order to allow simulation of high and low risk options
[16] Main data input for economics calculations

214

```
*************************************************************************
MaintenanceMarker[17]
*************************************************************************
30                      :LABOUR RATE ($,£,?,€)
3.1                     :INTEREST RATE (PERCENT)
90                      :SPECIALIZED LABOUR RATE ($,£,?,€)
5                       :PERSONNEL USED
110000                  :LOGISTICS COST ($,£,?,€)


!cost of components:
1000                    :NO COMPONENT REPLACED ($,£,?,€)
520000                  :COMP1 COST ($,£,?,€)
200000                  :COMP2 COST ($,£,?,€)
195000                  :COMP3 COST ($,£,?,€)
9500                    :COMP4 COST ($,£,?,€)
!switches
1                       :CBM,  SWITCH (1 = CBM , 2 = NO CBM)
1                       :SBM    SWITCH (1 = SBM,  2= NO SBM)  ! PM is always
                        calculated
5                       CBM Percentage
8760        scheduling limit !program skips next action if it occurs within this period


*************************************************************************
PowerCostMarker[18]
*************************************************************************
POWER (MW)   COST ( $)
21846       9928800
23091        1010900
24770       10164300
25490       10522300
```

_____

[17] Main data input for maintenance calculations
[18] Allows the calculation of engine acquisition cost automatically via interpolation, source: GT Handbook 2011

25500	10443100
26200	10786100
26300	10476200
27520	11086100
27630	11241800
27970	11260900
29060	11537900
29316	9932800
29500	11276600
29962	11024900
30000	11716800
30464	11015400
30850	12102300
30982	9932900
31000	12096900
32120	12588700
33165	12143700
36333	11131000
42100	15129300
42732	16472300
43068	15373600
43843	14319100
45400	16412200
47000	16765500
47505	16389200
48092	16105000
50836	15387000
51000	17829600
51685	18165700
53500	17473100
56300	19082200
56340	19306100
62006	20739700
64000	19374800
77100	24341800

85100	25954400
85400	25709100
99044	35445900
103045	34033700
113600	30160700
115400	30610900
126100	32732500
144090	36386000

****

Degradation&Economics2Marker[19]

****

Year	Degradation factor	Cost of fuel/GJ	CO2 tax $/metric ton	NOx tax $/metric ton	LNG cost $/MMBTU	Electricity cost c$/kWh
1	1.005	5.22	16	15	4.44	6.7
2	1.0160	5.35	16	15	4.55	6.7
3	1.0313	5.49	16	15	4.67	6.7
4	1.0488	5.63	16	15	4.79	6.7
5	1.0698	5.77	16	15	4.91	6.7
6	1.091	5.90	16	15	5.03	6.7
7	1.113	6.04	16	15	5.14	6.7
8	1.133	6.18	16	15	5.26	6.7
9	1.158	6.32	16	15	5.38	6.7
10	1.181	6.45	16	15	5.50	6.7
11	1.204	6.59	16	15	5.62	6.7
12	1.228	6.73	16	15	5.73	6.7
13	1.253	6.87	16	15	5.85	6.7
14	1.278	7.00	16	15	5.97	6.7
15	1.304	7.14	16	15	6.09	6.7
16	1.330	7.28	16	15	6.20	6.7
17	1.356	7.42	16	15	6.32	6.7

---

[19] A marker for data set which allows the inout of expected degradation of fuel and also prices of fuel and emissions

18	1.383	7.56	16	15	6.44	6.7
19	1.411	7.69	16	15	6.56	6.7
20	1.439	7.83	16	15	6.68	6.7

****

ScheduleMarker[20]

****

4000   :ROUTINE MTCE-1 MTBM (HOURS)

48   :ROUTINE MTCE-1 MTTR (HOURS)

8000   :ROUTINE MTCE-2 MTBM (HOURS)

60   :ROUTINE MTCE-2 MTTR (HOURS)

7000   :CORRECTIVE MTCE-1 MTBF (HOURS)

24   :CORRECTIVE MTCE-1 MTTR (HOURS)

30000   :CORRECTIVE MTCE-2 MTBF (HOURS)

60   :CORRECTIVE MTCE-2 MTTR (HOURS)

8000   :ALIGNMENT MTBM (HOURS)

36   :ALIGNMENT MTTR (HOURS)

4000   :BORESCOPE MTBM (HOURS)

24   :BORESCOPE MTTR (HOURS)

25000   :RECONDITIONING MTBM (HOURS)

120   :RECONDITIONING MTTR (HOURS)

50000   :OVERHAUL MTBM (HOURS)

144   :OVERHAUL MTTR (HOURS)

****

DesignMarker[21]

****

0[22]   :1D_selector (0=0D lifing used, 1=1D lifing used)

0.13   :Turbine Inlet Mach number

1.8   :Mean line diameter (m)

---

[20] Data set for maintenance module which informs of the default routine and corrective actions
[21] Data set for simulating the design of an engine (turbine section) in order to estimate turbine component sizes to allow stress modelling in lifing stage of calculations
[22] Will control weather sizing of engine is done based on available engine data

92   :Number of blades

3   :No of stages of HPT

0.1   :profile factor (if data are known input otherwise ignore)

****

EmissionMarker[23]

****

.0756	: VC	Combustor volume (m^2)
.000378	: VE	Primary zone evaporation fuel volume (m^2)
.00251	: TRES	Residence Time (S)
.36	: FRAC	Fraction of Primary zone occupied by air
.99	: EFFC	Combustor Efficiency
0	: MODEC	Combustion mode (0 for CVC, 1 for CPC)
1	: IFUEL	Fuel type (1 for natural gas, 7 for kerosene)
0.	: X	Carbon number, ignore
0.	: Y	Hydrogen number, ignore
0.	: HF	Enthalpy of fuel, ignore
0	: ALT	Altitude (km)
12	: CBR	Number of combustion chambers
1	: SWITCH	1- FR7&9 2- LM6000 3-LMS100

****

ProcessMarker[24]

****

3000000	!compressor cost
0.8	!overall process efficiency
0.8	!water cooling ratio
35	!Cp (KJ/Kmol of LNG)
80	!temperature change
2	!starter motor switch (=1 starter motor always on, =2 starter motor off)

---

[23] Data set for emissions module detailing the combustor geometry, fuel type and residence time etc

[24] Allow to mimic the process technology based on simple process efficiencies so as to provide a basic estimation of process requirements in terms of power required and consequent production of LNG or power generated

7.0[25]   !starter motor power [MW]

A.2 Turbomatch Input Files

Below are examples of input files which are created in a notepad file format with a .dat extension. These files act as instructions to the Turbomatch thermodynamic performance code and instruct the building and running of a gas turbine in simulation. Key features of the input file have been annotated.

Frame 7EA – Example 1:

Frame 7EA

Programmed by RSR Khan (date)

////

OD SI KE VA FP[26]

-1

-1

INTAKE[27]	S1,2	D1-4		R300	
COMPRE	S2,3	D5-11		R301	V5 V6
PREMAS	S3,4,9	D12-15			
BURNER	S4,5	D16-18		R302	
MIXEES	S5,9,6				
TURBIN	S6,7	D19-26,301,27		V20	
NOZCON	S7,8,1	D28			
PERFOR	S1,0,0	D19,29-32,300,302,0,0,0,0,0,0,0,0,0			
CODEND					

DATA ITEMS[28]

////

1   0.0   ! INTAKE ALTITUDE

---

[26] Code Settings: off-design, SI units, fuel type, variable geometry, and full-print format of results

[27] **Brick Data:** Pre-programmed units; most of them correspond to particular engine component, but there are bricks for arithmetic operations and for final calculation of performance (PERFOR). PREMAS and MIXEES are for bleed out and bleed entry at points along the engine. There may be station numbers, results and variables associated with each brick

[28] **Data Items**: Series of data corresponding to component bricks in particular order. Each brick has a set of predefined data items needed to model it

```
2   0.0        ! ISA DEVIATION

3   0.0        ! MACH NO

4   1.0        ! PRESSURE RECOVERY

! COMPRESSOR

5   -1.0       ! Z PARAMETER

6   -1.0       ! ROTATIONAL SPEED N

7   12.7       ! PRESSURE RATIO

8   0.88       ! ISENTROPIC EFFICIENCY

9   0.0        ! ERROR SELECTION

10  4.0        ! MAP NUMBER

11  0.0        ! STATOR ANGLE REL. TO DP

! PREMAS

12  0.90       ! BLEED AIR

13  0.0        ! FLOW LOSS

14  1.0        ! PRESSURE RECOVERY

15  0.0        ! PRESSURE DROP

! BURNER

16  0.06       ! FRACTIONAL PRESSURE LOSS DP/P

17  0.99       ! COMBUSTION EFFICIENCY

18  -1.0       ! FUEL FLOW

! TURBINE

19  87300000.0! AUXILIARY WORK

20  -1.0       ! NDMF

21  -1.0       ! NDSPEED CN

22  0.89       ! ISENTROPIC EFFICIENCY

23  -1.0       ! PCN

24  1.0        ! COMPRESSOR NUMBER

25  4.0        ! TURBINE MAP NUMBER

26  1000.0   ! POWER LAW INDEX

27  0.0        ! NGV ANGLE REL. TO DP

! NOZCON

28  -1.0       ! THROAT AREA

! PERFOR
```

29 1.0   ! PROPELLER EFFICIENCY

30 0.0   ! SCALING INDEX

31 0.0   ! REQUIRED THRUST

32 0.0   ! NOZZLE GROSS THRUST

-1

1 2 296.0   ! INLET MASS FLOW (kg/s)

! TETmarker[29]

5 6 1418.0   ! COMBUSTION OUTLET TEMPERATURE; TET (K)

! ODmarker

 -1

 2   0.00000[30]

 -1

        5   6   1300.00

 -1

 -1

        5   6   1350.00

 -1

 -1

        5   6   1400.00

 -1

 -1

        5   6   1450.00

 -1

 -1

        5   6   1500.00

 -1

 2   5.00000

-1

    5   6   1300.00

-1

-1

    5   6   1350.00

-1

-1

    5   6   1400.00

-1

-1

    5   6   1450.00

-1

-1

    5   6   1500.00

-1

-1

-3

Aero-derivative (LM6000) - Example 2:

LM6000

Programmed by RSR Khan (date)

////

OD SI KE VA FP

-1

-1

INTAKE[31]	S1-2	D1-4	R300		
COMPRE	S2-3	D5-11	R301	V5	V6
PREMAS	S3-4,13	D12-15			
COMPRE	S4-5	D16-22	R302	V16	V17

---

[31] Different brick set-up due to different build-up of engine

```
PREMAS      S5-6,14       D23-26

BURNER      S6-7          D27-29              R303

MIXEES      S7,14,8

TURBIN      S8-9          D30-37,302          V31

MIXEES      S9,13,10

TURBIN      S10-11        D39-46,301,47       V39 V40

NOZCON      S11-12,1      D48                 R304

PERFOR      S1,0,0        D39,49-51,304,300,303,0,0,0,0,0,0,0,0,0

CODEND
```

DATA ITEMS

////

```
1 0.0        ! INTAKE ALTITUDE

2 0.0        ! ISA DEVIATION

3 0.0        ! MACH NUMBER

4 -1.0       ! PRESSURE RECOVERY

! LP COMPRESSOR

5 0.8        ! Z PARAMETER

6 1.0        ! ROTATIONAL SPEED N

7 2.28       ! PRESSURE RATIO

8 0.85       ! ISENTROPIC EFFICIENCY

9 0.0        ! ERROR SELECTION

10 5.0       ! MAP NUMBER

11 0.0       ! IGV ANGLE

! PREMAS

12 1.0       ! BYPASS RATIO

13 0.0       ! MASS FLOW LOSS

14 1.0       ! PRESSURE RECOVERY

15 0.0       ! PRESSURE LOSS
```

! HP COMPRESSOR

16 0.8   ! SURGE MARGIN

17 1.0   ! SPOOL SPEED

18 12.25   ! PRESSURE RATIO

19 0.853   ! EFFICIENCY

20 0.0   ! ERROR SELECTOR

21 5.0   ! COMPRESSOR MAP NUMBER

22 0.0   ! IGV ANGLE

! PREMAS

23 0.85   ! BYPASS RATIO

24 1.80   ! MASS FLOW LOSS

25 1.0   ! PRESSURE FACTOR

26 0.0   ! PRESSURE LOSS

! BURNER

27 0.075   ! FRACTUAL PRESSURE LOSS

28 1.0   ! COMBUSTION EFFICIENCY

29 -1.0   ! FUEL FLOW

! HP TURBINE

30 0.0   ! AUXILIARY POWER REQUIRED

31 0.8   ! NON-DIMENSIONAL MASSFLOW

32 0.6   ! NON-DIMENSIONAL SPEED

33 0.90   ! EFFICIENCY

34 -1.0   ! COMPRESSOR TURBINE

35 2.0   ! COMPRESSOR NUMBER

36 5.0   ! TURBINE MAP NUMBER

37 -1.0   ! POWER LAW INDEX

38 0.0   ! NGV

! IP TURBINE

39 43679000.0 ! AUXILIARY POWER REQUIRED

40 -1.0   ! NON-DIMENSIONAL MASS FLOW

226

41 -1.0   ! NON-DIMENSIONAL SPEED

42 0.90   ! EFFICIENCY

43 -1.0   ! COMPRESSOR TURBINE

44 1.0   ! COMPRESSOR NUMBER

45 5.0   ! TURBINE MAP NUMBER

46 3   ! POWER LAW INDEX

47 0.0   ! NGV

! CONVERGENT NOZZLE

48 -1.0   ! AIR FIXED

! PERFORMANCE

49 1.00   ! PROPELLER EFFICIENCY

50 0.0   ! SCALING INDEX (0=NO SCALING)

51 0.0   ! REQUIRED THRUST

-1

1 2 124.0   ! INLET MASS FLOW

! TETmarker

7 6 1580.0   ! COMBUSTION OUTLET TEMPERATURE

! ODmarker

-1

-1

-3

A.3 Materials Database Input File

---IN738-----------------------------------

IN738	:Material specifier
20.0	:Larson Miller (LM) constant
7	:Number of data on LM curve
52.21	:LM curve: LM parameters in decreasing order
51.21	
49.90	
46.255	
45.09	
42.885	
41.95	
10	:LM curve: stresses (KSi) corresponding to the LM parameters in the orders they had been written
13	
17	
35	
40	
65	
75	
8110.0	:Material density (kg/m^3)
1	:Number of data in yield stress (ys) curve
0	:ys in MPa
0	:Temperature in K relative to the previous ys
0	:Elastic modulus of the material in MPa
0	:Fatigue ductility strength in mm
0	:Fatigue strength coefficient in MPa
0	:Fatigue strength exponent
0	:Fatigue ductility exponent
0	:Linear coefficient of thermal expansion in mm/°C
0	:Poisson's ratio
1	:LM equation selector (1= equation in Imperial units, 2=equation in SI)
20	: Larson Miller constant for the risk curves
4	:number of LMP curves available for the risk module

2		:LM equation selector for risk analysis (1: imperial units, 2: S.I units)
6		:number of LMP measures available for the 1st LMP curve
5		:number of LMP measures available for the 2nd LMP curve
5		:number of LMP measures available for the 3rd LMP curve
5		:number of LMP measures available for the 4th LMP curve
200	26.30	:1st curve Stress (MPa) +LM parameters in the decreasing order
250	25.41	
300	25.11	
350	24.60	
400	24.12	
500	23.24	
350	24.56	:2nd curve
400	24.05	
500	23.28	
550	22.92	
600	22.54	
100	27.64	:3rd curve
150	27.23	
200	26.36	
300	25.25	
400	24.10	
100	27.78	:4th curve
150	27.28	
200	26.60	
250	25.71	
300	25.04	

---RENE80---

Rene80	:Material specifier
20.0	:Larson Miller (LM) constant
6	:Number of data on LM curve
31.4	:LM curve: LM parameters in decreasing order
30.2	

29

28.04

27.24

26.52

50   :LM curve:stresses (MPa) corresponding to the LM parameters in the orders they had been written

100

150

200

250

300

8160.0	:Material density (kg/m^3)
1	:Number of data in yield stress (ys) curve
1274.99	:ys in MPa
300.00	:Temperature in K relative to the previous ys
217000.0	:Elastic modulus of the material in MPa
0.16	:Fatigue ductility strength in mm
1780	:Fatigue strength coefficient in MPa
-0.09	:Fatigue strength exponent
-0.60	:Fatigue ductility exponent
11.5E-6	:Linear coefficient of thermal expansion in mm/°C
0.3	:Poisson's ratio
2	:LM equation selector (1= equation in Imperial units, 2=equation in SI)
20	:Larson Miller constant for the risk curves
4	:number of LMP curves available for the risk module
2	:LM eqation selector for risk analysis (1: imperial units, 2: S.I units)
6	:number of LMP measures available for the 1st LMP curve
5	:number of LMP measures available for the 2nd LMP curve
5	:number of LMP measures available for the 3rd LMP curve
5	:number of LMP measures available for the 4th LMP curve
200 26.30	:1st curve Stress (MPa) +LM parameters in the decreasing order
250 25.41	
300 25.11	
350 24.60	
400 24.12	

500	23.24	
350	24.56	:2nd curve
400	24.05	
500	23.28	
550	22.92	
600	22.54	
100	27.64	:3rd curve
150	27.23	
200	26.36	
300	25.25	
400	24.10	
100	27.78	:4th curve
150	27.28	
200	26.60	
250	25.71	
300	25.04	

---GTD111---

GTD111	:Material specifier
20.0	:Larson Miller (LM) constant
5	:Number of data on LM curve
27.08	:LM curve: LM parameters in decreasing order
25.81	
24.90	
23.94	
23.00	
189.6	:LM curve: stresses (MPa) corresponding to the LM parameters in the orders they had been written
296.5	
372.3	
482.6	
565.4	
8160.0	:Material density (kg/m^3)
1	:Number of data in yield stress (ys) curve

0		:ys in MPa
0		:Temperature in K relative to the previous ys
0		:Elastic modulus of the material in MPa
0		:Fatigue ductility strength in mm
0		:Fatigue strength coefficient in MPa
0		:Fatigue strength exponent
0		:Fatigue ductility exponent
0		:Linear coefficient of thermal expansion in mm/°C
0		:Poisson's ratio
2		:LM equation selector (1= equation in Imperial units, 2=equation in SI)
20		:Larson Miller constant for the risk curves
4		:number of LMP curves available for the risk module
2		:LM eqation selector for risk analysis (1: imperial units, 2: S.I units)
6		:number of LMP measures available for the 1st LMP curve
5		:number of LMP measures available for the 2nd LMP curve
5		:number of LMP measures available for the 3rd LMP curve
5		:number of LMP measures available for the 4th LMP curve
200	26.30	:1st curve Stress (MPa) +LM parameters in the decreasing order
250	25.41	
300	25.11	
350	24.60	
400	24.12	
500	23.24	
350	24.56	:2nd curve
400	24.05	
500	23.28	
550	22.92	
600	22.54	
100	27.64	:3rd curve
150	27.23	
200	26.36	
300	25.25	
400	24.10	
100	27.78	:4th curve
150	27.28	

200   26.60

250   25.71

300   25.04

Appendix B: Performance Data & Results

B.1   Turbomatch Results[32]

The Units for this Run are as follows:-

Temperature = K   Pressure = Atmospheres   Length = metres

Area = sq metres Mass Flow = kg/sec   Velocity = metres/sec

Force = Newtons   s.f.c.(Thrust) = mg/N sec   s.f.c.(Power) = mug/J

Sp. Thrust =   N/kg/sec   Power = Watts

1

***** DESIGN POINT ENGINE CALCULATIONS *****

***** AMBIENT AND INLET PARAMETERS *****

 Alt. =   0.0   I.S.A. Dev. =   0.000   Mach No. = 0.00

 Etar = 1.0000   Momentum Drag =   0.00

***** COMPRESSOR 1 PARAMETERS *****

 PRSF = 0.11471E+02   ETASF = 0.10602E+01   WASF = 0.16625E+01

 Z = 0.85000   PR = 12.700   ETA = 0.88000

 PCN =   1.0000   CN = 1.00000   COMWK = 0.10360E+09

 STATOR ANGLE =   0.00

***** COMBUSTION CHAMBER PARAMETERS *****

 ETASF = 0.99000E+00

 ETA = 0.99000   DLP = 0.7620   WFB =   6.0377

***** TURBINE 1 PARAMETERS *****

 CNSF = 0.75379E+02   ETASF = 0.10449E+01   TFSF = 0.44756E+00

 DHSF = 0.27601E+05

 TF = 414.346   ETA = 0.89000   CN = 2.060

 AUXWK = 0.87300E+08   NGV ANGLE = 0.00

---

[32] This is the raw results format when the simulation is run and shows the first result for only a single ambient temperature and pressure. This information is then sorted into multidimensional tables where it can be used in a more useful way

***** CONVERGENT NOZZLE 1 PARAMETERS *****

NCOSF = 0.10000E+01

Area = 5.0014   Exit Velocity = 136.87 Gross Thrust = 40172.78

Nozzle Coeff. = 0.97174E+00

Scale Factor on above Mass Flows, Areas, Thrusts & Powers =   1.0000

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area
1	0.00000	296.000	1.00000	1.00000	288.15	288.15	0.0	******
2	0.00000	296.000	******	1.00000	******	288.15	******	******
3	0.00000	296.000	******	12.70001	******	629.71	******	******
4	0.00000	266.400	******	12.70001	******	629.71	******	******
5	0.02266	272.438	******	11.93801	******	1409.00	******	******
6	0.02040	302.038	******	11.93801	******	1338.96	******	******
7	0.02040	302.038	******	1.04188	******	808.44	******	******
8	0.02040	302.038	1.00000	1.04188	800.18	808.44	136.9	5.0014
9	0.00000	29.600	******	12.70001	******	629.71	******	******

 Shaft Power = 87300000.00

 Net Thrust = 40172.78

 Equiv. Power = 89890216.00

 Fuel Flow =   6.0377

   S.F.C. = 69.1606

   E.S.F.C. = 67.1677

 Sp. Sh. Power =   294932.44

 Sp. Eq. Power =   303683.19

 Sh. Th. Effy. = 0.3353

     Time Now 23:27:16

B.2   Tabulated Results[33]

T0 [C]	T3 [K]	T4 [K]	Turb_in[K]	Power [MW]	Wf [kg/s]	RPM
W_1 [kg/s]	P3 [K]	P4 [K]	IGV Dev. [deg]	W_3 [kg/s]	W_4[kg/s]	
T6[K]						

DesignPoint

15.0000	629.710	1418.00	1347.20	87.3000	6.11610	1.00000
296.000	1286.83	1209.62	0.00000	266.400	272.520	817.830

Combustor_life

15.0000	630.170	1428.00	1356.40	88.8120	6.19660	1.00000
295.830	1289.97	1212.96	0.00000	266.240	272.440	823.330

AmbientMarker

1	32.20	644.508	1257.40	1201.23	58.460	4.410	0.9995
	281.235	1166.89	1088.21	0.00000	253.111	257.524	729.534

2	30.25	641.634	1250.23	1194.43	58.460	4.404	0.9995
	283.263	1171.78	1092.69	0.00000	254.938	259.343	724.233

3	29.88	641.087	1248.86	1193.13	58.460	4.403	0.9995
	283.652	1172.73	1093.54	0.00000	255.288	259.692	723.222

.

.

35	19.58	625.755	1210.52	1156.74	58.460	4.370	0.9995
	294.932	1199.71	1118.01	0.00000	265.437	269.803	694.983

36	19.40	625.484	1209.84	1156.09	58.460	4.370	0.9995
	295.139	1200.20	1118.45	0.00000	265.624	269.988	694.487

---

[33] This is a display of the results after interpolation for the right power and ambient temperatures and pressures pertaining to the operating conditions of the actual engine

B.3 Performance Charts: Efficiency of Isolated Components
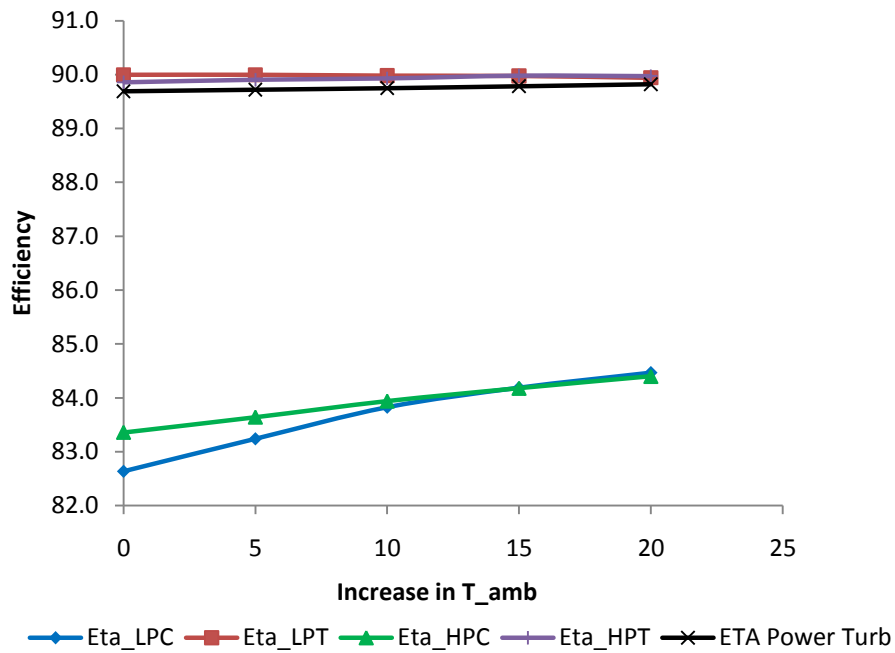
Figure 112: Changes in component efficiencies for LMS100
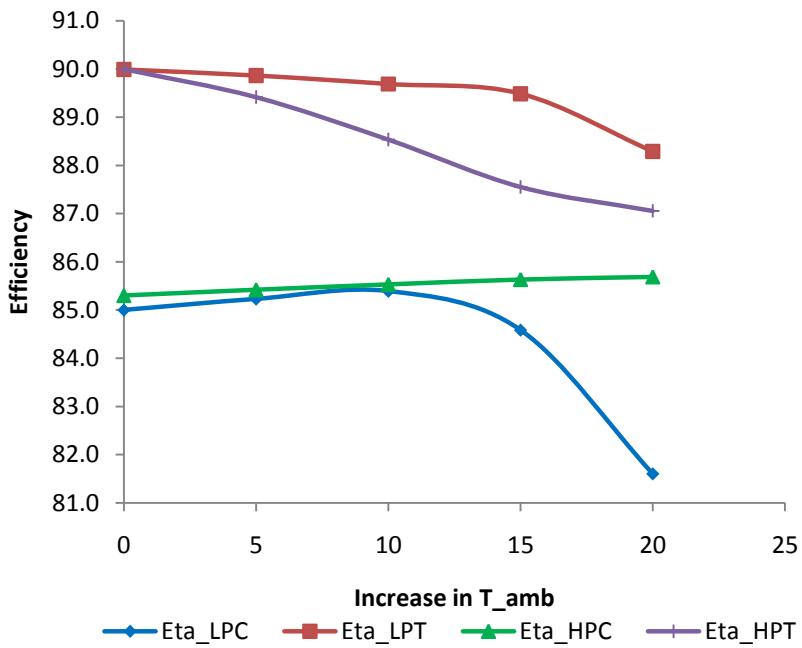
Figure 113: Changes in component efficiencies for LM6000
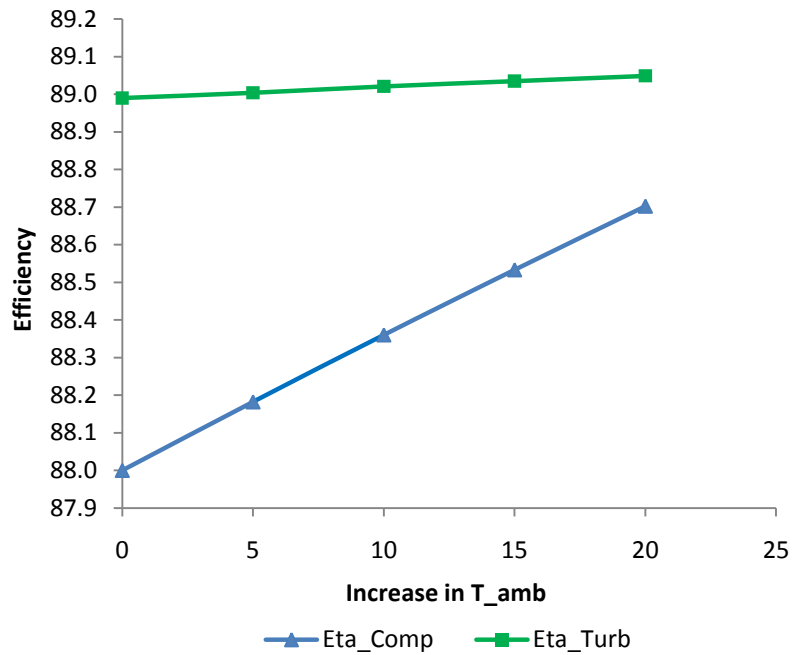
Figure 114: Changes in component efficiencies for FR7EA

Comments:

1. The turbines for the LMS100 hold their efficiency with increasing ambient temperature whilst the compressor efficiency increases with ambient temperature

2. The same trend can be seen for the FR7EA engine as was seen for the LMS100

3. The LM6000 HPC suffers from a lowered efficiency with time as do both the turbines; this is the reason for lower power and efficiency overall for odd design as presented in the results section for the aero-derivative engines

4. It must also be noted that the LMS100 has a separate power turbine which is aerodynamically connected to the load whilst the LM6000 has a direct drive link to the load, however, the LM6000 is different to the Frame engines since it is a 2 spool machine whilst the frame engines are single spool industrial machines

238

B.4   Performance Charts: Compressor Maps
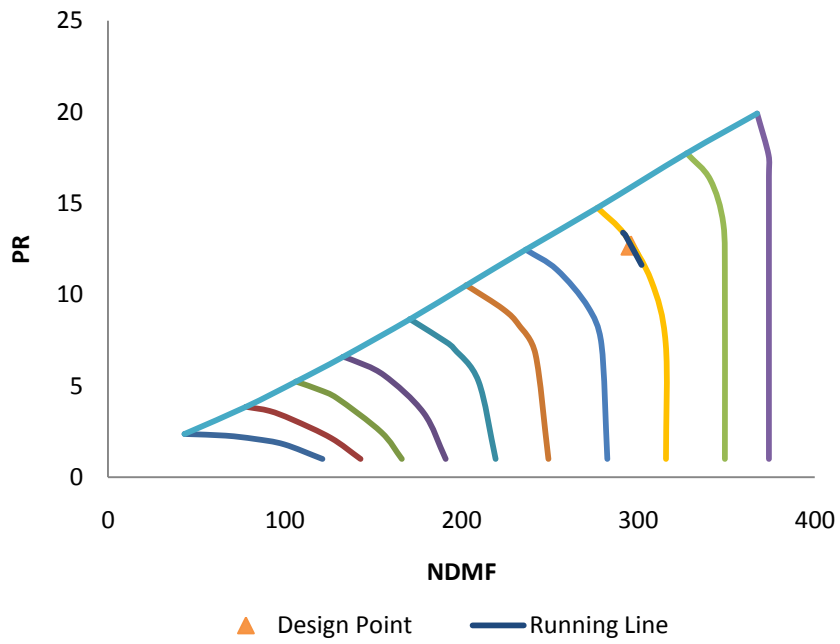
Figure 115: Compressor map of FR7EA with design point and running line
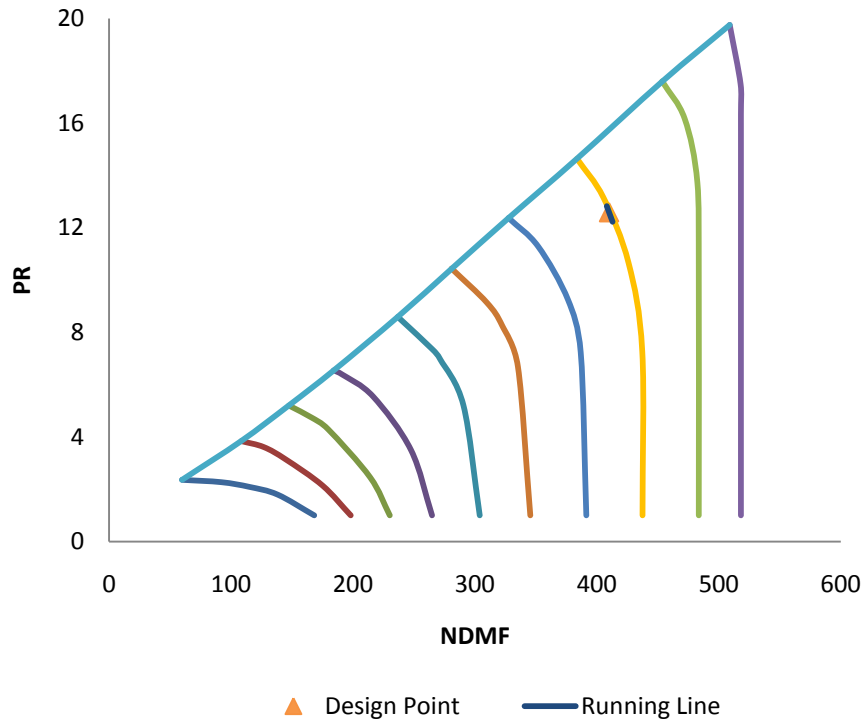
Figure 116: Compressor map of FR9E with design point and running line
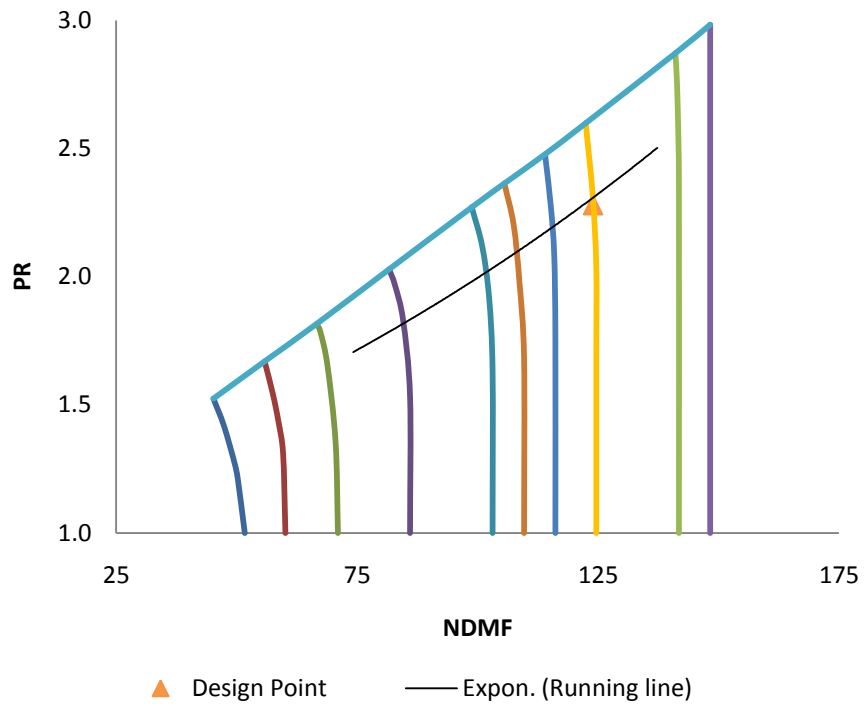
Figure 117: Compressor map of LM6000 with design point and running line
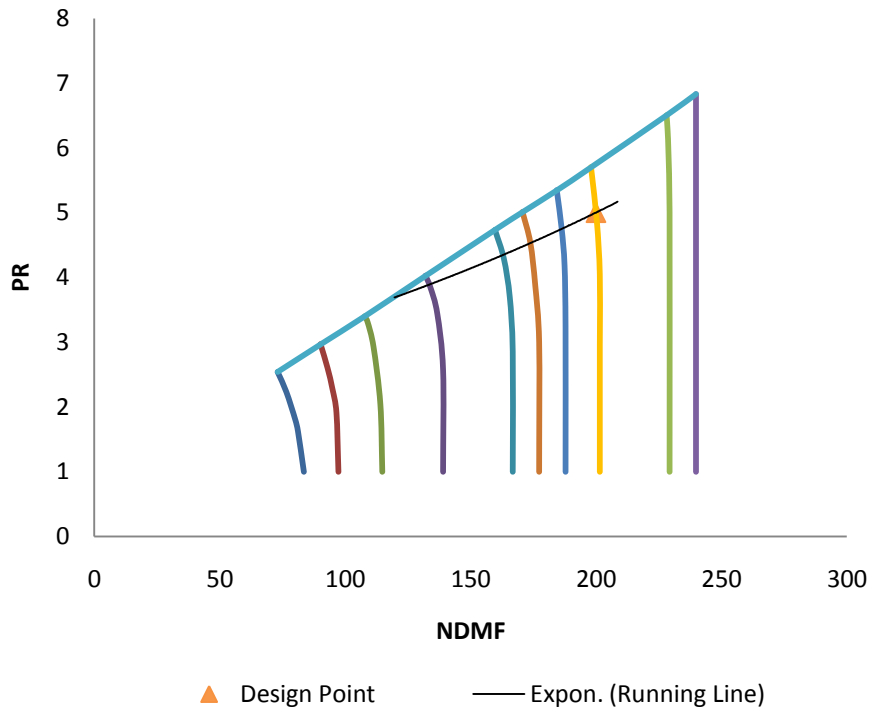
Figure 118: Compressor map of LMS100 with design point and running line

Comments:

1. The compressor maps of the frame engines show running lines which are short and lie on a given rotational speed line. This is because these engines are directly coupled to the load and thus the rotational speed cannot vary too much if a constant production of LNG is required whereby the gas turbine is to deliver a set power to the gas compressor which is in the LNG refrigeration cycle.

2. In this case, the fuel consumption is aggravated with lower firing temperatures and power demands

3. As fuel flow increases with increased power demand the working line moves up towards the surge line, but does so very slowly

4. For the multiple spool machines the compressor maps show the high pressure compressor in each case and this produces a running line which slants across the non-dimensional speed lines. In essence, this is because the load is not directly coupled to the gas generator in the case of the LMS100 and in the case of the LM6000 it is not

242

coupled to the shaft with the HPT of course, so in both cases the HPC speed is different to the load speed.

5. Thus as the power demand falls the shaft speed can be reduced to move the system to a better efficiency point, whereas in the directly coupled case it does not have this flexibility.

6. The running line of the intercooled aero-derivative also depends on the sink temperature ratio to the ambient temperature (Walsh and Fletcher, 2004). This ratio is held constant is off design in this simulation. It adds the extra slant towards surge and a different slant would be achieved for each ratio that can be chosen.

Appendix C: Modelling Details & Schematics

C.1   Stress Model

This section presents a series of schematics depicting the original lifing model based on Larson-Miller parametric techniques. First one can see the isolated stress model:
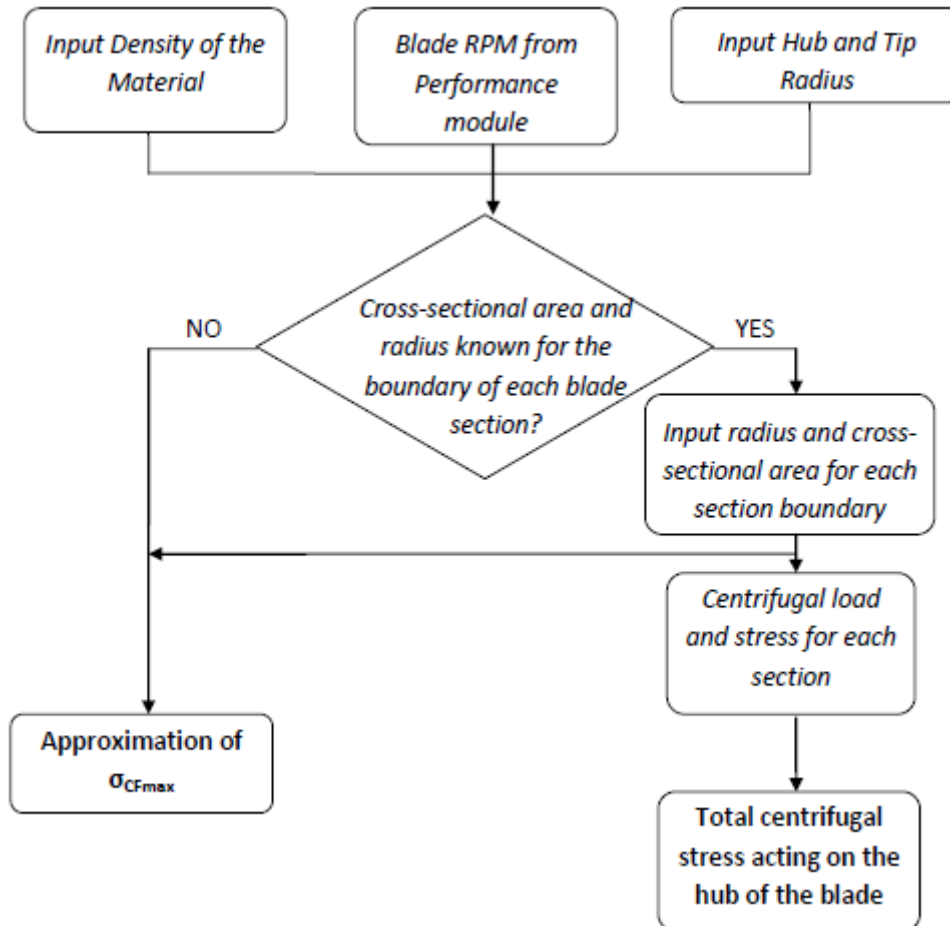
Figure 119: Schematic for Stress Model (Vigna Suria, 2006)

The model uses three types of input:

1. User defined input:
   a. Blade material
   b. Blade geometry and Engine diameters
   c. Number of segments blade is split up into
2. Performance based input:
   a. RPM
3. Materials Input:
   a. Density of blade material

The output is an approximation of the stress and a detailed 'stress-at-each-segment' analysis.

C.2   LMP (Stress-Temperature-Time) Model
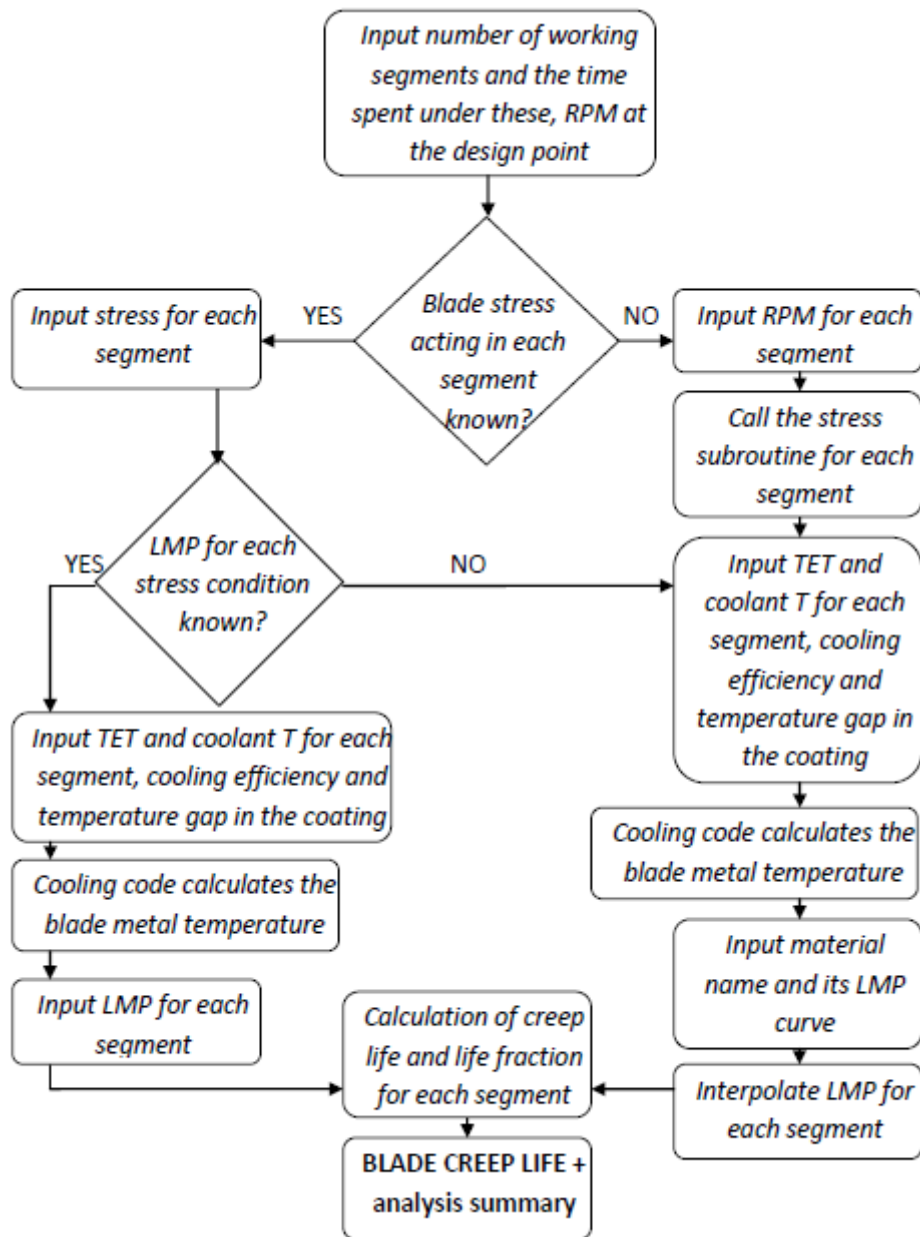
Figure 120: Schematic of the greater lifing module wherein stress and thermal models are incorporated (Vigna Suria, 2006)

Further, the stress model is used in conjunction with a thermal model to create an overall parametric analysis (stress-temperature-time) of the life of the blade. It then uses the Miner's

Law to summate the life usage in each operating condition till the blade material reaches failure.

Additional Inputs (apart from Stress model requirements):

2. User defined:
    a. Time spent in each segment or operating condition
    b. Cooling switch; whether blade cooling in use or not
    c. Coating delta T (effective reduction in temperature by coating)
    d. Cooling effectiveness of blade (for thermal analysis model)
    e. Blade stress selector switch (if stresses are known)
    f. Blade stresses (to be entered if known, in which case stress model will not need to run)
    g. LMP data (essentially test house data for the material)
    h.

3. Performance Based Inputs:
    a. Firing temperature at each operating condition
    b. Compressor exit temperature

4. Materials Inputs:
    a. Larson Miller Parameter constant (or entire LMP curve made up of LMP values and stress values)
    b. Curve for LMP must contain at least 6 points to give satisfactory interpolation/extrapolation

Broad Steps:

1. The module starts by calculating stresses in each segment
2. If stresses are known it proceeds to calculate the life of the blade
3. Further, the blade metal temperature is required which is either known or calculated
4. If calculation required it is done by using cooling effectiveness, compressor bleed temperature and firing temperature
5. The temperature and stress are then used to find a point on the curve which corresponds to an LMP value, which in turn links the temperature and stress to a time to failure for the segment.

C.3   Coating Probabilistic Model
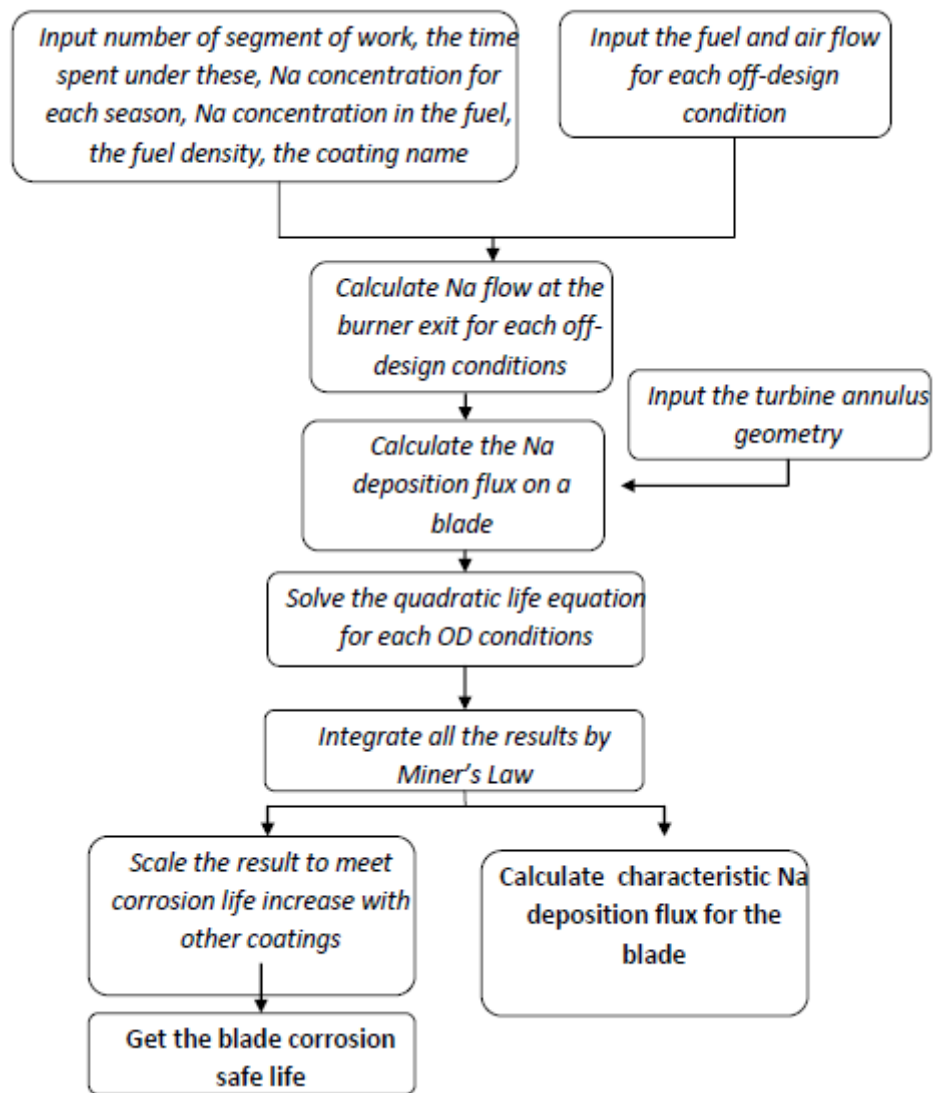
Figure 121: Schematic of Turbine Blade Coating Model (Burgmann, 2010)

The modelling is based on the sodium deposition on the blades and the sodium concentrations in the atmosphere as explained earlier in the thesis. It must be noted that the modelling is very sensitive to temperatures above 1200K and can fluctuate a lot. Burgmann (2010) and Maccapani (2011) have charted the sensitivity of the model.

C.4 Combustor Liner Lifing and Thermal Models

Input number of segments of work, the time spent under these, the combustor type, the number of combustors, the equivalence ratio, the proportion of fuel injected into the primary zone, the presence of a thermal barrier coating on the liner, the liner inner diameter, the liner thickness and the casing diameter, OEM life value

Calculate the Von Mises stress for each condition

Input the fuel and air flow, the compressor outlet pressure and temperature for each OD condition, the DP and at a TET 10 K higher than DP

Calculate the liner temperature for each condition

From DP and TET 10 K higher than DP conditions get U_0 and g

For each condition of work get the combustor life

Miner's Law

Apply the variation of life between DP and combustor life for the given conditions of work around the OEM life

Combustor Life

Figure 122: Schematic for the Combustor lifing model (Burgmann, 2010)

The model uses the kinetic of destruction of liner as explained in the main body of thesis. The assumption is that, based on literature values, the life of the combustor liner is reduced by a given factor for a given increment in firing temperature. Further, the liner is deemed the critical component within the combustor and its life is mapped to the life of the combustor.
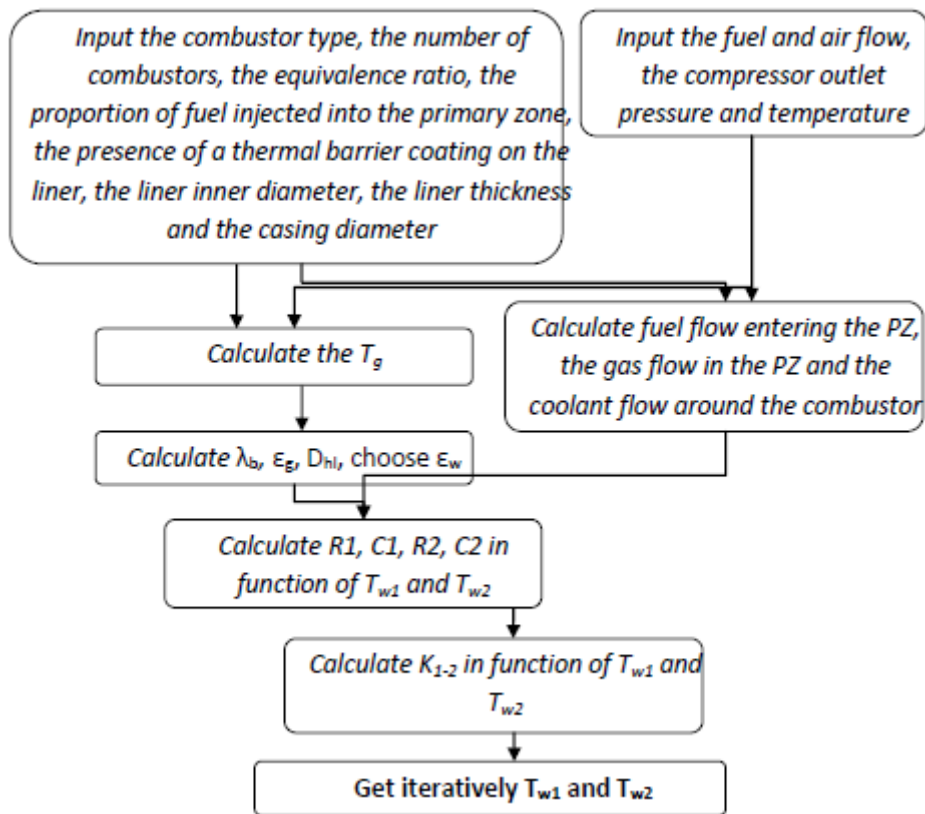
Figure 123: Schematic for the Combustor Liner Thermal Model (Burgmann, 2010)

Required Inputs:

1. User defined inputs:

    a. No. of operating conditions and time spent in each condition

    b. Combustor type: annular, can-annular, can, and no. of cans

    c. Primary zone fuel percentage

    d. Equivalence ratio of the combustion

    e. Thermal barrier coating (yes or no)

    f. Liner thickness (m), Liner Inner diameter (m), Casing Inner diameter (m)

2. Performance based inputs:

    a. Compressor outlet pressure (Pa) and temperature (K)

    b. Mass Flow (kg/s)

    c. Fuel flow (kg/s)

Broad Steps:

1. Von Mises stress calculations: inner liner diameter and combustor pressure

2. Liner temperature calculated taking account of generic values of emissivities, viscosities, conductivities and convection heat transfer coefficients for a generic super-alloy at a temperature of 1300 K. The wall emissivity is set at 0.75 W/m/K by default except if a thermal barrier coating protects the liner; in that case this emissivity is set at 0.35 W/m/K (Tinga et al., 2007)

3. Fuel-to-air ratio calculated from the equivalence ratio

4. Gas temperature is approximated via equation of a fuel-to-air ratio curve versus the temperature increase

5. All flow and area values calculated to get all heat transfer rates

6. T_{w1} calculated minimizing the equation $R_2 + C_2 - K_{1-2}(T_{w1}-\text{function } (T_{w1}))$ where T_{w2} is expressed as a function of T_{w1}. This expression must be equal to 0

7. U_0 and g calculated from DP condition where the life is equivalent to the OEM life and from the condition TET at the DP + 10 K

8. Life is calculated for all OD conditions

9. Miner's law applied to get cumulative life estimates

C.5 Risk Analysis Models
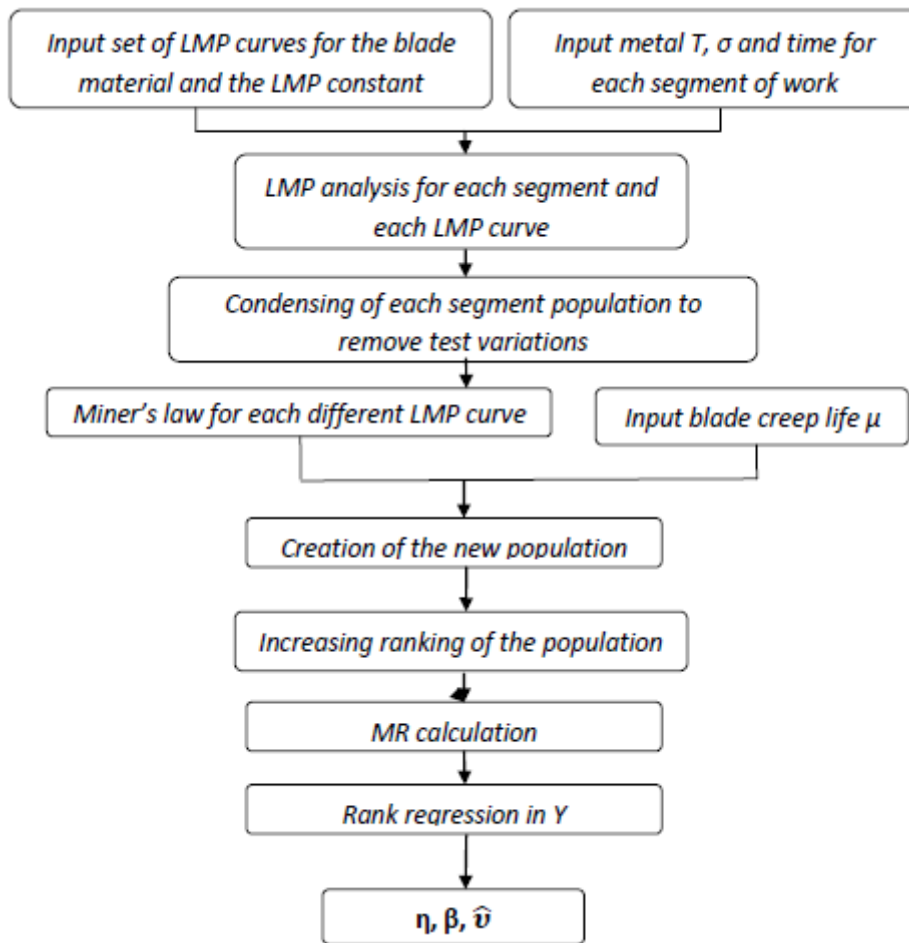
Figure 124: Schematic for the Risk routine used to determine the Weibull parameters for a component based on the lifing results (Burgmann, 2010)

This requires:

1. Blade creep life
2. Creep analysis; including stress and blade metal temperatures
3. Creep curves (from materials database) with each curve having a recommended 6 points else the analysis will be questionable as to its accuracy/dependability
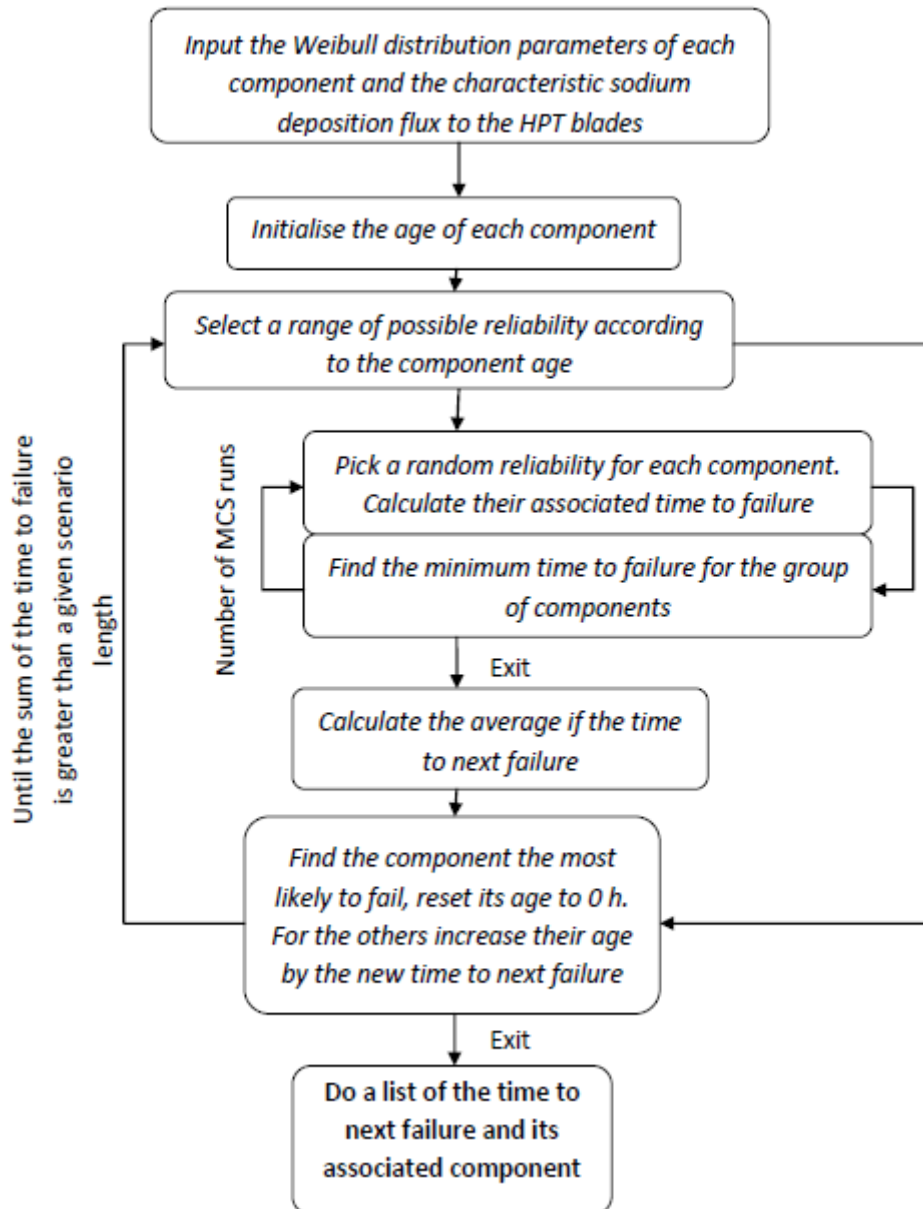
Figure 125: Schematic for the Risk routine used to determine a list of failures for an engine (Burgmann, 2010)

252
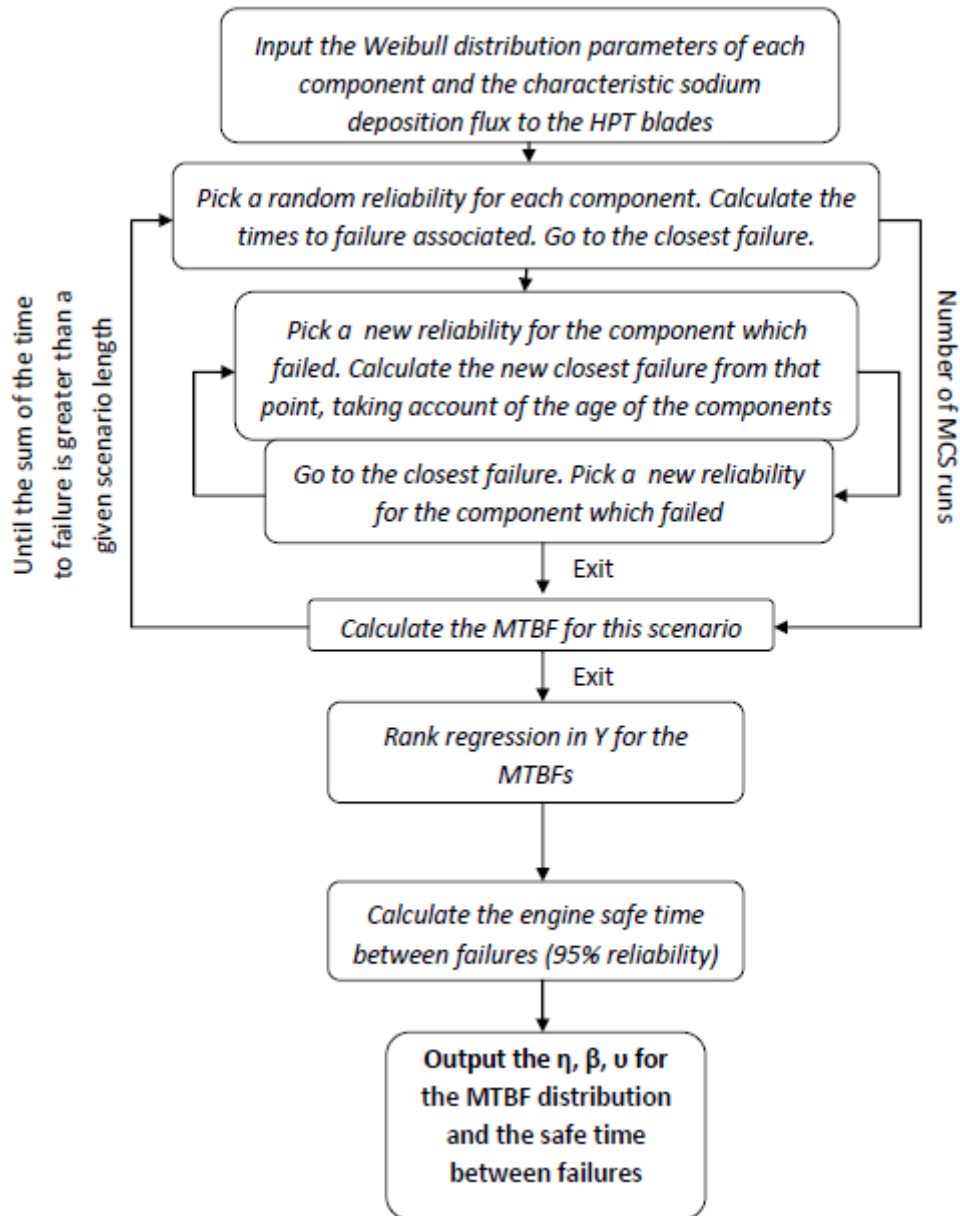
Figure 126: Schematic for the Risk routine used to determine the failure distribution for each engine and component (Burgmann, 2010)

Appendix D: ID Modelling Methodology

The lifing was also conducted using a slightly more advanced method known as the 1D lifing method because it took into account the details of the geometry and the changing nature of the stress and temperature along the profile of the blade. This requires one to carry out preliminary design calculations which are rooted in thermodynamic knowledge of the hot gas path. Using the flow angles, turbine Mach number, mean line diameter and other assumptions for flow behaviour, it is possible to get an idea of the blade geometry.

The main reason for conducting the 1D was because the dimensions of all engines analysed were not readily available. Hence the 1D modelling developed as a necessity and as a by-product it also gave greater accuracy in lifing estimations.

The calculations can be split into two sections themselves; firstly there is the blade height estimations and consequent mapping of the velocity triangles at various stages of the turbine. The second set of calculations pertains to the estimation of the blade profile using the velocity triangles and the Zweifel method which helps to work out the cross sectional area of the blade profile.

D.1   Preliminary Design Blade Height Calculation and Velocity Triangles

The example used here is one of the LM6000 zero staged version. The original spreadsheet used to do this estimation was created by the author in Microsoft Excel and later programmed in FORTRAN code. After this Maccapani (2011) used it to design the LM6000 zero staged version of engine. The 5 stages of compression are converted to 6 stages by adding a zero stage and the pressure ratio of the LPC is increased from 2.28 to 3.0. This also meant a check of the design feasibility of the HPC since the thermodynamic conditions therein were expected to have changed.

The procedure is thus:

1. Estimate the mean line diameter, turbine mach number and rotational speed (RPM)
2. Calculate/estimate the inlet annulus geometry and hence get the blade height and hub to tip ratio

3. Predict the blade speed and axial velocity and hence define the characteristics; namely stage loading ad stage flow coefficients

4. Estimate the outlet geometry

5. Based on Free Vortex design, estimate all the flow path angles and velocities required to draw up the velocity triangles (details of procedure can be found in Walsh and Fletcher, 2004 and Saravanamuttoo et al., 2001)

Assumptions (Maccapani, 2011):

- *Constant air properties*. The properties of the working fluid, namely specific heat (C_p) and ratio of specific heats (γ), are assumed to be constant during the compression process.

- *No heat transfer effects*. The compression process is assumed to be adiabatic, hence the heat transfer between the airstream and the compressor components is neglected.

- *No pressure losses*. Possible pressure losses at the inlet of the compressor and in the inter-connection ducts are neglected. A 5% pressure drop is imposed across the combustor section.

- *No tip clearance*.

- *Constant mass-flow rate*.

- Constant LPC hub diameter and constant HPC tip diameter.

- The axial length of the rotor and the stator blades is assumed to be the same.

- *Constant stage temperature rise*. The temperature rise distribution is constant through the stages of the machine. This choice is not an optimum in general, since in part load operations or during transients the first and the last stages are expected to move towards stall or choke. A common practice is to overload the middle stages, while unloading the first and the last ones, in order to ensure adequate part load and transient safety margins.

- *Free vortex flow.* The whirl velocity at the exit of the rotor is assumed to be inversely proportional to the distance from the axis of the machine. This implies that the work done is equal at all the radii of the annulus.

- *Constant axial velocity span-wise.*

- *Axial leaving velocity stages* ("zero alpha nought stage").

- *The axial velocity is constant* through the stages.

- The engine is operating at *ISA SLS conditions.*

Further, the graph in Figure 127 shows that the design constraints are not demanding beyond feasibility of design.
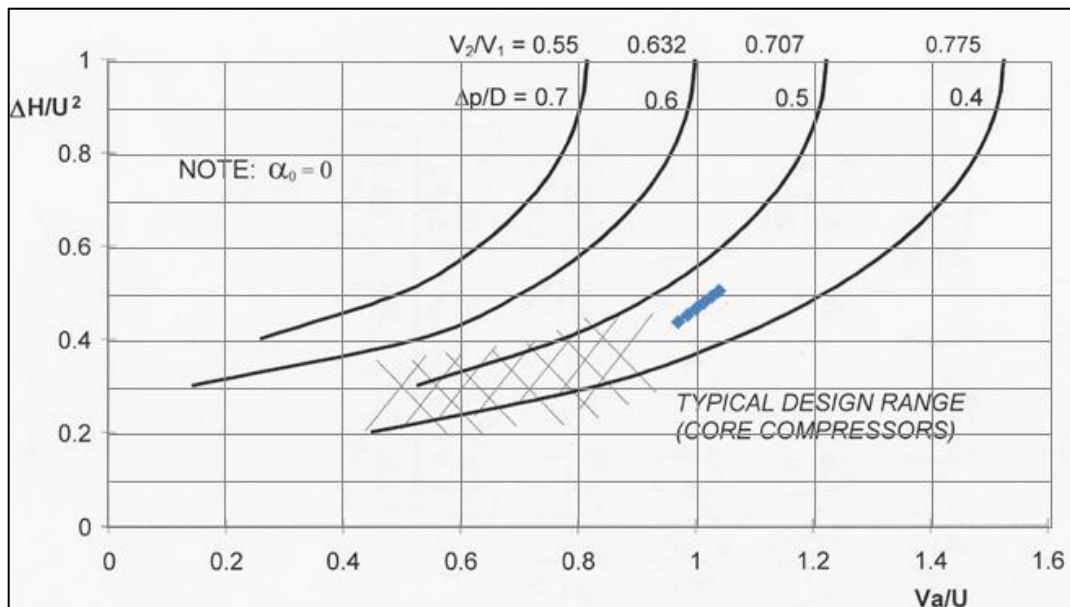
Figure 127: Typical design range for core compressor - dashed area (Ramsden et al., 2010). The graph indicates the position of the LPC stages on the chart (reproduced from Maccapani, 2011)

On the other hand, the HPC undergoes more demanding thermodynamic conditions. Whilst the parameters such as de Haller number, flow coefficient and stage loading are satisfactory, the blade speed is higher than typical limitations according to Walsh and Fletcher (2004) amongst other notable GT manuals, however, high blade velocities are possible based on advanced materials, and whilst this experiment is a simulation only at this stage, it can be

assumed that perhaps in the future such blades can be manufactured if not already possible. Anyhow, it is the aim of the feasibility to chart the requirements for such an engine, and not prove out and out that the engine can be manufactured. This is a hypothetical scenario. The performance and design parameters are listed in Table 13 and Figure 128 shows the charting of the stage loading and flow coefficients as per typical range for these parameters.

Table 13: Comparison between the design limitations and the main parameters of the HPC (Maccapani, 2011)

Parameter	Description	Value	Limit(s)	Check
$\psi = \dfrac{\Delta H}{U^2}$	Stage loading coefficient	0.61 (max)	< 0.7	✓
$\phi = \dfrac{V_a}{U}$	Flow coefficient	0.51 ÷ 0.86	0.5 ÷ 0.75	≈
dH_r	De Haller no. Rotor	0.79 (min)	> 0.72	✓
dH_s	De Haller no. Stator	0.82 (min)	> 0.72	✓
$\dfrac{\Delta p}{D}$	Pressure rise coefficient	0.38 (max)	< 0.5	✓
$M_{r\,tip}$	Rotor inlet relative Mach no. (tip)	1.2	< 1.3	✓
μ	Hub-to-tip ratio	0.92 (max)	< 0.92	✓
α_3	Last stator deflection	24° (max)	< 50°	✓
U_{mean}	Mean blade speed	398 m/s (max)	< 365 m/s	≈
U_{tip}	Tip blade speed	414 m/s	< 400 m/s	≈
PR_{stage}	Stage pressure ratio	1.13 ÷ 1.30	1.05 ÷ 1.5	✓
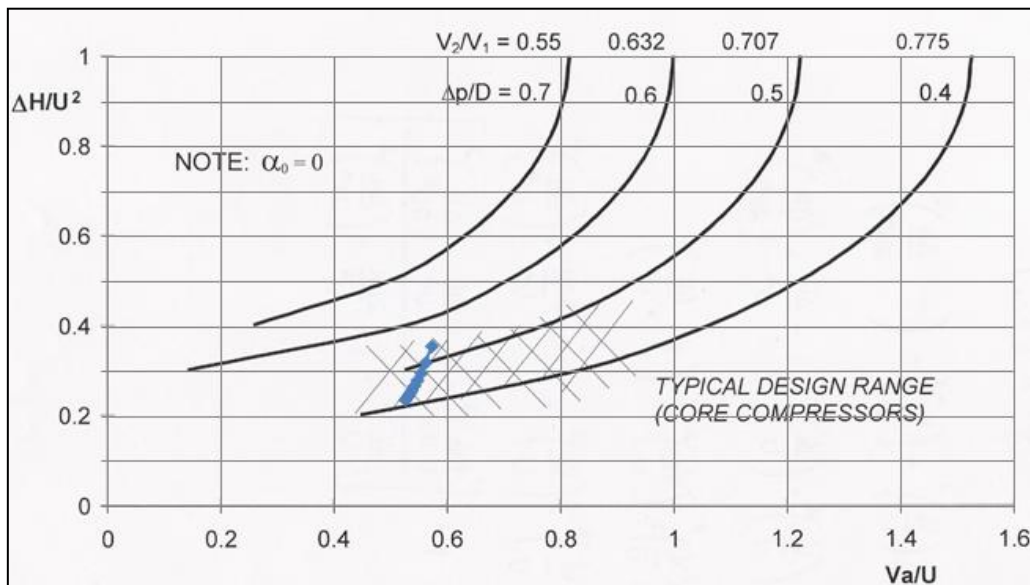
Figure 128: Typical design range for core compressor - dashed area (Ramsden et al., 2010). The graph indicates the position of the HPC stages in the chart (reproduced from Maccapani, 2011)

The HPT design follows a similar trend in that the design seems feasible as detailed in Table 14 barring the fact that the blade sped is once again on the higher side.

The assumptions made for the preliminary design of the HPT are the following (Maccapani, 2011):

- *Constant gas properties*

- *5% pressure loss in the combustor section*

- *Constant axial velocity*

- *Constant mean diameter*

- *Free vortex flow*

- *50% reaction at mid-span.*

- *Axial inlet flow*

- *Inlet Mach number of 0.2*

- *TET = 1650 K*

- *No pressure loss*

- *No heat transfer effects*

258

Parameter	Description	Value	Limit(s)	Check
U_{tip}	Tip blade speed	488 m/s	< 430	≈
U_{hub}	Hub blade speed	388 m/s	< 400	✓
α_3	Rotor exit swirl angle	35°	< 20°	≈
μ_{in}	Inlet hub to tip ratio	0.88	< 0.9	✓
μ_{out}	Outlet hub to tip ratio	0.79	<0.9	✓
α_0	Nozzle exit angle	72-75°	65°÷73°	≈
$\alpha_0 + \alpha_{in}$	Nozzle deflection	72-75°	< 130°	✓
$\alpha_1 + \alpha_2$	Rotor deflection	124°	< 130°	✓
$\dfrac{V_0}{V_{in}}$	Nozzle tip acceleration	3.77	> 1.15	✓
$\dfrac{V_2}{V_1}$	Rotor root acceleration	2.04	> 1.15	✓
U	Mean blade speed	438 m/s	< 350 m/s	≈
M	Exit Mach number	0.26	< 0.55	✓
$\psi = \dfrac{\Delta H}{U^2}$	Stage loading coefficient	1.43	1.0÷2.5	✓
$\phi = \dfrac{V_a}{U}$	Flow coefficient	0.4	0.6÷0.8	≈

At this point, it is enough information to now calculate the blade stresses using the 0D procedure, but if one wants more accuracy then a temperature profile should be used and the area of the cross section of the blade calculated with increasing distance from shaft to tip. Hence, detailed estimates for stresses can be achieved.

The Zweifel method is not charted here, please refer to Ramaswamy (2011) and Mattingly (2005) for further information.

Appendix E: Minutes of Key Meetings

Minutes of the kick-off meeting for the Shell LNG project, a collaboration between Royal Dutch Shell (here on addressed the Sponsor) and Cranfield University, UK.

Location: Cranfield University, Date/Time: Wednesday 30th April 2008 at 09.30

Present:

Pr P Pilidis, Cranfield	(Academic Supervisor and Chair)
Dr Ian Bennett, Royal Dutch Shell	(Industrial Supervisor)
Dr Stephen Ogaji, Cranfield	(Academic Supervisor)
Raja Khan	(EngD student)
Javier Barreiro	(MSc student)
Maria Chiara Laganà	(MSc student)

Agenda

Meeting was an update session for Dr Bennett. The following points were discussed:

1. Presentations with regards to Cranfield University activity and TERA framework delivered by Professor Pilidis.

2. Introductory and initial plans presentation given by Raja Khan.

3. LNG presented by Javier Barreiro

4. Engine simulations presented by Maria Laganà.

5. Discussions on TERA and discussion of possibilities for work.

6. Siemens discussed as the alternative vendor to General Electric.

7. It was understood that the doctorate study would concentrate and be based on the methods and not the results.

8. Parallels to previous studies drawn and discussion of pollutant concentrations using weather models, Cambridge.

9. Important factors to consider:

     i.   Safety

     ii.   Reliability   - Aspects of degradation or cleaning process

     iii. Availability   - (Same as above)

     iv.   Operation   - How we undertake maintenance

10. Consider that 3000 RPM is better than 3600 for compatibility due to lower efficiency losses with 3000 RPM.

11. Question and answer session yielded:

     i.   Australia plant was selected as starting point, NW Karatha.

     ii.   Use Frame 7 as benchmark starting point

    iii.   Guess the plant life to be 25 years to begin with

    iv.   The most limiting component is the combustor, circa 20 000 hours, and then process compressors are next in list.

    v.   We want to be in a position where we tell vendor what we want and don't buy off the shelf

    vi.   Use standard Cranfield system for emissions modelling – suggestion by Professor Pilidis

    vii. CO_2 tax versus trading a long term consideration as business issue for the doctorate – consideration for Raja

    viii.   DLE 25 ppm NO_x is standard for the purposes of the sponsor.

    ix.   Use NASA technology readiness levels – suggestion by Professor Pilidis

12. The two parties involved agreed that the next meeting will be held in three weeks time and will be a phone conference

Actions

1. Send out minutes of the meeting to all members concerned (Raja)

2. Send Ian the TERA and three student presentations (Raja)

3. Look for ways/units to express safe operation (see point 9(i), Raja)

4. Information on plant life, in terms of how many years to design for (Ian)

5. Availability data and stoppage frequency and why stoppages occur (Ian)

6. Economic implications for one day shut down? In terms of percentage turnover lost (Ian)

7. Data on CO_2 emissions and standards governing this (Ian)

8. Figures for Cost, durability, availability, maintainability and reliability as a measure of number of days (Ian)

There being no further business, the meeting was closed by the Chair at 15:00.

Recorded by: Date: 30.04.2008

Raja Khan (Doctoral student, EngD)

Confirmed by: Date: 30.04.2008

Pericles Pilidis (Chairperson)

Minutes for Telecom between Cranfield team and Dr Bennett for the Shell LNG project.

Location: Cranfield University   Date/Time: Tuesday 1ˢᵗ July 2008 at 08.00

Present:

Pr P Pilidis, Cranfield	(Academic Supervisor)
Dr Ian Bennett, Royal Dutch Shell	(Industrial Supervisor) - Linked via phone
Raja Khan	(EngD student)
Javier Barreiro	(MSc student)
Maria Chiara Laganà	(MSc student)

Agenda

1. The TurboMatch simulations and risk models were outlined in a presentation. The theory behind the risk model was explained.

2. Current work concentrates on Risk and Performance models; economic and environmental models will be borrowed for the time being.

3. Possibility of retrieving data from the field from either Shell and/or General Electric for degradation of mechanical equipment/components

4. The 4 year plan was explained via Gantt chart

5. Need to decide what possible work an MSc will do during the MBA year. Initial work may be risk related to finish that module.

6. Ian will not be present at the first review, copies of presentation and report will need to be sent to Ian and a further presentation to be held when visit is made to sponsor in October.

7. Possibility Ian will visit in September to see MSc presentations

Actions

1. Send out minutes of the meeting to all members concerned (Raja)

2. Take matter of information gathering from Shell or GE further, discussions with GE representatives (Ian)

3. Send Maria and Javier email details to Dr Bennett (Raja)

4. Add slides for TurboMatch simulations to show that the selected engines have been correctly simulated (Javier and Maria)

5. Ideas for what the possible MSc(s) will do during MBA (Raja and Pr Pilidis)

6. Add a one sentence aim to current presentation for clarification (Raja)

There being no further business, the meeting was closed at 10:00.

Recorded by: Date: 01.07.2008

Raja Khan (Doctoral student, EngD)

Confirmed by: Date: 01.07.2008

Pericles Pilidis (Chairperson)

Minutes for the first year review meeting.

Student Name: Raja Khan

Thesis Title: Turbomachinery Selection for LNG Plant Equipment

Date/Time: Tuesday 28th October 2008 at 16.00

Present:

Dr James Whidborne	(Chairperson)
Pr Pericles Pilidis, Cranfield	(Academic Supervisor)
Dr Ivan Li	(Second Reader)
Raja Khan	(EngD student)

Agenda

1. Meeting was preceded by presentation made to EngD committee on 8th September 2008 which was followed by questioning and student was successful in said initial review

2. Dr Li did not get a copy of the project report though enough copies were handed into the departmental office by student

3. Presentation of 5 minutes made to update Dr Whidborne and Dr Li since they were not present at the initial presentation on 8th September 2008 nor had any prior knowledge of the project details

4. Dr Li: criticism on scope of project and as to what the objective function is; he felt there were too many topics/things going on; advised to narrow project down

5. Dr Whidborne: advice to read more broadly to able to better answer technical questions on the general topic

6. Student was notified after a 5 minute wait that he was successful in the review

There being no further business, the meeting was closed at 16:45.

Recorded by:

Raja Khan (Doctoral student, EngD)   Date: 28.10.2008

Confirmed by:

Pericles Pilidis (Academic Supervisor)   Date: 28.10.2008

Minutes for the meeting between the Cranfield team and Dr Bennett. Introduction of new MSc students and discussions of proposals for work.

Location: Cranfield University   Date/Time: Thursday 20th November 2008 at 13.45

Present:

Dr Ian Bennett, Royal Dutch Shell	(Industrial Supervisor)
Raja Khan	(EngD student)
Joe Ekanem	(MSc student)
Carlo Andrea Baioni	(MSc student)
Tuboalabo Wellington	(MSc student)

Agenda

1. Mr Bernard Charnley (Senior Research Officer) and Badar Al Abri (PhD student, PDO) were present for lunch only.

2. MSc students introduced themselves to Dr Bennett.

3. Raja presented the first years work to the MSc's and put forward proposals for work to Dr Bennett for the coming year.

4. Proposals include:

   i. Continuation of work on risk modelling. Taking the TRL scaling system and linking it to downtime and reliability. This will involve incorporating scheduled downtime into the model and converting the VBA code to FORTRAN for flexibility and compatibility purposes.

   ii. Performance modelling of two new engines; the Siemens SGT6-2000E (V84) and a pseudo engine.

   iii. Looking at maintenance schedules: compare industrial and aero-derivative engines.

5. The proposals are to be discussed amongst the Cranfield team and finalised

6. Dr Bennett requested an update for two weeks from date of this meeting on what is finally decided amongst the Cranfield team as proposals for work. One slide for each MSc.

7. Dr Bennett requested that a monthly phone conference should take place between him and the team at Cranfield for updates. A fixed date/time of the month should be set for this.

8. The idea of the Cranfield team visiting a refinery at a U.K. site or visiting the GE site in Florence, Italy was raised. Dr Bennett is supportive of this and agreed to arrange this with GE if it goes ahead.

Actions

1. Send out minutes of the meeting to all members (Raja)

2. Finalise the proposals for work (Cranfield Team)

3. Phone conference relating to final proposal for work - circa 4th December (Cranfield Team and Dr Bennett)

4. Arrange for possibility of Raja and MSc's to visit GE's Florence site or a site in the U.K. (Dr Bennett)

There being no further business, the meeting was closed at 17:00.

Recorded by:

Raja Khan (Doctoral student, EngD)   Date: 20.11.2008

Confirmed by:

Ian Bennett (Industrial Supervisor)   Date: 20.11.2008

Minutes for the meeting between the Cranfield team and Dr Bennett. Interim progress report of MSc students.

Location: Cranfield University   Date/Time: Thursday 7th April 2009 at 11.00

Present:

Pr Pericles Pilidis, Cranfield	(Academic Supervisor)
Dr Ian Bennett, Royal Dutch Shell	(Industrial Supervisor)
Dr Stephen Ogaji, Cranfield	(Academic Supervisor)
Raja Khan	(EngD student)
Joe Ekanem	(MSc student)
Carlo Andrea Baioni	(MSc student)
Tuboalabo Wellington	(MSc student)

Agenda

1. Meeting addresses next three months work; last opportunity to shape projects, consequently, the proposals were finalised.

2. Shell previously agreed to basic proposals on 10th December 2008 with revisions on 12th December and 17th December telecoms (see notes at end)

3. Developments for Joe Ekanem:
    i. Possibly not consider off design
    ii. Ian could get weighting factors from suppliers
    iii. Bring FR5 to forefront; drop FR7 if not enough time
    iv. Provide sample maintenance schedule; different for different locations
    v. Look at Richard Spector work; LM2500, aero-derivatives, think of proposals for maintenance schedules for LMS100

4. Developments for Andrea Baioni:
    i. Looking for flexible method and not solid input data
    ii. Aim o add value to existing model

5. Developments for Wellington Tuboalabo:
    i. Focus is efficiency <u>not</u> power
    ii. Shell study; carbon trust and abatement

iii.   Cost of ownership model? Make one? Cost-CO2 ratios?

Actions

1. Send out minutes of the meeting to all members (Raja)
2. Arrange meet for end of work reviews for August/September (Raja)

There being no further business, the meeting was closed at 15:00.

Notes

Previously agreed works from December 2008 telecoms:

Joe Ekanem: Maintenance schedules for Siemens V84 and LMS100 gas turbines

Andrea Baioni: Upgrades of existing risk model with changing of code from VBA to FORTRAN. Include scheduled downtime and TRL scale linking.

Wellington Tuboalabo: Engine appraisal to include evolution studies of Frames 5, 7 and 9.

Recorded by:

Raja Khan (Doctoral student, EngD)   Date: 07.04.2009

Confirmed by:

Pericles Pilidis (Academic Supervisor)   Date: 07.04.2009

Minutes for the meeting between the Cranfield team and Dr Bennett. Final progress report of MSc students.

Location: Cranfield University   Date/Time: Thursday 13th August 2009 (11.00)

Present:

       Pr Pericles Pilidis, Cranfield   (Academic Supervisor)

       Dr Ian Bennett, Royal Dutch Shell   (Industrial Supervisor)

       Dr Stephen Ogaji, Cranfield   (Academic Supervisor)

       Raja Khan   (EngD student)

       Joe Ekanem   (MSc student)

       Carlo Andrea Baioni   (MSc student)

       Tuboalabo Wellington   (MSc student)

Agenda

1. Tuboalabo Wellington: The project was presented but there were many inconsistencies and data/graphs which didn't confine to theory or known trends. Project was exploratory and not in direct line of focus.

2. Joe Ekanem: Well presented maintenance model. Exemplified how the code and model work for PM and CBM. Showed possibilities of how it could integrate to the risk for potential RBM system. Showed that all targets from onset were met.

3. Andrea Baioni: Value was added to existing model but limitations were highlighted in the sense that lack of field data meant only generic results could be presented. Code successfully upgraded to FORTRAN and scaling of input parameters to mimic the performance effect.

Post review discussions

1. Only Raja and Ian present
2. Made some plans for how the integration between risk and maintenance might take form
3. Ideologies/principles shared for how the tool can be useful to Shell
4. Outlined the need for reliability to be mapped for each component and then fed to the maintenance; perhaps new MSc's can do this for one main component each?
5. Discussion on creating unique maintenance schedules based on reliability
6. Discussion on need of tool to aid in sparing philosophy

7. Ian highlighted the need for clarity over each model and how each model is related to the next and what exactly the inputs and outputs were.

8. Focus should turn to commercial value and exemplifying this in the third year.

Actions

1. Send out minutes of the meeting to all members (Raja)

2. Begin to draw proposals for next MSc in line with discussions (Raja)

There being no further business, the meeting was closed at 15:00.

Recorded by:

Raja Khan (Doctoral student, EngD)   Date: 13.08.2009

Confirmed by:

Pericles Pilidis (Academic Supervisor)   Date: 13.08.2009

Minutes for the second year review meeting.

Student Name: Raja Khan

Thesis Title: Turbomachinery Selection for LNG Plant Equipment

Date/Time: Monday 11th January 2010 at 14.00

Present:

Dr James Whidborne, Cranfield	(Chairperson)
Pr Pericles Pilidis, Cranfield	(Academic Supervisor)
Dr Stephen Ogaji, Cranfield	(Academic Supervisor)
Pr Ian Bennett[*], Shell	(Industrial Supervisor)
Dr Panos Laskaridis, Cranfield	(Second Reader)
Raja Khan	(EngD student)

Agenda

1. Presentation and question and answer session lasting one hour

2. Dr Whidborne:

    i. Pointed out some possible typing mistakes for formulations presented with regards the Weibull distribution

    ii. Must find MBA supervisor soon since missed out on this in the first year too, but keep it to Risk/Economics since this will be MBA contribution to the research

    iii. Report should have had 'what', 'why' and 'how' to make it complete, the 'why' was missing - Student explained that he felt the reference to the first year report should cover this

3. Dr Laskaridis:

    i. Lifing is critical/original contribution of the research

    ii. Why not consider ancillary/other systems which are critical in the plant? Student answered that the GT was the focus and perhaps other systems can be incorporated when the basic modelling is complete

4. Student was notified after a 5 minute wait that he was successful in the review

---

[*] Joined the meeting via a telephone link, not present at venue of review

There being no further business, the meeting was closed at 15:00.

Recorded by:

Raja Khan (Doctoral student, EngD)   Date: 11.01.2010

Confirmed by:

Pericles Pilidis (Academic Supervisor)   Date: 11.01.2010

Minutes for the meeting between Raja Khan and Professor John Nicholls. Discussion on risk analysis and lifing.

Location: Cranfield University   Date/Time: Monday 24th March 2010 at 17.00

Present:

    Pr John Nicholls, Cranfield   (Management Supervisor)

    Raja Khan   (EngD student)

Agenda

1. Raja: Summarised the project, the need to create maintenance schedules and thus for lifing and risk analysis.

2. John Nicholls' advice:

    i. Corrosion is not modelled by a Weibull distribution. Use Gumbell instead. Corrosion is a maximum life model, whilst Weibull mimics a maximum lifetime model.

    ii. The scatter for creep is low, low variation, the scatter is high in fatigue applications.

    iii. Look at 'creep/fatigue interactions'

    iv. The mathematics of statistics is not so well defined

    v. To capture material variability you need 6-9 creep curves from different test houses, look at university research programs for such data

    vi. For disks it's about crack propagation, LCF, forget creep

    vii. Scatter occurs due to fracture toughness, stress concentration etc, look for books o probabilistic fatigue failure

    viii. For maintenance schedule use gated process, when do you want maintenance, weakest link studies

    ix. Understand central limit theorem; the idea that for a large sample, it doesn't matter which distribution you pick

    x. Perform a macro and micro system study, one for component wise studies and one which is the whole engine and its failure

Actions

1. Confirm Professor Nicholls as management supervisor (Raja)

2. Pass information with regards materials and methodology of analysis (John Nicholls)

There being no further business, the meeting was closed at 19:00.

Recorded by:

Raja Khan (Doctoral student, EngD)   Date: 24.03.2010

Confirmed by:

John Nicholls (Management Supervisor)   Date: 24.03.2010

Minutes for the meeting between the Cranfield team and Dr Bennett. Introduction to third generation MSc.

Location: Cranfield University   Date/Time: Monday 29th March 2010 at 10.00

Present:

      Pr Pericles Pilidis, Cranfield   (Academic Supervisor)

      Pr Ian Bennett, Royal Dutch Shell   (Industrial Supervisor)

      Dr Stephen Ogaji, Cranfield   (Academic Supervisor)

      Pr Riti Singh, Cranfield   (Combustion Specialist)

      Raja Khan   (EngD student)

      Paul Burgmann   (MSc student)

Agenda

1. Raja summarised the current project architecture and Paul presented his CV and background theory for lifing analysis. Raja presented current challenges and a proposal for works.

2. Different GT components and modes of failure for each component were discussed. It was decided that the focus will be on combustors and turbine blades, the compressor, at this stage, shall not be considered. The primary modes of failure were agreed as creep and wear (fretting). Oxidation/Hot Corrosion should be investigated further to see if analytical relationships can be found.

3. Ian said he wanted to see a string of modules working together by the end of this academic year.

4. The works shall be limited to analytical techniques, CFD and FEA will be time consuming and engine specific, Shell want a generic, simple code.

5. Professor Singh gave advice on combustor lifing and advised on simple technique with metal temperature prediction and also advised to denote mode of failure properly and look at whether the fuel is causing trouble

6. Badar Al-Abri (PDO, Oman) joined and presented his project, contributed to understanding on GT control at off design.

Actions

1. Send out minutes of the meeting to all members (Raja)

2. Draw detailed proposals for MSc in line with discussions (Raja)

3. Combustor and Turbine lifing module development as outlined above (Paul)

4. Existing module integration, creation of a wrapper to call the different modules to work together (Raja)

There being no further business, the meeting was closed at 17:00.

Recorded by:

Raja Khan (Doctoral student, EngD)   Date: 29.03.2010

Confirmed by:

Pericles Pilidis (Academic Supervisor)   Date: 29.03.2010

Minutes for the meeting between Raja Khan, Paul Burgmann and Professor John Nicholls. Further discussion on risk analysis and lifing.

Location: Cranfield University   Date/Time: Monday 25th May 2010 at 16.30

Present:

      Pr John Nicholls, Cranfield   (Management Supervisor)

      Raja Khan   (EngD student)

      Paul Burgmann   (MSc student)

Agenda

1. Raja: Explained to John that analysis was now limited to creep and oxidation/corrosion, the components will be combustor and turbine only, no compressor lifing.

2. Showed him NIMS scatter and Boyer's 15% test house scatter due to testing variables – he feels our methodology is viable as long as we state the assumptions and limitations

3. Advised us to look at creep boundaries via materials diagram for extrapolation purposes, since our creep curves don't cover the whole range

4. General advise to Paul on distributions and matching of distributions

Actions

None.

There being no further business, the meeting was closed at 17:40.

Recorded by:

Raja Khan (Doctoral student, EngD)   Date: 25.05.2010

Confirmed by:

John Nicholls (Management Supervisor)   Date: 25.05.2010

Minutes for the meeting between the Cranfield team and Dr Bennett. Introduction to third generation MSc.

Location: Cranfield University   Date/Time: Monday 19th July 2010 at 10.00

Present:

Pr Ian Bennett, Royal Dutch Shell	(Industrial Supervisor)
Raja Khan	(EngD student)
Paul Burgmann	(MSc student)
Adinweruka Mba	(MSc student)
Vasanth Ramaswamy	(MSc student)
Dennis Uwakwe	(MSc student)
Pr Pericles Pilidis, Cranfield	(Academic Supervisor) - only present for an hour

Agenda

1. Raja & Paul: Presented integrated TERA modules to Ian. The modules were controlled by a 'wrapper' code. The workings of Performance, lifing and risk analysis were exemplified successfully. Combustor lifing is final task yet to complete, the lifing of the turbine in terms of creep and coatings has been accomplished.

2. Ian brought an extra person from Shell who has access to the Shell suite of data, possible contact for doing the integration work. Raja gave him an introduction to TERA.

3. New MSc students introduced to Ian. Happy with Adin's role but not so sure about Vasanth and Dennis. Wanted an emphasis on integration and usage of the tool as opposed to further development of modules. The importance of doing Emissions and Economics to the completeness of the TERA was highlighted. Further detailed proposals will follow in the next meeting.

4. Agreement that the coding should be finished this year, with view to having economics integrated by October so that Ian can present the work to other peoples at Shell. Integration to Shell suite to begin this year, utilising either Paul if he can be secured on a studentship, or to extend Adin's work. Raja will oversee this process.

5. Was highlighted that Paul's affiliation with the project can be extended and plans were made to realise this. This would enable Paul to stay at Shell and help with some of the integration work.

6. Talks took place between Professor Pilidis and Ian Bennett to agree a studentship for Paul.

Actions

1. Draw detailed proposals for new MSc's in line with discussions (Raja, Stephen)
2. Complete combustor lifing code in next two weeks (Paul)
3. Extend the code to include Economics by October/November (Raja, Adin)
4. Integrate code to Shell suite by end of 2010 (Raja, Paul)
5. Secure studentship for Paul (Prof Pilidis, Ian Bennett)

There being no further business, the meeting was closed at 16:00.

Recorded by:

Raja Khan (Doctoral student, EngD)   Date: 19.07.2010

Confirmed by:

Ian Bennett (Industrial Supervisor)   Date: 19.07.2010

Minutes for the meeting between the Cranfield team and Pr Bennett; involving MSc progress review and Paul Burgmann planning for works at Shell.

Location: Cranfield University   Date/Time: Monday 18th October 2010 at 11.00

Present:

      Pr Ian Bennett, Royal Dutch Shell   (Industrial Supervisor)

      Dr Stephen Ogaji   (Academic Supervisor)

      Raja Khan   (EngD student)

      Paul Burgmann   (MPhil student)

      Adinweruka Mba   (MSc student)

      Vasanth Ramaswamy   (MSc student)

      Dennis Uwakwe   (MSc student)

Note: Four new MSc joined for lunch and introduction to Ian and listened to Paul's presentation.

Agenda

1. Adinweruka Mba:

    i.   Presented maintenance and economics module progress. Simulation Based Maintenance (SBM) outlined.

    ii.   The maintenance is being informed by the risk module output called 'failure schedule' which is the result of Monte Carlo runs of the risk distributions of GT components.

    iii.   Some problems were highlighted with failure schedule but the output from risk is now stable and further modelling plans were detailed.

    iv.   Adin asked about typical plant set ups and Ian explained that plants run on fixed schedules and that the three engines most useful would be Frame 7, LMS 100 and Trent 60.

    v.   Ian is interested in seeing how we can extend maintenance schedules and how the tool might simulate this.

2. Vasanth Ramaswamy:

    i.   Presented the design aspects of the module he is developing; weights and dimensions module, in order to compliment the inputs to lifing.

    ii.   Ian suggested creating look up tables as opposed to put in new code to the lifing module (correction factor versus performance parameters).

3. Dennis Uwakwe:

   i. Presented empirical model for estimating emissions; chemistry based model has been dropped and empirical model is being developed.

   ii. Ian would like to see a minimum of a useful literature survey relating specifically to gaseous fuels and a basic computer working model. Justification for methodology and empirical model.

   iii. Ian suggested investigating the Wobbe number of different fuels.

4. Paul Burgmann:

   i. Showed plans for integration of code to Shell suite and highlighted the areas where the integration can take place.

   ii. Looking to use Shell data in place of Cranfield performance code.

   iii. Also looking to use data to look at history of engines and simulate plants which are some way through their life as opposed to totally new plants.

5. New projects:

   i. Ian wants to use two of the four new MSc's for other Shell projects.

   ii. Plans at Cranfield to use two MSc's to continue work on maintenance and economics and to help run scenarios of aero derivative versus frame engine and scenarios of extending operation by optimising the schedule/planning.

6. Plans for overall objectives and usefulness of tool:

   i. SELECTION: to investigate via comparison of engines; aero derivative versus frame engine, accounting for cost of components, fuel and calculation of downtime, to use LMS 100 and Frame 7EA (Cranfield).

   ii. OPTIMISATION: Operational Planning methodology; finding ways to extend planned maintenance (Shell /Cranfield).

   iii. It was also established that *tuning* of the models will need to be done at the Shell end using site data (Shell only).

   iv. Look at creating code/capability to simulate multi-spool engines (Shell only); Note: Cranfield already has this ability within Turbo-match.

7. Separate talks took place between Professor Pilidis and Ian Bennett.

Actions

1. Detailed proposals for new MSc's in line with discussions – November 2010 (Ian, Raja, Stephen)

2. Complete maintenance and economics code - November 2010 (Adin, Raja)

3. Look at using code to simulate stretching of schedule (Adin, Raja)

4. Provide look up tables for certain engines using modelling done thus far (Vasanth, Raja)

5. Show that the code can simulate industrial engines and amend coding (Dennis, Raja)

6. Work on integrating code to Shell based on plans agreed (Paul)

7. Hold telecoms every week to chart progress, Paul to minute telecoms (Paul, Raja)

8. Set up third year review for December/January (Raja)

9. Writing specifications for codes and detailing exactly what the TERA does – will be partly covered in end of year report and will extend into next year's work (Raja)

There being no further business, the meeting was closed at 16:00.

Recorded by:

Raja Khan (Doctoral student, EngD)   Date: 18.10.2010

Confirmed by:

Ian Bennett (Industrial Supervisor)   Date: 18.10.2010

Confirmed by:

Stephen Ogaji (Academic Supervisor)   Date: 18.10.2010

Minutes for the meeting between the Cranfield team and Paul Burgmann; involving MSc progress review and final expectations alignment.

Location: Cranfield University   Date/Time: Monday 26th November 2010 at 09.00

Present:

     Dr Stephen Ogaji   (Academic Supervisor)

     Raja Khan   (EngD student)

     Paul Burgmann   (MPhil student)

     Adinweruka Mba   (MSc student)

     Vasanth Ramaswamy   (MSc student)

     Dennis Uwakwe   (MSc student)

Agenda

1. Adinweruka Mba:

    i. Presented maintenance and economics module progress – module is complete.

    ii. Multiple engines can now be simulated

    iii. GT power demand is linked to a rate of production of LNG

    iv. Simulation based on Shell DMR technology

    v. Process needed more detailed, information about compressor duties and coolant properties, so simplified version used

    vi. Process is being simulated by assuming overall efficiencies and water cooling power requirements; using ETA = Q / W.net formula, where W.net is addition of gas compressor and water cooling power requirements.

    vii. Cannot run at low power setting due to limitations in risk analysis coding (Paul explained this was due to root square function in risk analysis)

    viii. Possible solution is to look at developing an intrinsic function in FORTRAN which will resolve this issue, needs investigating. Run a test on the argument.

    ix. The second turbine is critical because the first one is slightly under utilised.

    x. Aim to have Frame engine analysis in slide format (Due: 29.11.10)

2. Vasanth Ramaswamy:

   i. Presented progress on 0D and 1D analysis and the marked difference achieved in the lifing between the original Paul module and the new module

   ii. Still some integration issues, discussions took place between Paul and Vasanth before and after the main meeting. Issues surround the fact that blade is split and maximum creep point is located.

   iii. It was decided that Vasanth should try to create look up tables of correction factor versus power of GT if feasible, else an attempt to integrate his module directly can be considered but is not favourable to Shell. (Due: 13.12.10 at latest)

   iv. The problem with look up tables: may need a look up table for each creep curve for the same analysis when we get to the risk analysis part; this would mean multiple look up tables and may not be feasible.

3. Dennis Uwakwe:

   i. Presented empirical model for estimating emissions; tuning of empirical correlations doe for Frame engines successfully to match GE published trends.

   ii. Code includes stoichiometric CO_2 calculation and correlation based UHC, NOx and CO calculations.

   iii. Detailed literature to be presented as part of final thesis, partly done.

   iv. Summary slides to be sent to Shell through Raja (Due: 29.11.10)

4. Paul Burgmann:

   i. Showed successful transfer of coding from Fortran Format to VBA

   ii. Concerns raised about how much ground can be covered; it was made mention that MSc to continue Paul's work should have an overlap with Paul at Shell for knowledge transfer purposes (to be discussed in next telecon.)

   iii. Detailed some discussions between him and Ian. Shell require scaling:

      i. Identify which components fails

      ii. Identify where is the problem area within component / mode of failure

      iii. What to change/replace

      iv. Failure distribution for the ideal new component can be generated

   iv. Project 1 is to be an in depth analysis into engine types and their operation; industrial and aero. engine comparisons

285

> v. Project 2 to be component specific and scaling thereof; develop the methodology for scaling

5. Separate talks took place between Professor Pilidis and Paul Burgmann.

Actions

1. Summary of progress and plans for final year (slides) - 29.11.10 (Raja)

2. Maintenance and Economics results for frame engines (slides) - 29.11.10 (Adin, Raja)

3. Look up tables for factors between 0D and 1D lifing – Mid Dec 2010 (Vasanth, Raja)

4. Emissions results for Frame engines (slides) – 29.11.10 (Dennis, Raja)

5. Enquire about two outstanding proposals from Ian, set up telecom to discuss (Paul)

6. Discuss whether new MSc can overlap with Paul's time at Shell for knowledge transfer purposes, discuss timings for MSc's to spend at Shell (Stephen, Ian, next telecom)

There being no further business, the meeting was closed at 14:00.

Recorded by:

Raja Khan (Doctoral student, EngD)   Date: 26.11.2010

Confirmed by:

Paul Burgmann (MPhil student - Shell based)   Date: 26.11.2010

Confirmed by:

Stephen Ogaji (Academic Supervisor)   Date: 26.11.2010

Minutes for the third year review meeting.

Student Name: Raja Khan

Thesis Title: Turbomachinery Selection for LNG Plant Equipment

Date/Time: Monday 10th January 2011 at 12:00

Present:

Dr James Whidborne, Cranfield	(Chairperson)
Prof. Nicholls	(Management Supervisor)
Prof. Ian Bennett[*], Shell	(Industrial Supervisor)
Dr Panos Laskaridis, Cranfield	(Second Reader)
Raja Khan	(EngD student)

Agenda

1. Presentation and question and answer session lasting one hour

2. Dr Whidborne:

   i. General editing and presentation remarks

   ii. Enquired about publications to support methods developed

3. Dr Laskaridis:

   i. The stress analysis results should be put into perspective since they have a high sensitivity according to DR Laskaridis' experience

   ii. Clarity over relationship between method and results, define the process well, improve the diagrams and add details of information transfer

4. Prof. Nicholls:

   i. Combining results; how to put results into perspective? How to look at blade creep and liner lifing in conjunction?

   ii. What system of turning the separate component results into integrated maintenance?

5. Student was notified after a 5 minute wait that he was successful in the review

There being no further business, the meeting was closed at 13:00.

Recorded by:

Raja Khan (Doctoral student, EngD)   Date: 10.01.2011

Confirmed by:

Ian Bennett (Industrial Supervisor)   Date: 10.01.2011

---

[*] Joined the meeting via a telephone link, not present at venue of review

Minutes for the meeting between the Cranfield team and Shell team; involving March 2010 MSc progress review and September 2010 MSc proposals discussion.

Location: Cranfield University   Date/Time: Friday 4th February 2011 at 11.30

Present:

Prof. Pericles Pilidis	(Academic Supervisor)
Prof. Ian Bennett	(Industrial Supervisor)
Dr Giuseppina Di Lorenzo	(MSc Supervisor)
Raja Khan	(EngD Researcher)
Paul Burgmann	(MPhil Researcher)
Vincent Desnos	(MSc student)
Julien Karlsson	(MSc student)
Matteo Maccapani	(MSc student)
Adinweruka Mba	(MSc student)
Vasanth Ramaswamy	(MSc student)
Lukasz Sznajder	(MSc student)
Dennis Uwakwe	(MSc student)

Agenda

1. Private meeting between Professor Pilidis and Professor Bennett took place between 11.30 and 12.00.

2. Introductory presentation by Raja Khan to highlight aims and context of project to new students and academics.

3. March MSc Presentations:

    i. Vasanth Ramaswamy:

        i. Presented the methodology and results of a 1D lifing technique using stress and thermal distributions

        ii. Exemplified the use of his modelling and accuracy achieved

        iii. First runs on aero-derivative done, but input data was lacking and may have distorted results, but scenarios show how aero-derivatives can be analysed

        iv. Code is able to make estimates for both life of components and sizes and dimensions which may not be readily available; verified with frame engine data

288

    ii.   Dennis Uwakwe:

        i.   Presented the use of an empirical code to estimate emissions

        ii.   Trends matched to GE public domain established results

        iii.   No trends to match aero-derivative engines with; further, key parameters not easily available for aero-derivative modelling

        iv.   For better simulations a physics based model should be adopted, this is the recommendation from the literature when looking at DLE /DLN combustion; the staged reactions require different trends to be established at each stage of combustion which cannot be followed by conventional methods of empirical based emissions estimation.

    iii.   Adinweruka Mba:

        i.   Presented the modified maintenance and newly created economics models

        ii.   Showed sensitivities of gas price, LNG price, years of simulation and discount rates

        iii.   Sensitivity is lacking in respect to changes in economics when levels of risk are altered, not enough change in NPV when extremes of risk chosen, this requires further work

        iv.   Aero-derivative modelling not limited by economics, only a lifing/risk issue, else modelling is ready to carry out the analysis

4.   Future MSc proposals discussion:

    i.   Paul Burgmann Presentation: Detailed two non-TERA Shell projects. Both require fundamental thermodynamic modelling and predictive methods for analysing failure, can be done on spreadsheet with minimal coding; emphasis on methodology development as opposed to robust code.

        i.   Project 1: Plunger Pumps; positive displacement, akin to piston engine, but seals are stationary to allow better cooling.

        ii.   Project 2: Hot Gas Expanders: Can be centrifugal or axial machine.

    ii.   Two TERA projects to be conducted. All projects have potential for Shell based placement. Full briefs and methodology/steps to be confirmed by end of March.

        i.   TERA Project 1: to answer the question whether Shell should use aero-derivatives instead of industrial frame engines. To be

conducted in the context of Frame 7EA, LMS 100 and LM6000 engines, with view to Rolls Royce Trent 60 if time permits.

ii. TERA Project 2: to look at prolonging time before maintenance actions are required. To advise on how aged engines are to be operated. Optimisation in context of operation as opposed to coating or component upgrades/changes.

Actions

1. All presentations to be emailed to supervisors – 08.02.11(Raja)

2. Detailed step-by-step methodology to be outlined for new MSc projects – end of March 2011 (Cranfield Team)

3. MSc Theses to Professor Bennett / Dr Di Lorenzo – 21.02.11 (Raja)

There being no further business, the meeting was closed at 16:00.

Recorded by:

Raja Khan (Doctoral Researcher, EngD)   Date: 04.02.2011

Confirmed by:

Ian Bennett (Industrial Supervisor - Shell)   Date: 04.02.2011

Confirmed by:

Pericles Pilidis (Academic Supervisor)   Date: 04.02.2011

Confirmed by:

Giuseppina Di Lorenzo (MSc Supervisor)   Date: 04.02.2011

Minutes for the meeting between the Cranfield team and Shell team; involving and September 2010 MSc progress review and proposals discussion.

Location: Cranfield University   Date/Time: Wednesday 11th May 2011 at 10.00

Present:

Prof. Pericles Pilidis	(Academic Supervisor)
Prof. Ian Bennett	(Industrial Supervisor)
Dr Giuseppina Di Lorenzo	(MSc Supervisor)
Raja Khan	(EngD Researcher)
Vincent Desnos	(MSc student)
Julien Karlsson	(MSc student)
Matteo Maccapani	(MSc student)
Lukasz Sznajder	(MSc student)

Agenda

1. Private meeting between Professor Bennett and Raja Khan (10.00 - 10.30):

    i. Thesis structure and content discussions

2. Meeting between Professor Bennett, Raja Khan and Dr Di Lorenzo:

    i. Discussion of possible changes to initial proposals for the two MSc's who are to work on non-TERA related projects; outcome was to reject changes to proposal; agreement reached to continue with existing brief

    ii. To utilise either another MSc/ doctoral researcher for new work required by Shell

    iii. Highlighted that June and July are the main period of work, August is out for writing thesis; timelines discussed

3. MSc Presentations for progress and plans:

    i. Matteo Maccapani:

        i. Presented the methodology and plan for aero derivative engine selection

        ii. Plans to utilise the TERA tool to do this

        iii. Main challenge: data for aero engines in terms of sizes of components and materials understanding/creep curves

    ii. Vincent Desnos:

        i. Presented the methodology and plans for using the TERA to select old engines and optimise the maintenance actions taken

        ii. Shell expressed an interest in the idea that this piece of work could 'check' new designs before they were used in the field to

291

look at the risks of deploying new technology, this may be additional work after the core deliverables have been achieved

    iii.   Lukasz Sznajder:

        i.   Presented the plans for simulation and diagnostics of Hot Gas Expanders

       ii.   Concerns/questions over design of tool, so Professor Bennett gave elaborate details of Shells framework (not discussed here) after which methodology became clear; tool needs to communicate with Shell database and perform calculations based on performance and vibrations metrics

    iv.   Julien Karlsson:

        i.   Presented plans and progress for simulation and diagnostics of Plunger Pumps

       ii.   Point (ii) for Sznajder applies here; same details were needed for clarifications as to set up/ type of tool required by Shell

      iii.   Additionally, Karlsson described advanced methods of diagnostics including 'rough sets' and 'neural networks' which may be deployed as methodologies

4. Separate meeting over lunch between Professor Pilidis and Professor Bennett, including Dr Di Lorenzo and Raja Khan

There being no further business, the meeting was closed at 14:30.

Actions

1. Arrange a telecom for progress review for mid June (Raja)

2. Make arrangements/timeline for Julien and Lukasz to spend time at Shell (Prof Bennett); Shell agreed to pay for flights and accommodation

3. Email copies of NDA's to Shell (Gillian Hargreaves)

Recorded by:

Raja Khan (Doctoral Researcher, EngD)   Date: 11.05.2011

Confirmed by:

Ian Bennett (Industrial Supervisor - Shell)   Date: 11.05.2011

Confirmed by:

Pericles Pilidis (Academic Supervisor)   Date: 11.05.2011

Confirmed by:

Giuseppina Di Lorenzo (MSc Supervisor)   Date: 11.05.2011

Minutes for the meeting between the Cranfield team and Shell team; involving and September 2010 MSc final review and LNG TERA tool discussions.

Location: Cranfield University   Date/Time: Wednesday 31st August 2011 at 10.30

Present:

Prof. Pericles Pilidis	(Academic Supervisor)
Prof. Ian Bennett	(Industrial Supervisor)
Giuseppina Di Lorenzo	(MSc Supervisor)
Raja Khan	(EngD Researcher)
Vincent Desnos	(MSc student)
Julien Karlsson	(MSc student)
Matteo Maccapani	(MSc student)
Lukasz Sznajder	(MSc student)
Noureldin Azhari	(MSc Student)

Agenda

1. Presentation – Raja Khan (11.00 - 13.00):

    i. Review of works since last meet

    ii. Structure of LNG TERA tool as current and hand over details

    iii. MSc Presentations:

        i. Matteo Maccapani:

            1. Presented the results for the economics and full LNG TERA scenarios

            2. Showed how ID model can be used to enhance the tool and make it flexible

            3. Sensitivity of economics and emissions charted

        ii. Vincent Desnos:

            1. Presented the results for upgraded maintenance module and explained the algorithms

    iv. Discussions:

        i. Code hand-over will be tedious since Shell won't have Turbomatch, hence performance tables need to be created or Shell need to use an alternative e.g. GT Pro

        ii. The upgraded maintenance scheduling model can ONLY be run using a thermodynamic performance code and is NOT feasible with look up tables since it runs the performance code after each

293

and every deterioration, even with performance code each simulation takes 30 minutes

2. Thesis discussions (14.00 - 15.00)

    i.   Hand-over of code and code manual will be after thesis is written and viva done

    ii.   Thesis hand-in aimed for December 2011

3. Prof Bennett, Prof Pilidis Private meeting (12.30 - 13.00)

4. Shell Based MSc Presentations (15.00 – 16.00):

    i.   Details withheld, not applicable to LNG TERA project

There being no further business, the meeting was closed at 17:00.

Actions

1. Arrange a telecom/ face-to-face for progress review for September/ November for Noureldin Azhari (Raja)

Recorded by:

Raja Khan (Doctoral Researcher, EngD)   Date: 31.08.2011

Confirmed by:

Ian Bennett (Industrial Supervisor - Shell)   Date: 31.08.2011

Confirmed by:

Pericles Pilidis (Academic Supervisor)   Date: 31.08.2011

Confirmed by:

Giuseppina Di Lorenzo (MSc Supervisor)   Date: 31.08.2011

Minutes for the meeting between the Cranfield team and Shell team; involving March 2011 MSc review and LNG TERA tool discussions.

Location: Cranfield University   Date/Time: Friday 18th November 2011 at 11.00

Present:

Prof. Pericles Pilidis	(Academic Supervisor)
Prof. Ian Bennett	(Industrial Supervisor)
Raja Khan	(EngD Researcher)
Noureldin Azhari	(MSc Student)

Agenda

1. MSc discussions (11.00 - 13.00):

    i. Review of works since last meet

    ii. MSc Presentation:

        i. Noureldin Azhari:

            1. Presented the methodology for using the code as a power generation tool

            2. Explained how modifications might be done – this will be a small change to the existing code of no more than 100 lines

    iii. Thesis on target and 70% written

    iv. Will need to incorporate the power generation results to show extended use of the TERA tool, this will delay the submitting of the thesis

    v. Thesis hand-in aimed for February 2012 due to change in circumstances and extension applied for up to March 2012

2. Prof Bennett, Prof Pilidis Private meeting (14.00 - 16.00)

Actions

1. Arrange a telecom for December for progress review for Noureldin Azhari (Raja)

2. There being no further business, the meeting was closed at 16:00.

Recorded by:

Raja Khan (Doctoral Researcher, EngD)   Date: 18.11.2011

Confirmed by:

Ian Bennett (Industrial Supervisor - Shell)   Date: 18.11.2011

Confirmed by:

Pericles Pilidis (Academic Supervisor)   Date: 18.11.2011