CRANFIELD UNIVERSITY

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Evaluating Gas Turbine Fouling Degradation and Impact of Washing on Engine Performance

School of Aerospace, Transport and Manufacturing

MSc by Research
Academic Year: 2016 - 2017

Supervisor: **Dr. Uyioghosa Igie**
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ABSTRACT

Fouling of the compressor of a gas turbine is one of the major contributors to its performance degradation, not only in terms of a reduction in the potential power output revenue and increased fuel costs but also raising the operating temperatures to levels that will have an impact on the servicing intervals and costs. In view of the current economic climate and with the ever-increasing pressure on governments to reduce emissions that contribute to global warming, the need to operate power generating gas turbines in the most efficient way possible is becoming more important.

The aim of this study is to demonstrate that using a single compressor dual high-pressure washing system, on multiple gas turbines and a combination of a strict on-line compressor washing regime it is possible not only reduce the rate of compressor degradation, that will enable the period between off-line washes to be extended but also maintain a higher rate of power output throughout this period. Additional benefits will include better fuel efficiency which will lead to a lowering of emissions and the added flexibility of the overall plant operation by reducing the service interventions and shutdowns for off-line washes to the minimum.

This study utilises the readily available data from the gas turbine control system to understand how the performance is affected by compressor fouling over time. Once corrected to remove the variations caused by changes in the ambient conditions, the performance trend of the data can be examined in 2 ways. The comparison of the recorded degradation against the gas turbine’s own historic figures and secondly against the relative performances of adjacent machines over similar time periods.

The data gathered, from 4 gas turbines, over the 3 years 8 months recording period, provided the opportunity to select 'like for like' starting points in the various life cycles. This enabled direct comparisons of the results, between the various gas turbines that had operated with different compressor washing regimes. These comparisons demonstrated that maintaining an effective on-line compressor washing regime allows for greater potential revenue from exported power; whilst at the same time being more fuel efficient and lowering operating temperatures.

Keywords:

Heat rate, base-load, on-line wash frequency, operating hours, productive hours

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P_{act}	Actual Power Output
T_{amb}	Ambient Temperature
P_{amb}	Atmospheric Pressure
η	Compressor Efficiency
P_1	Compressor Inlet Pressure
T_1	Compressor Inlet Temperature
P_2	Compressor Outlet Pressure
T_2	Compressor Outlet Temperature
T_{2i}	Compressor Outlet Temperature (ideal)
P_{corr}	Corrected Power Output
CF_{T+RH}	Correction factor for ambient temperature and relative humidity
CF_P	Correction factor for atmospheric pressure
CBA	Cost-benefit analysis
C	Cross-Sectional Area
EGT	Exhaust Gas Temperature
ρ	Fluid Density
A	Fluid Velocity
GT	Gas Turbine
IGV	Inlet Guide Vanes
Nm^3/h	Normal cubic metres per hour
OAT	Outside Air Temperature
ΔP	Pressure differential across the filter (delta P)
PR	Pressure Ratio
RH	Relative Humidity

1 Introduction

1.1 Background

Power generation from fossil fuels must be achieved using the most efficient methods available for both ecological and economic reasons. The ability to effectively evaluate the production performance will highlight any shortcomings and provide justification for the introduction of changes where necessary.

Gas turbines are used globally to produce electricity and their performance can be measured in numerous ways: these include power output in terms of the electricity produced, heat rate, exhaust gas temperature and compressor efficiency. The choice of which parameters the operator selects to monitor the gas turbines performance will depend on what is most important and may vary from site to site. For example in a petrochemical site that operates a gas turbine on a fuel that is a by-product of the site’s refining process, meaning that is effectively ‘free of charge’, the heat rate of the gas turbine may be of little importance, however on a different site where the fuel costs are high the opposite may be true. Similarly, if the gas turbine operates at base-load conditions 24 hours a day and exports all the electricity it produces then the performance is probably measured by the gas turbine's power output making this the key performance indicator. Furthermore, because the chemical nature of different fuel types varies, specifically the percentage of hydrocarbon by weight, this has an impact on the maintenance interval. This is displayed in the Figure 1-1 below and shows that burning natural gas has the least adverse effects while using some heavy distillates could have a dramatic reduction in the maintenance interval.

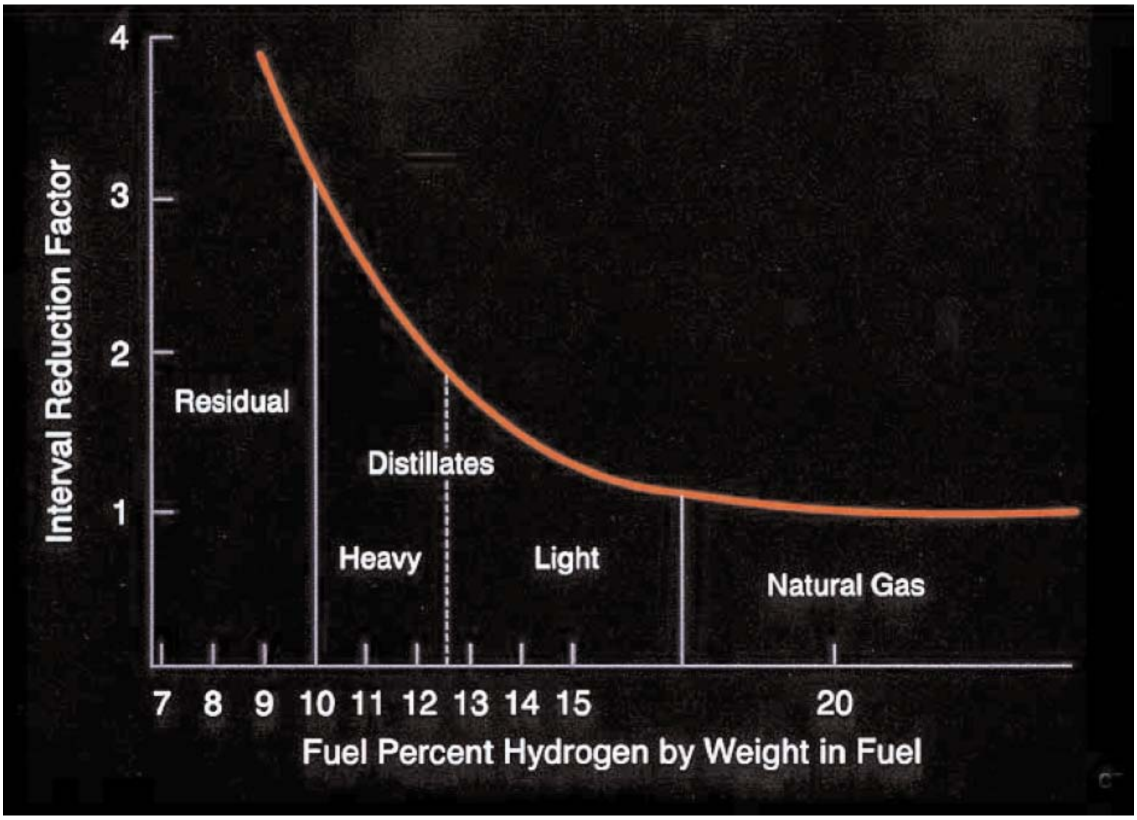

Figure 1-1: Estimated effect of fuel type on maintenance [1]

In the UK, when the New Electricity Trading Arrangements (NETA) was first introduced in 2001 it had a dramatic effect on the way in which gas turbine power producers operated. What NETA effectively did was to allow for electricity to be traded as any other commodity, meaning that each power generation company had to state their intended power output, in megawatts (MW), that they would provide to the grid for a period of time two hours in advance; any shortfall in their production would not only incur a fine but also the extra costs that the grid incurred in sourcing and purchasing the required MW at short notice. The result is that the provider rarely declared the absolute maximum possible because of the threat of the financial penalties; as a consequence of this, and the inherent flexibility in the operating cycles of gas turbines which meant that the gas turbines no longer operated at their optimal setting of base-load for the majority of the time and therefore the way that performance was monitored had to be revised.

In other parts of the world, there have also been changes in the primary choice for the generation of electricity from gas turbines to other means as wide-ranging as solar or wind to nuclear; this has been brought about by political policies and environmental pressure. This has meant, due to their flexibility of operation, gas turbines are used to ‘top up’ the demand from the national grid. Historically there may have been little incentive to closely monitor the performance of land-based power generating gas turbines, but with the ever-changing economic climate, this is no longer the case.

1.2 Aim and Objectives

The aim of the study is to investigate and quantify the impact that degradation has on the ongoing performance of gas turbine engines, alongside the effects of differing compressor washing regimes. Results from these differing compressor washing regimes will form a basis for a techno-economic study to highlighting the cost implications of the various scenarios; this will offer gas turbine users a more accurate picture of their site’s performance and possible new options for future operations. The objectives are to:

- Determine the performance degradation experienced during normal operations of a number of gas turbines, of the same type, that were load sharing the demand at the same location and therefore subject to similar airborne contaminants.
- Provide evidence as to the benefits of employing on-line compressor washing as a means of maintaining performance.
- Determine any variances recorded in the relative performances of adjacent gas turbines when following differing compressor washing regimes.
- Identify any problems through the use of incorrectly mixed, namely over diluted, compressor wash fluid for both off & on-line washing.
- Quantify the effects of online and off-line compressor washing respectively.
- Calculate the incurred operating costs of washing and revenue implications.

1.3 Thesis Structure

1.3.1 Chapter 1:

Provides an introduction to the potential problems encountered when operating gas turbine engines from airborne contaminants and their subsequent effects. Outlines the methodology involved analysing the data, collected from a number of gas turbines over a recording period of more than 3½ years, to produce detailed trends to enable the operators to enhance efficiency and profitability.

1.3.2 Chapter 2:

This literature review encompasses the nature of degradation, the different types and most common causes; how it occurs, the methods available to operators to combat or minimise the effects, the history of compressor washing as well as any shortcomings with current practices.

1.3.3 Chapter 3:

Describes the methods commonly used to evaluate the performance of gas turbines, highlights the weaknesses of each, then formalises a more structured wider ranging approach for interpreting raw data in the future along with data filtering techniques and equations utilised within this paper. The approach to the investigation is described that includes the means of data gathering and planned structure of the trial.

1.3.4 Chapter 4:

The types of gas turbines utilised for this trial, their installation and operational regime are identified, along with the compressor washing equipment and details of the washing regime employed during the trial period. The effect of how changes in atmospheric conditions alter the recorded performance of a gas turbine is also discussed.

1.3.5 Chapter 5:

Results of the trial, detailing the findings of the study into the relative performances of each gas turbine, the variations recorded and the reasons. The resulting benefits provided by effective compressor washing, with regards to not only the differences between on and off-line but also due to the variations in compressor wash fluid concentrations.

1.3.6 Chapter 6:

Contains the conclusions made following the analysis of the relative performances of the gas turbines and the various compressor washing regimes employed during trial period. Makes recommendations for the future monitoring and operational management of the gas turbines to optimise performance and enhance profitability.

2 Literature Review

2.1 Performance Degradation

The performance of all gas turbines is affected whilst operating because the air being swallowed contains airborne particles these will affect the performance in a variety of ways. One of the most readily available indicator of losses in gas turbine performance is a drop in output, either mechanical or electrical depending upon the installation, although this can sometimes be overlooked, especially if the GT is operating at part-load conditions and not at base-load. This is because when at part-load a gas turbine has a degree of flexibility, within the operating parameters and limitations, to meet the demand placed upon it by increasing the fuel flow or permitting a higher exhaust gas temperature to suit the situation. Whilst this allows the gas turbine to continue to operate, the full repercussions of the degraded performance may not become apparent until weeks or even months later at the next service outage. An alternative method reported by operators and one that requires a certain amount of calculations, is that of compressor efficiency, however, it does have its limitations. Firstly the range of compressor efficiency is relatively small and therefore any variations, both good and bad, are also small and harder to detect; secondly and perhaps more importantly is the fact that once identified it is quantified as a percentage, meaning that these benefits or losses cannot be provide a monetary values for budgetary purposes.

The losses experienced are split into two groups, recoverable and non-recoverable, which affect various sections within the gas turbine in different ways. Recoverable losses can be regained during normal operations, the main type due to compressor fouling is usually rectified by carrying out a compressor wash; this can be either on-line, whilst the gas turbine is operating, or off-line, when shutdown [2], [3]. Non-recoverable losses can be due to both the normal wear of internal components, such as blade tips that increase the tip clearance and also to the ingested material that causes erosion or corrosion.

The damage that the impact of airborne particles in the air flow causes to the compressor blades is called erosion and alters the aerofoil profile of the blades thereby changing it from the design point. These changes can be a reduction of the blade chord, shortening of blade length which increases tip losses, blunting the leading edges and sharpening the trailing edges.

Corrosion, on the other hand, is induced by contaminants that adhere to, and react with, the material of the blades leading to pitting of the surface, as shown in Figure 2-1. This causes roughness and disruption of the airflow, which, could ultimately lead to failure of the equipment due to localised stress points [1].

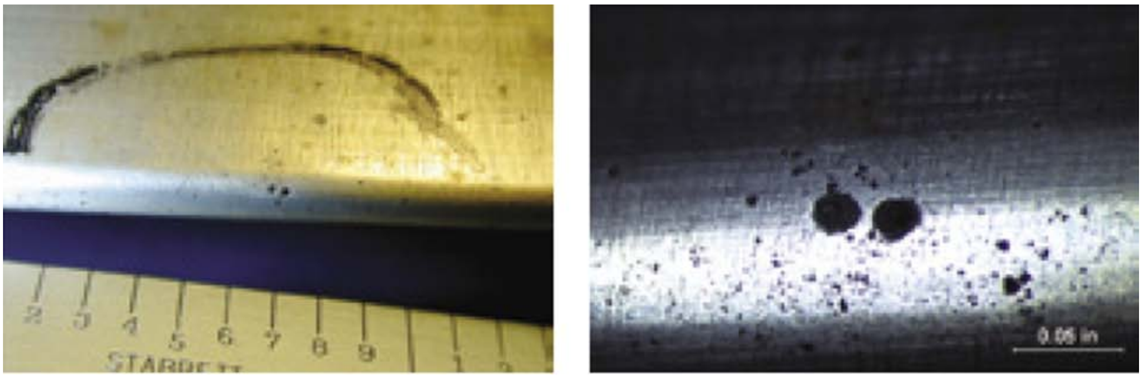

Figure 2-1: Compressor blade corrosion [4]

Some coastal sites suffer from damage from the corrosive sea salt atmosphere whilst GT's operating in industrial areas may be affected by the presence of gaseous products, such as sulphur oxides and nitrogen oxide, being present in the airflow [5].

2.2 Compressor Fouling

Gas turbines by their very nature of operation ingest vast volumes of air of which a proportion will inevitably be material that could cause fouling for the compressor section, it has been estimated by Diakunchak [6] and Meher-Homji et al [7] that 70 – 85% of lost performance of gas turbines can be attributed to compressor fouling. Additionally, as fouling of the compressor section of the gas turbine not only promotes performance losses it can shorten the life and increase the emissions which could incur financial penalties.

Operating in a wide variety of different locations means that fouling can be a very site-specific problem [8] [9]. Installations can vary from large combined cycle gas turbine (CCGT) power generating sites to small district combined heating and power (CHP) plants, deserts to tropical climates and from high altitude down to sea level, on board both offshore platforms and marine vessels. Seasonal and daily changes in the ambient conditions also affect the performance of the gas turbines, most significant being variations in the ambient air temperature. This is because when the air is warmer it becomes less dense thereby reducing the potential mass flow of the GT and reducing the power output and efficiency [10]; the opposite is true if the temperature decreases. Due to these variations, the performance figures need to be standardised, to what is known as ISO conditions, this will be discussed later in this paper.

The type of contaminants present is as diverse as the locations stated and come in both natural forms; such as pollens, dust, and ash, as well as man-made pollutants such as industrial chemicals, soot and hydrocarbon vapours. Some of these contaminants and their relative positions within this range can be seen in Figure 2-2.

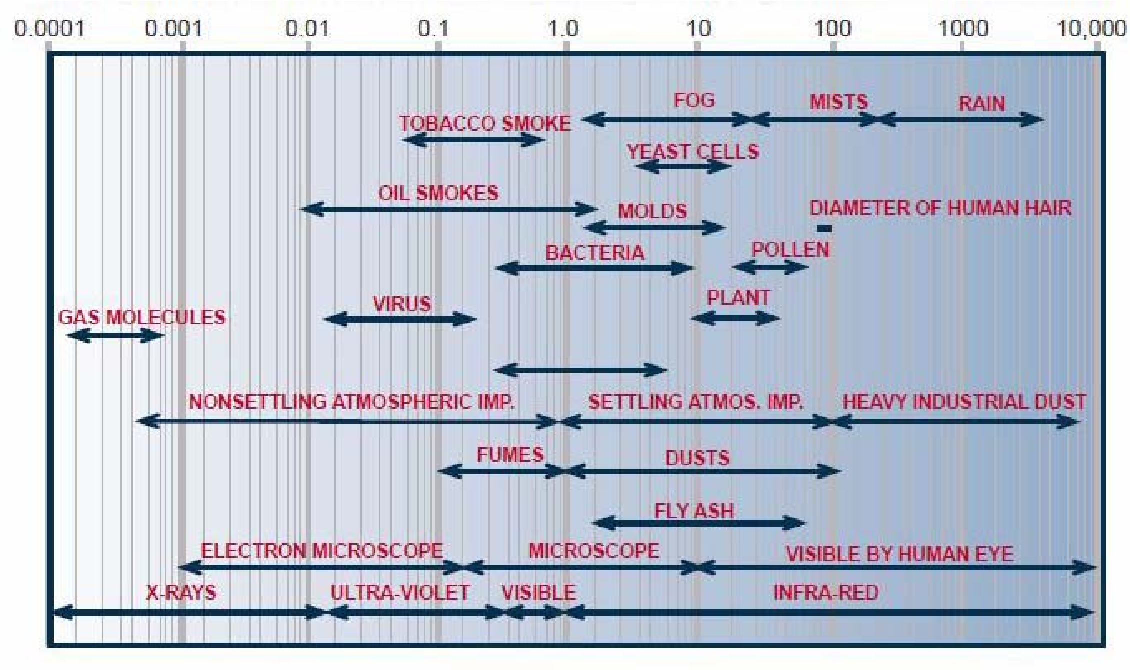

Figure 2-2: Relative sizes of common airborne contaminants in micrometres [11]

The presence of oil, in the form of a mist from breather vent or from an internal leak, if permitted to enter the compressor section, will increase the rate of fouling because it will help bind the airborne particles to the internal surfaces [12], as shown on the right in Figure 2-3.

Figure 2-3: Different types of fouled compressor blades [13]

The quality of air varies not just with different types of contaminants but also the quantity by weight, measured in parts per million, ppm. Rural and coastal areas can be expected to contain between 0.01 to 0.1 ppm whilst an industrial region could be much higher at 0.1 to 10 ppm.

Sited in an industrial desert environment a gas turbine is likely to suffer from a large amount of 'dry' dusty fouling, heavily laden with man-made particles from the local area; whereas a tropical coastal location is more likely to experience more natural pollutants such as pollen, spores etc and even airborne salts. According to Meher-Homji et al [3] and Thames et al [14], these pollutants will combine to form a coating of the internal surfaces of the gas turbine, which, if left unchecked will severely hamper the smooth flow of air through the system.

As an example, an industrial atmosphere containing approximately 1 ppm by weight of contaminants, a gas turbine, with a mass flow of 450kg/sec would swallow approximately 12,500kg of contaminants per 8000 operating hours if no filtration system were installed, as stated by Schneider [15].

Gas turbine installations feature filter housings mounted on the inlet to remove the majority of these potential fouling materials, however, the efficiency of the filters will have an effect on the performance of the gas turbine. This is due to the pressure differential across them, the more effective the filter is then larger the pressure differential will be, which will have a detrimental effect on the performance [16], [17]. This differential pressure across the filters, also known as 'delta P' or 'ΔP', will, as the filters become heavily loaded increase, which could be detrimental to their performance, possibly allowing a greater proportion of potential fouling material to pass through [18].

The size of the particles that is permitted to pass through the filter package will affect the type of potential damage to the gas turbine; particles greater than 10 microns will cause erosion whereas those smaller than 10 microns are more likely to cause fouling. Both effects are unwanted when operating a gas turbine and can lead to different problems within the compressor. Filters packages are made up of a series of elements each of which is selected to remove different types of particles by a variety of techniques that include sieving, impaction, interception, diffusion, viscous impingement, and electrostatic charge as described below:

- Sieving removes medium-sized particles by virtue that the space between individual fibres is smaller than the particles flowing through.
- Impaction uses the inertia of heavier particles to trap them once they have impacted the fibres of the filter and is typically found in high-velocity applications.
- Interception is another technique used to medium-sized particles, which catch and retain the particle on impact.
- Diffusion is utilised in low flow rates to remove very small particles.
- Viscous impingement is a type of impaction method but involves a thin layer of oil to collect medium to large particles.

- Electro-statically charged filter are often used to attract particles between 0.01 – 10 microns, this charge is lost over the time of the filter.

The above techniques are incorporated into various types of individual filter stages which are then combined to make a filter package that progressively removes smaller and smaller particles, see Figure 2-4, below.

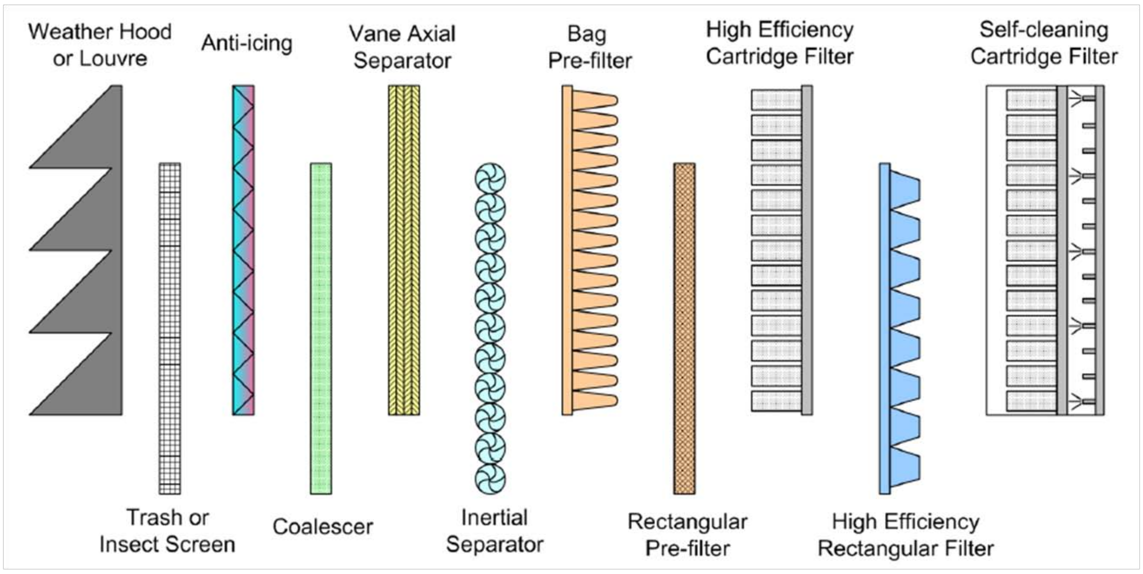

Figure 2-4: Individual stages that can be combined to form a filter package [13]

A large proportion of potential contaminants can be prevented from entering the compressor by means of filters. These are available in a wide variety of forms, some of which can be combined into a very effective barrier for a range of particle types and sizes. The most effective filter types according to [6], [19] are:

- Efficient Particulate Arrestor, EPA: efficiency rating of 85%.
- High-Efficiency Particulate Arrestor, HEPA: 99.95% efficient, stops particle >0.3 microns.
- Ultra-Low Particulate Arrestor, ULPA: 99.9995% efficient removing particles >0.12 microns.

The effectiveness of an improved or more efficient filter system must be balanced by taking into consideration any financial impacts that may be incurred. These range from the initial capital expenditure of an upgraded system, the increased maintenance work and the associated costs, and the increased delta P across the filter, which is in effect a reduction of revenue [20].

A high level of effectiveness will have its own limitations and it cannot be considered to be a complete solution; not only because of the costs involved, both initial and replacement, but also the space envelope required and likely pressure drop experienced downstream.

Whilst not all of the particles that pass through the filter package will adhere to the internal faces of the compressor section, a proportion will. Once the fouling deposits are allowed to build-up on the blades, both rotor, and stator, their surfaces will no longer be at their design point. Gbadebo et al [21] stated that the leading edge profile and smoothness are very influential to the performance. The roughness will increase [2], [6], [22], [23], [24] causing localised turbulence over the aerofoil section, increasing the boundary layer, narrowing of the gas path thus disrupting the airflow, see Figure 2-5. The reduced throat area between the blades will reduce the mass air flow, leading to a decrease in the compression ratio, efficiency, potential power output and ultimately an under-performing gas turbine [25]. If the gas turbine operates in conjunction with a steam turbine, as part of a combined cycle plant, there will be additional losses of power output caused by the reduced mass flow.

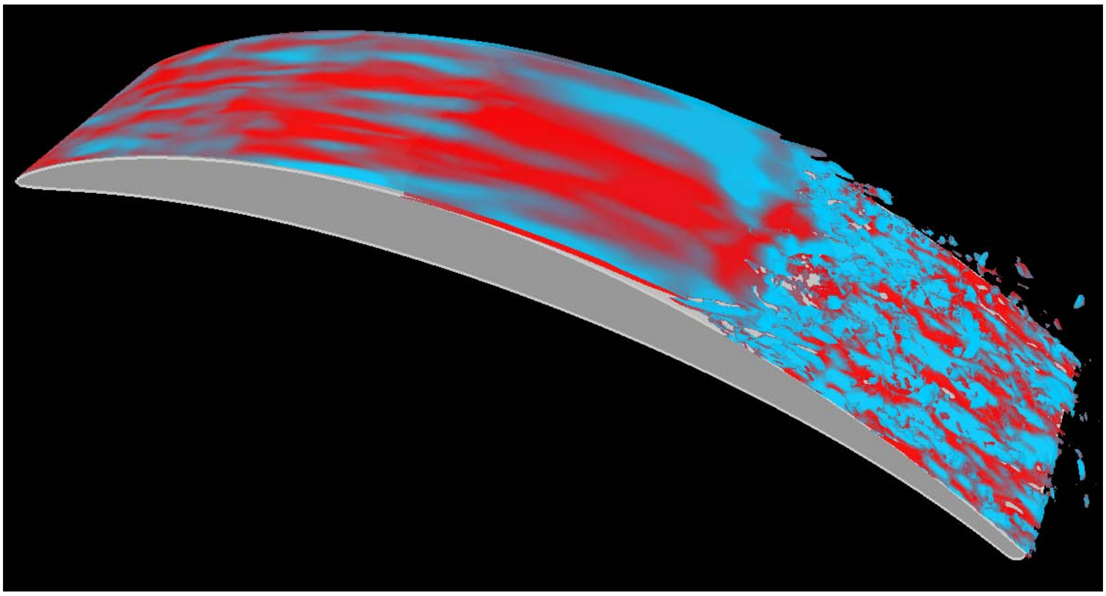

Figure 2-5: Boundary layer separation and turbulence [26]

It is stated by [6], [17], [27] that any losses in performance at the 1st stage will compromise the delivery of air to the 2nd stage. The less than ideal conditions, in terms of angle of attack for the 2nd blade leading edge, will compromise their potential performance. This will continue through the compressor with incrementally small losses accumulating to a significant amount when considering the gas turbine as a whole.

Figure 2-6, is an example of a compressor map, the area below the surge line, running diagonally upwards from the bottom left to top right, defines the safe operating envelope of the gas turbine. It can be seen that the curved vertical lines, called constant speed lines move to the left with a reduction of mass flow thus reducing the maximum possible compressor ratio. Combining these two effects will reduce the available safe operating area, compromise performance and if left unchecked could result in a surge condition [28].

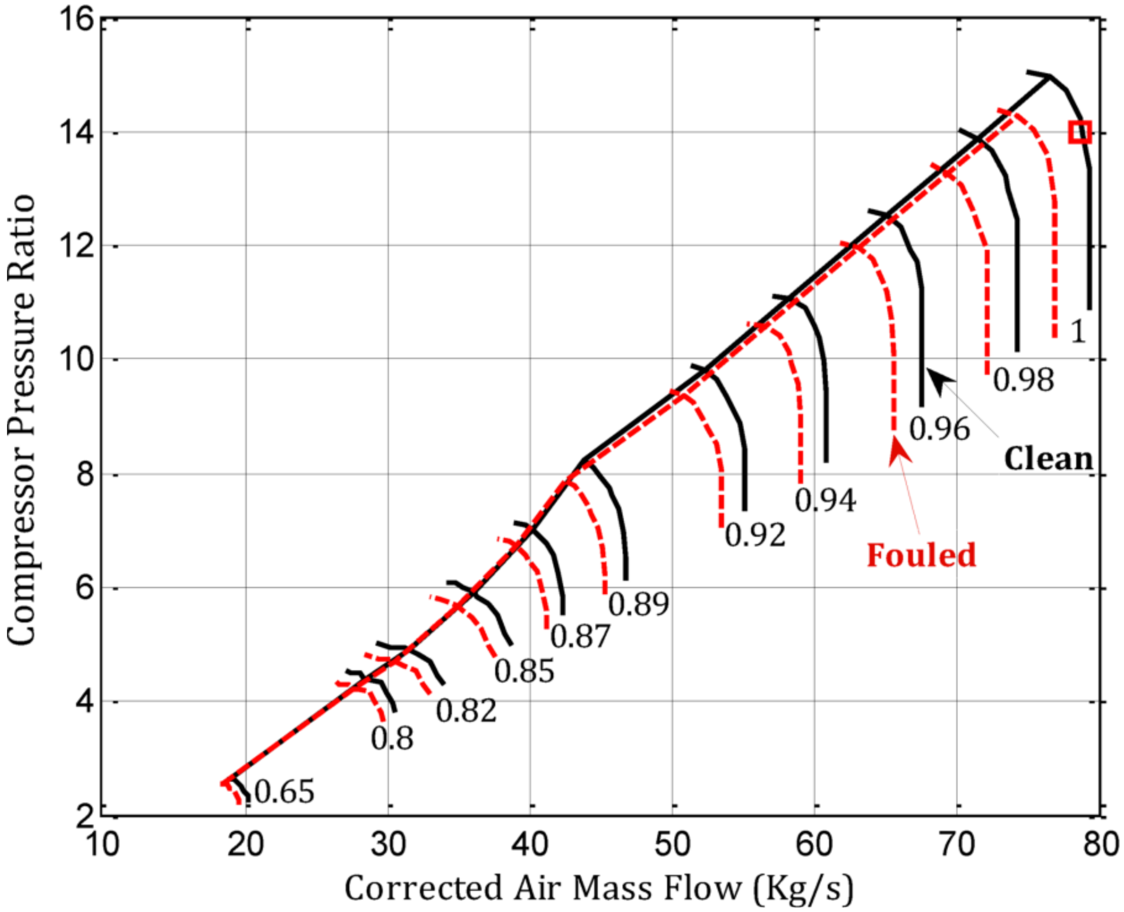

Figure 2-6: Example of a compressor map, clean and fouled states [29]

The effects of this loss of mass flow and reduction of the compression ratio not only lower the operating line of the gas turbine; it also has an adverse effect on the heat rate and the potential power output of the gas turbine, as illustrated in Figure 2-7. This illustrates that if there is a loss of 5% in the mass flow due to the compressor being fouled then the heat rate will increase by more than 5% whilst the loss of potential output exceeds 12%.

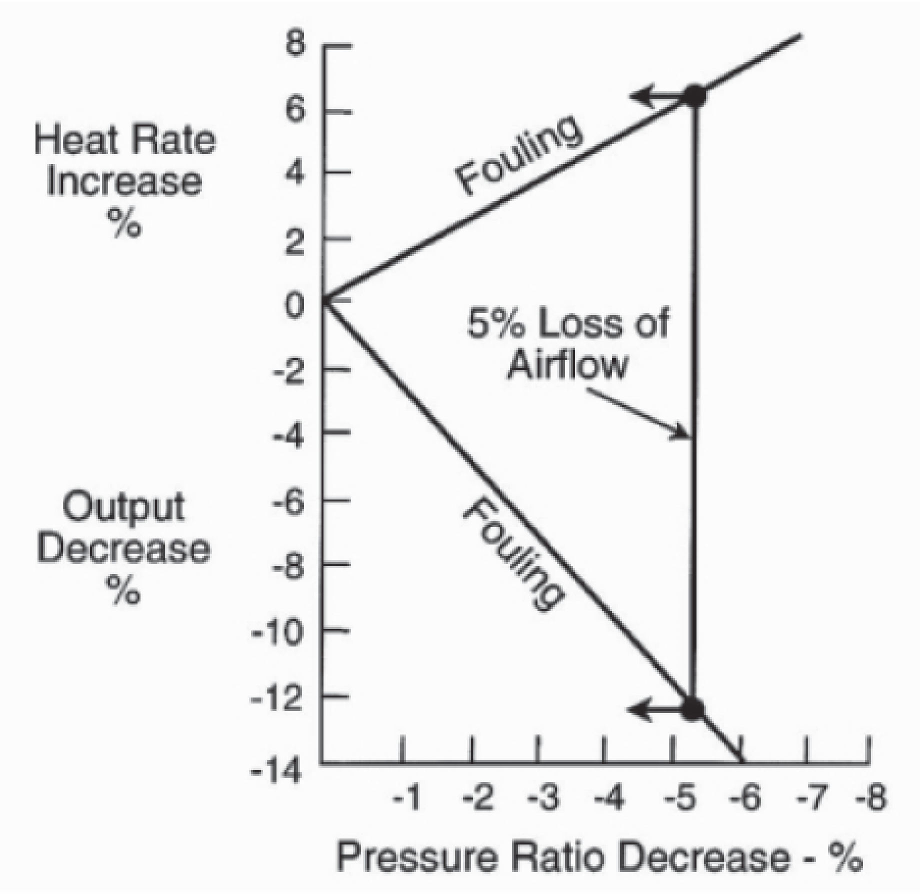

Figure 2-7: Deterioration of GT performance due to compressor blade fouling [1]

The increase in heat rate, caused by operating a fouled compressor section was reported by Hartloper et al [30], this fact is also illustrated in Figure 2-8, which formed part of a presentation during a short course at Cranfield University entitled, 'Gas Turbine Technology for Operations and Maintenance Engineers', in November 2016. The 'BLUE' line shows that when a gas turbine is operating with a clean compressor at base-load, the maximum turbine exit temperature or TET, permitted by the controlling system to ensure safe operation, also permits the production of the rated power output, 50MW; however when the compressor is fouled the TET limit is reached before GT reaches its maximum power output. If the gas turbine is matching the demand placed upon it by the customer this 'lack of power output' may not be noticed by the operator but, as the 'RED' line illustrates, there are consequences, namely that of an increased heat rate and operating closer to the TET limit.

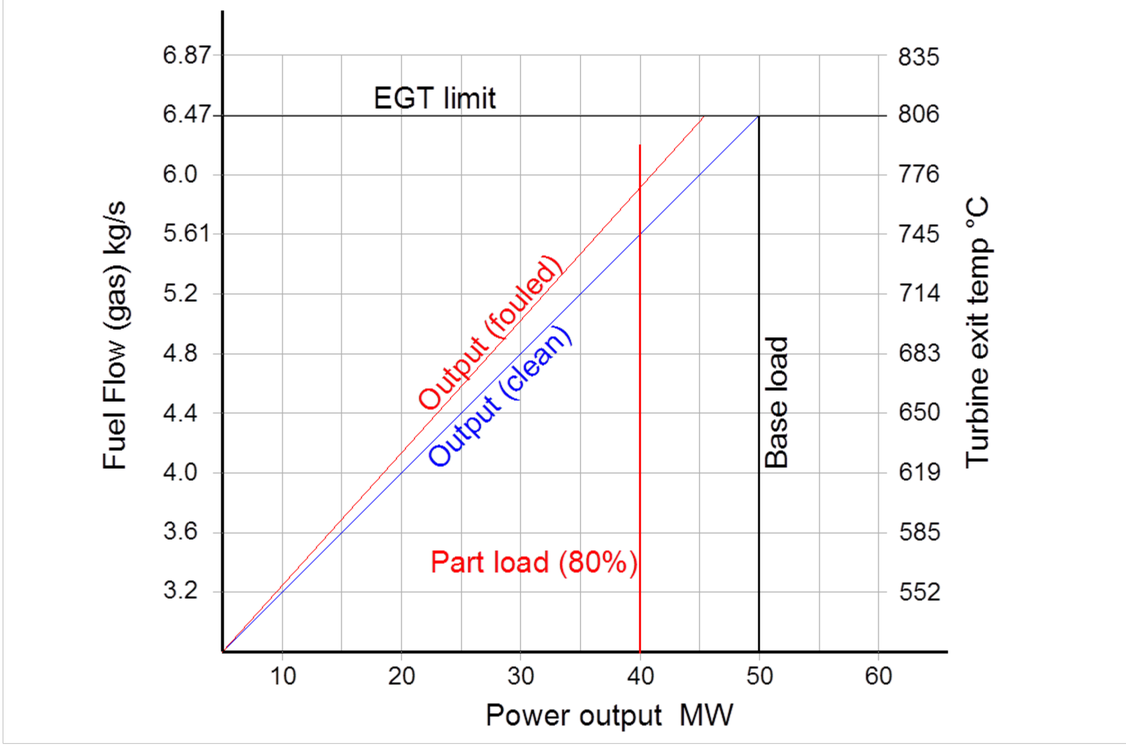

Figure 2-8: Degraded performance of fouled compressor [31]

If the gas turbine was operating with a fouled compressor and therefore with a reduced mass flow, but still had to meet the demand placed on it, the firing temperature would have to be raised to compensate. The effects of this increase in the firing temperature would have an additional impact upon the maintenance factor that would have to be applied. The graph in Figure 2-9, displays what a change in the firing temperature, in ^{o}F, above normal base-load condition would have on the maintenance factor when applied to the life of the turbine blades or 'buckets'. If the gas turbine operated at for one hour at 80^{o}F higher firing temperature, in terms of turbine blade life, it would equate to six hours of normal base-load operations [32].

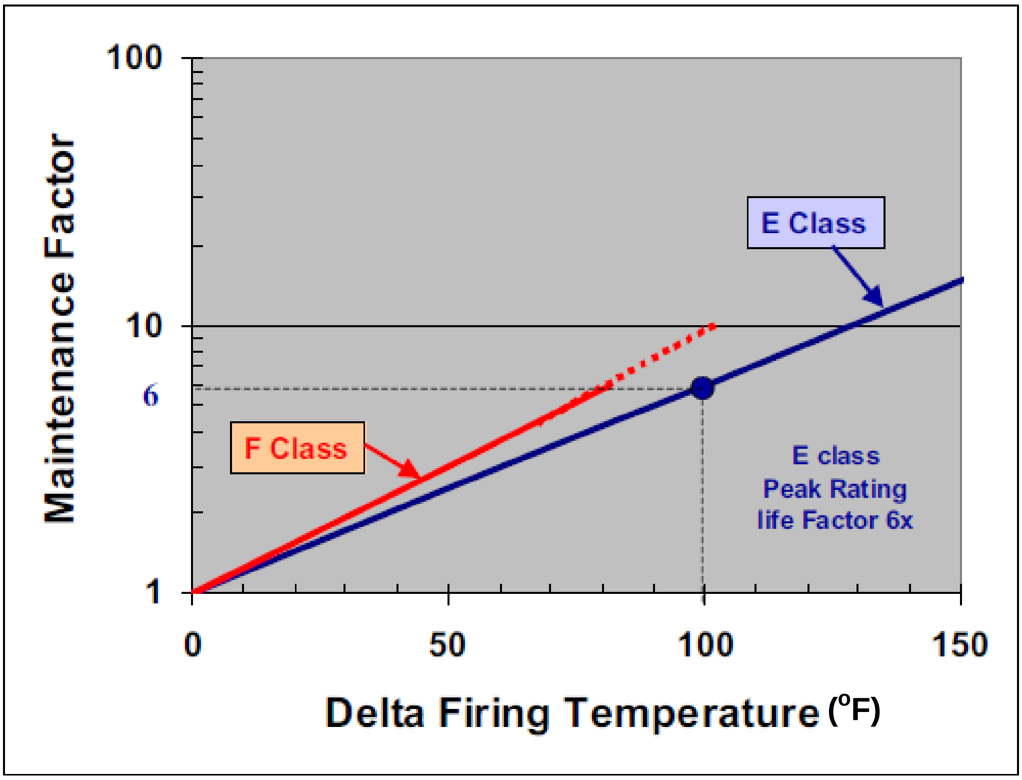

Figure 2-9: Bucket life firing temperature effect [1]

2.3 Compressor Washing

It has been stated by Tarabrin et al [33] that "regular washings (cleanings) of compressor blades are the most effective way to resist fouling" and in particularly recommended "the optimised regime of on-line and off-line compressor washing", a fact that was reiterated by Mund et al [25] where it is stated that on and off-line washes complement each other and that on-line washes can slow down the rate of fouling and extend the off-line wash interval. To remove this fouling from the compressor of gas turbine a number of methods have been established and made available for the operator in an effort to restore the performance, they comprise of hand cleaning, crank/offline washing, and online washing. A number of these procedures require the gas turbine to be removed from operations, stopped and cleaned before being returned to service and range from the manually cleaning each blade to rotating the gas turbine using the starter motor or generator and injecting the cleaning media directly into the inlet plenum and allowing the airflow to carry it into the compressor section. Alternatively, depending on the level of fouling and cleaning media used, the cleaning can be carried out whilst the gas turbine is running at full or part-load.

Hand cleaning is normally carried out during a major overhaul or when there has been a large loss of performance possibly due to oil contamination which has exacerbated the rate of fouling beyond acceptable levels. It involves removing the top half casing of the compressor to expose the rotor and possibly removing the entire rotor section which is not only time consuming but also very labour intensive, as see in Figure 2-10, and often involves the use of solvent-based cleaners.

Figure 2-10: Hand cleaning compressor blades (Courtesy of R-MC Power Recovery Ltd)

Crank washing allows the gas turbine to be rotated without firing and at relatively slow rpm's, by means of the starter motor or generator, this does, however, have an adverse effect on the life of the starter motor or generator by increasing the number of starts per operational hours [34]. Due to 'slow' rotational speed, typically 10% that of normal production operations and unfired nature of operation the conditions experienced inside the compressor are much less severe than during normal operations; this produces the potential for a much more thorough cleaning process and also the ability to use either solvent or aqueous based cleaning fluids.

Any gain in performance from carrying out an off-line wash on a large gas turbine needs to be balanced against the loss of revenue, in particular for the case of a power generator. When operating a large gas turbine there is a protracted period needed for cooling, to avoid thermal shock prior to the wash, the wash and rinse cycles along with bringing the gas turbine back into service. A study by Yang et al [35] noted that each additional start will have an adverse effect on the operating hours and subsequently reduce the interval between maintenance interventions. Furthermore, if the gas turbine is operated in conjunction with a steam turbine the loss of revenue from exported electricity might increase by a further 50% of the gas turbine itself [19], [36], [37]. In field tests reported by Haub et al [34], it was found that the performance losses in just 1 month had also meant the loss of revenue for a 6 hour period that was necessary when the gas turbine was shut down to carry out an off-line wash.

Online cleaning refers to the cleaning of the compressor whilst the gas turbine is at full or part-load operations and can be used with both solid and liquid cleaning agents.

Solid cleaning media, such as nut shells, which utilise the 'impact' method to loosen the fouling, has become less popular because it can have a detrimental effect on the internal components, like erosion and the blocking of air passages. The erosion occurs mainly on the leading edges of the blades where it alters their profile and weakens the structure, the blocking of the air passages is predominately at the 'hot end' of the gas turbine where they are used to cool items such as the turbine blades and allow them to withstand the ambient temperatures.

Liquid cleaning agents can range from water-based solvents to those containing surfactants, surface active agents, with the difference being how they break down the fouling. A solvent will dissolve those that it is compatible with and the possibility of relatively large sections of fouling to become free and damage latter stages of the compressor, whilst a surfactant breaks down the fouling chemically back into its component state and size.

Focusing on online compressor washing as the least invasive method to the day-to-day operations of the gas turbine and the one that can extend the period between crank/offline washes if carried out successfully there are a number of points that need to be considered with regards to the equipment and fluid [36]. A comparison between the rates of degradation in turbine power can be is shown in Figure 2-11, and highlights that allowing the compressor to become fouled can lead to a huge loss in potential output before the situation is rectified with an off-line or crank wash.

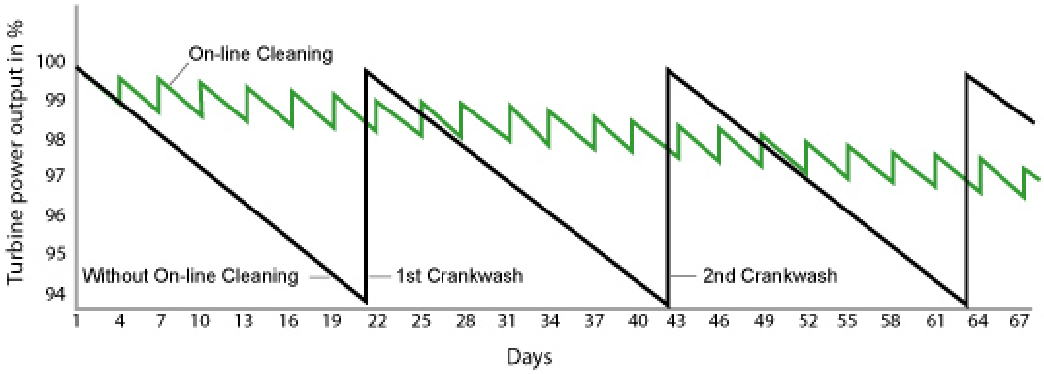

Figure 2-11: GT performance losses with different wash regimes [38]

The frequency of the online washes should be such that it keeps pace with the rate of fouling and therefore able to remove all of the recoverable losses that have accumulated since the previous online wash [39]; if this is not the case then the fouling that remains will allow any newly ingested contaminants to build up at an even greater rate which would lead to ever-increasing losses, ultimately require an offline wash to re-establish the performance. If the fouling is permitted to continue at a rate faster than the washing frequency can remove it, the only way to restore all the lost performance would be to carry out a crank wash possibly a hand clean.

The rate of fluid injection must also be controlled as mentioned by Mund et al [40] so that an injection rate of below 0.2% of the gas turbine’s air mass flow is considered to be acceptable and should not exceeded.

The injection equipment should be able to produce the correct sizes of droplets so that that can cope with the harsh environment within a compressor during normal operations because droplets of the incorrect size will either have little or no effect or may even cause damage. Droplets that are that are too small will not have sufficient inertia to penetrate the blade boundary layer and therefore have no cleaning value as they will not contact the fouling; conversely those that are too large may be centrifuged to the outer casing and have little or no cleaning effect or even alter the aerofoil profile of the blade due to erosion on the leading edges of the blades. Additionally, the droplets must be presented in such a way that they are able to cover the entire frontal area of the compressor and not coalesce on the inlet plenum, bearing support struts and casing which again would be a waste of fluid. The use of computational fluid dynamics, CFD, can assist with the correct positioning and number of nozzles to maximise the effective use of the wash fluid; evidence of this can be seen the Figure 2-12 which was produced by D. Fouflias at Cranfield university during his investigations into injection simulations into industrial gas turbine intake.

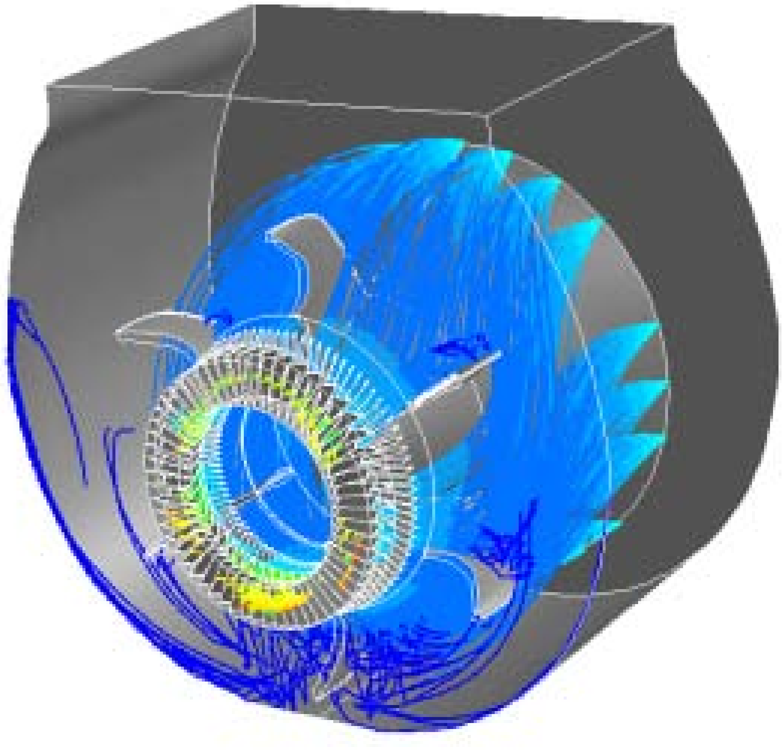

Figure 2-12: CFD of GT inlet air duct and airflow simulation [41]

The fluid must have the properties that will allow it to be effective against a wide range of deposits, both organic and inorganic, permit it to remain in a fluid state throughout the compressor length regardless of the changing conditions in terms of pressure and temperature and be non-aggressive to the materials inside the gas turbine.

The effects of compressor fouling will be evident because of a fall in the performance of the gas turbine, this could be in a variety of different ways and depending upon how it is operated will alter how this becomes apparent to the operator. As previously mentioned the fouling of the compressor will reduce the mass flow, as a consequence of this the compression ratio also reduces, meaning that the quantity of fuel required to maintain the correct fuel ratio must also be reduced; therefore, the turbine inlet temperature will be lower along with the power output. Increasing the amount of fuel in an effort to recover this loss of power output will work, however, this will raise the firing temperature and exhaust gas temperature which, if allowed to continue, would impact on the life of the 'hot end' components and also increase the specific fuel consumption of the gas turbine.

Whichever compressor washing method is selected it is important that it is adequate and effective; if not, then the debris that remains could cause further damage through corrosion which if left unchecked could lead to mechanical failure [8].

2.4 Gas Turbine Performance

It was stated by Back et al [24] that 90% of the overall life-cycle costs of operating a gas turbine can be attributed to fuel and maintenance, therefore, the performance of a gas turbine must be constantly monitored to ensure that the plant is operated at its optimum level. In terms of a power producer the maintenance interventions would ideally be planned to coincide with the periods of low demand and/or the smallest loss in revenue so as to maximise profits Additional constraints that make the task of planning production are the emissions limits that have been sent by governments and which will incur fines if exceeded. It was highlighted by Seydel [42] that optimising and forward planning of electricity production is not a simple task and that improving the thermal efficiency and lowering the heat rate would be beneficial to reducing emissions.

The effects of changes in ambient conditions on the performance of a gas turbine are varied and wide ranging. A gas turbine sweeps a fixed volume of air with each revolution but depending upon the air density the actual mass of air will change, this is as a direct result of the local conditions [43] [44], namely ambient temperature, atmospheric pressure (altitude) and to a lesser extent humidity, which will ultimately affect the performance of the gas turbine. To enable a meaningful analysis the above conditions need to be taken into account to standardise the actual performance of the gas turbine. Ambient conditions that are considered to be the standard to enable GT performance comparison are [45]:

- Outside air temperature (OAT) 15^{o}C
- Atmospheric pressure (altitude), 101.3kPa (sea level)
- Relative humidity (RH) 60%

The effects on the uncorrected power output of a gas turbine due to changes in the ambient temperature and atmospheric pressure can be clearly seen in Figure 2-13.

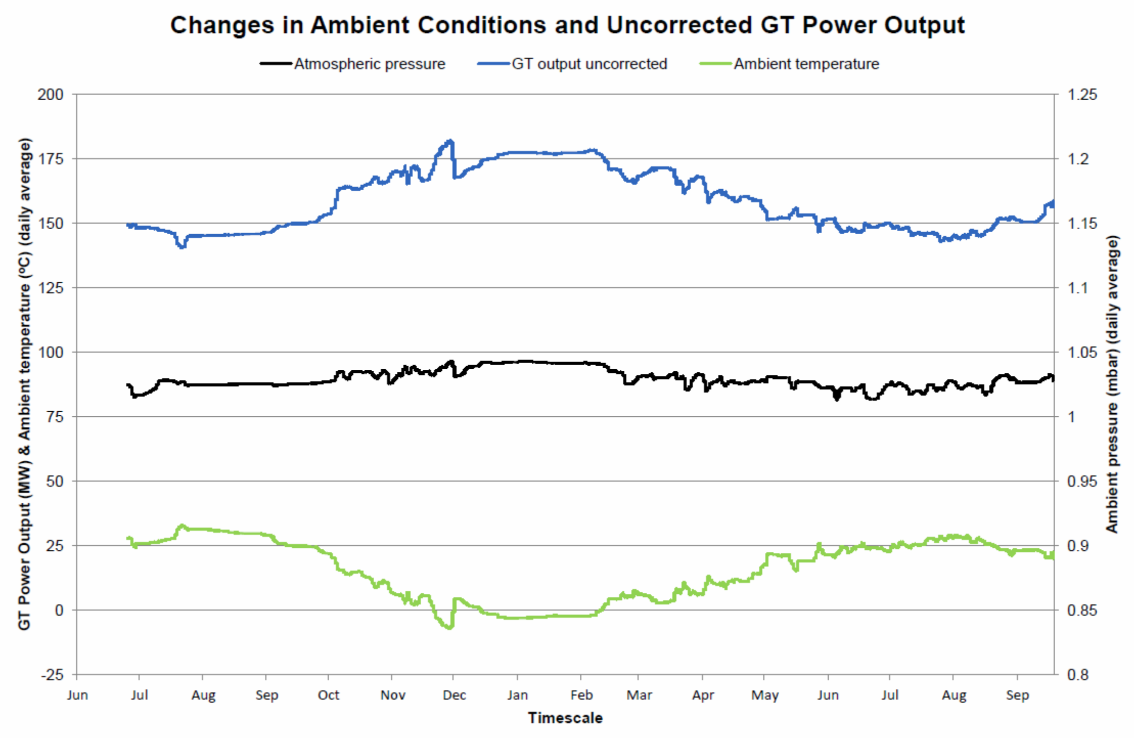

Figure 2-13: Changes in Ambient Conditions and Uncorrected GT Power Output

When the ambient temperature is low, the uncorrected power output increases. The power output also increases when the atmospheric pressure is higher. The relative humidity of the air drawn into the GT also has an effect on the performance, however, this is to a lesser extent and has not been included for clarity.

Correcting the performance figures to reflect the local site conditions permit the relative GT performance to be directly compared with that of similar units in other parts of the world and gas turbine manufacturers produce graphs, such as the one shown in Figure 2-14, to highlight the variances not only in output but also heat rate, exhaust flow and heat consumption that can be experienced.

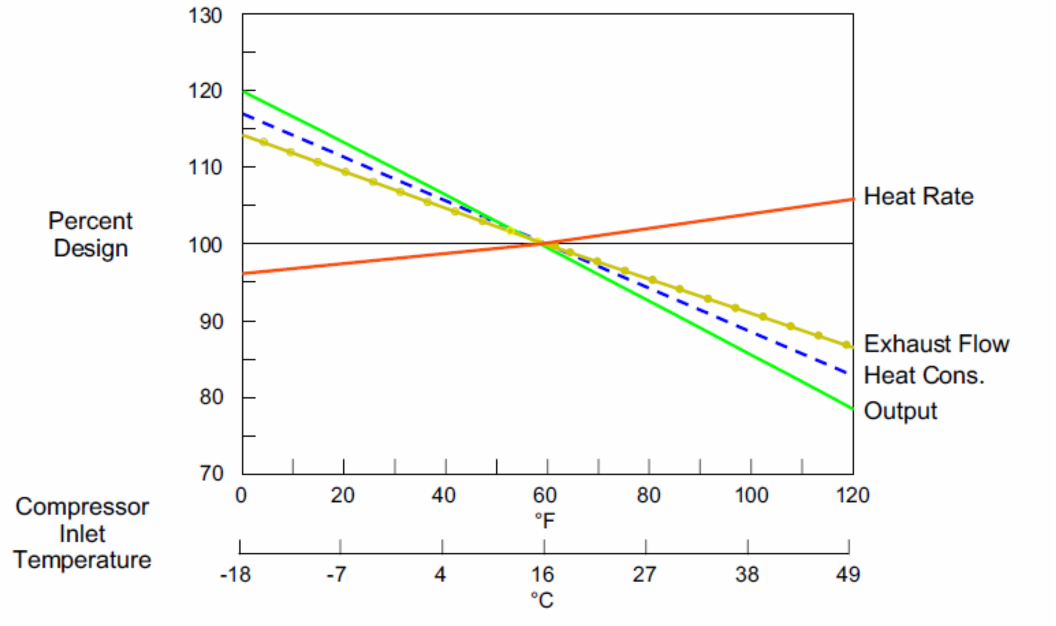

Figure 2-14: Effects of ambient temperature [46]

Changes in ambient conditions affect the GT performance in different ways and varying degrees, these are from the most to the least influential [47]:

- An increase in ambient temperature would reduce the air density and consequently the mass flow which would cause a drop in power output and rise in heat rate if the GT was operating at a constant speed and exhaust gas temperature (EGT), the reverse is also true.
- When the atmospheric pressure rises the air density is increased which would cause a rise in power output if the GT was operating at a constant speed and exhaust gas temperature (EGT), once again the opposite is true.
- The effects of relative humidity (RH) on the GT performance are not so straightforward due to the fact that at low ambient temperatures a high RH does not mean that there is a large amount of water present, whereas at high ambient temperatures the percentage of water by weight can be high. Therefore, there is negligible effect on GT performance by changes in RH at lower ambient temperatures with an increasing influence as the ambient temperature rise [48].

To establish how well a gas turbine is performing there are a number of methods available, requiring different parameters to be recorded on a regular basis and each with varying degrees of accuracy and relevance depending upon the operator's requirements.

- Power output such as electrical/mechanical/steam
- Heat rate or specific fuel consumption
- Compressor ratio
- Compressor efficiency

Focusing on only one aspect will not suffice when examining data from a gas turbine as a means to understand its performance; it is crucial that a combination of multiple parameters is considered.

2.5 Summary

To summarise it has been shown that degradation of performance of gas turbines due to compressor fouling is not something that can be stopped completely; rather it is a ‘fact of life’ when operating gas turbines, one that can be managed through a variety of different approaches. The effects range from a relatively small and short-term drop in output, corrected by carrying out an on-line compressor wash whilst still at base-load; through to a situation where accumulative fouling has been allowed to continue until the gas turbine has to be shut down and undergo a major overhaul. Some of the methods available to operators to reduce the effects of compressor fouling are the replacement of filters on a frequent basis, upgrading the filter types or the instigation of routine on-line compressor wash regime.

There is, however, a requirement for the operators of gas turbines to be fully aware of the implications that certain events may have on the performance of their GT’s, how to extract the relevant data from the control system, interpret it correctly and thereby manage the situation to maximise efficiency. It became apparent during this study that some operators had a tendency to focus on a single key performance indicator when monitoring the relative performance of their gas turbines; whilst this was not completely incorrect, it could be argued that it did ignore other relevant, readily available and important information. By looking at a variety of aspects of the GT performance and combining them in a structured manner, will result in a more rounded and complete assessment being made available thus enabling better decisions to be made regarding site operations.

3 Methodology

3.1 Trial structure

The requirement for the trial was initiated by the operators, who, in an effort to reduce site operating costs looked at all aspects within their control. The trial was broken down into 3 sections; firstly the planning and preparation, followed by the data handling and finally a review and refinement section; the following paragraphs contain the details of what each section covered.

3.1.1 Planning & preparation

Planning for the trial consisted of setting the criteria for the trial, selecting the gas turbines involved and the variables to be used to provide results for comparison. The criteria agreed upon were broken down into differing compressor washing regimes, the parameters required for a meaningful analysis and the frequency of recording of the parameters selected. The various different on-line compressor washing regimes included on & off-line washing on one GT against off-line washing only on another, whilst the second half of the trial compared on & off-line washing using different concentrations of wash fluid. The frequency of on-line washing was set to be every 50 hours +/- 4 hours, with off-line washes being carried out on an opportunity basis whenever the GT came out of service, either for maintenance or due to performance degradation.

The most readily available parameter that is typically used to monitor the performance of the gas turbine is the output which is readily available; however, because of the way that it is affected by changes in the ambient condition other parameters are required. These additional parameters allow for calculations to be made to adjust the output and remove the effects of any changes in ambient conditions. The plan was to include other parameters that would enable a more accurate evaluation of the performance data that looked at the conditions immediately before and after the compressor; in addition to the fuel usage and exhaust gas temperature.

To carry out this analysis on the relative performance of a number of gas turbines the type of information required to be recorded on a regular basis is listed below [45]; the frequency of recording was set at every 5 minutes for the duration of the trial:

- GT power output
- GT status signal (base-load/part-load/crank/etc)
- Ambient temperature
- Atmospheric pressure
- Relative humidity
- Pressure drop across inlet filter
- Compressor inlet temperature
- Compressor outlet temperature
- Compressor inlet pressure
- Compressor outlet pressure
- Fuel flow
- Fuel calorific value
- Exhaust gas temperature
- IGV angle
- Shaft speed
- IGV operating range (including base-load angle)

These parameters enable the operational health of a gas turbine to be monitored in a variety of ways and allow the cross-checking of the validity of the data by ensuring that all the parameters are within the expected value range and whether there were any issues with the serviceability of sensors etc.

When recording these parameters it is essential that the unit of measurement is also noted, so that they can be converted where necessary, to ensure compatibility within the calculations, the following units were used in this study:

- Pressures in kilopascals (kPa).
- Temperatures in Kelvin (K).
- Fuel flow in cubic metres per hour (Nm^3/h).
- Correct the gas turbine power output, megawatts (MW), to take into account the fluctuations in ambient temperature and pressure.

- Calculate the heat rate in kilojoules per kilowatt-hour (kJ/kWh).

The final task in this section was the assigning of specific gas turbines to each part of the trial; this along with the sequence of events is shown in the flow diagram below Figure 3-1.

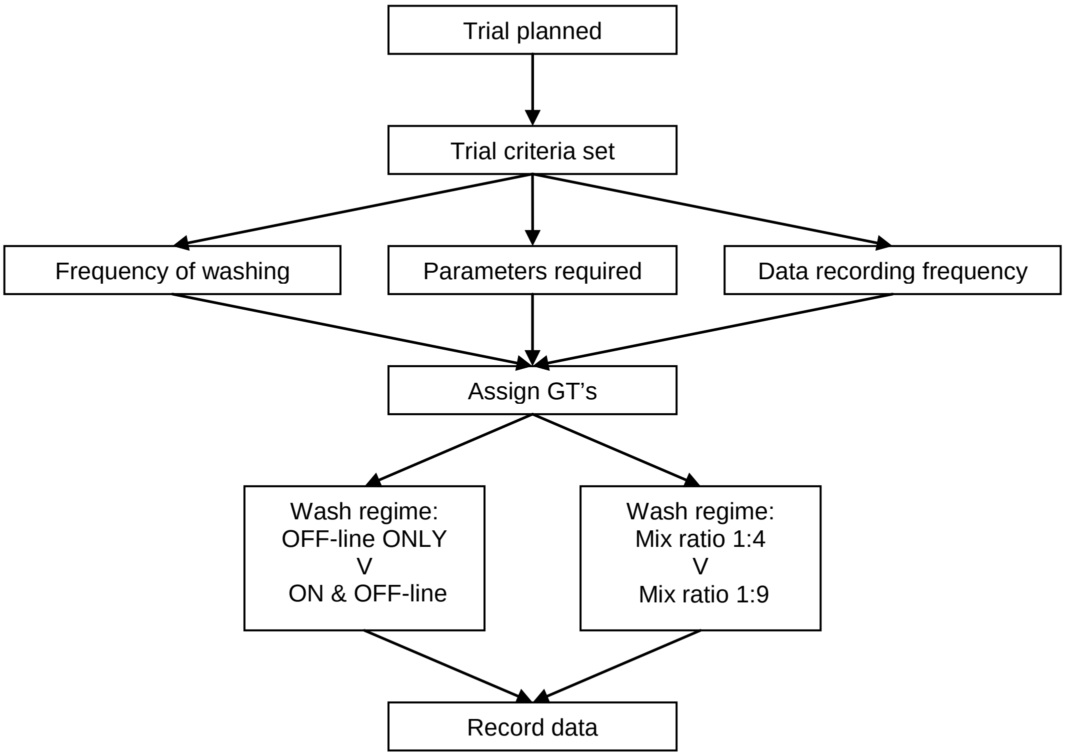

Figure 3-1: Planning & preparation flow diagram

3.1.2 Data handling

This section of the trial began with the receipt of the complete data set for 4 gas turbines, covering over 3½ years and consisting of 383904 lines of data for each GT and encompassing those parameters listed in paragraph 3.1.1. The following table, 3.1 shows the various and wide-ranging number of different GT statuses that were recorded and the number of occurrences, at 5-minute intervals, during the recording period.

Table 3-1: Distribution and quantity of lines of recorded data by GT status

GT status	GT21	GT22	GT23	GT24
Accelerating	1001	760	837	960
Base-load	13638	21038	15313	7907
Blank*	91601	60297	78392	105627
Comms. failure	240	240	240	240
Costing down	284	1192	1447	1822
Cranking	2488	1973	2130	2429
Fired shutdown	605	416	549	689
Firing	0	1	2	4
Full speed no load	230	256	246	238
Loading	36026	38350	37778	33011
Off cool down	3277	571	123	815
On cool down	5936	4672	10618	6560
Out of service	2418	3229	5504	8408
Part-load	190935	214033	193253	182526
Pre-selected load	2	2	1	0
Starting	0	1	0	0
Synchronising	11	12	24	16
Unloading	35141	36825	37358	32481
Warming up	71	36	89	171
Total lines of data recorded for each gas turbines = 383904				

* The status classified as ‘blank’ encompasses all occurrences when there was no specific GT status identified in the recorded data and as a result could not be assigned to any other status, regardless of whether the requirements of the data filters were fulfilled.

The table above provides evidence as to where the GT is operating the most, the majority of time being spent at ‘part-load’ conditions; this is when the gas turbine is operating outside base-load condition but still producing an exportable product, in this case, the electricity of the national grid. However, it can be seen that there is a large proportion of the time when the gas turbine is not exporting due to the nature of the GT status. In an effort to retain only the lines of data that were considered to be pertinent to this study, a number of steps were taken, in the form of data filters, to remove the surplus entries.

Firstly all non-operational lines of data or those with incomplete entries were removed; followed by the selection and removal of data lines that did not meet the criteria associated with the GT and the production of a viable export.

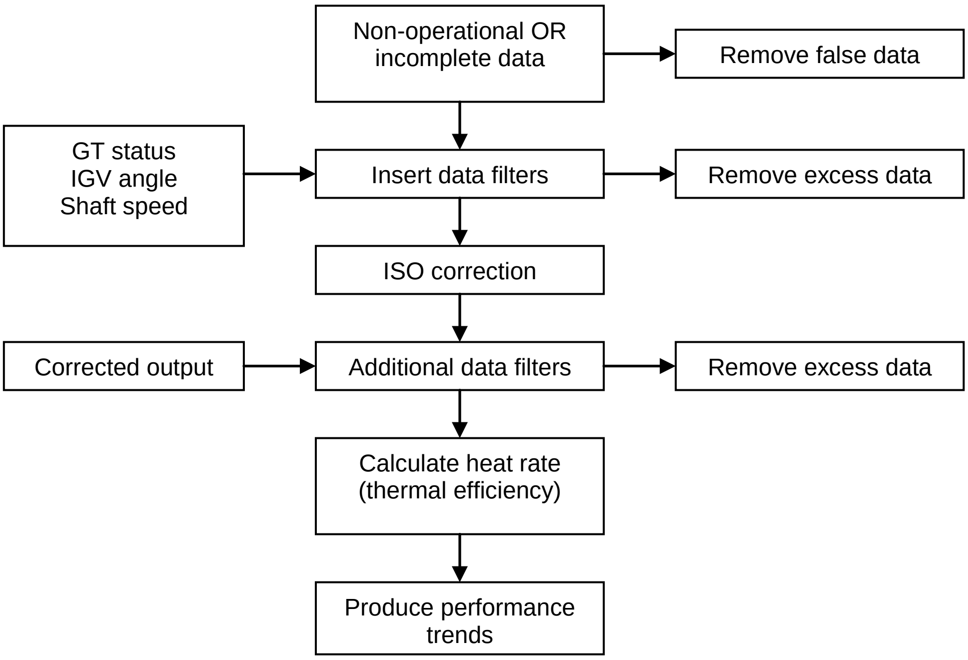

Figure 3-2: Data handling flow diagram

The remaining data was then corrected to ISO conditions so as to remove any effects of changes in ambient conditions, as shown in Figure 3-2. Following this, the heat rate (thermal efficiency) was calculated; combining this with the ISO adjusted data allowed for the performance trends to be produced.

3.1.3 Review & refinement

Reviewing the performance trends provided the basis for this final section of the trial as per Figure 3-3 below; it highlighted the fact that each of the gas turbines was at a different point in its life cycle, a fact that could have thrown doubt on the results. The analysis was therefore refined to remove this problem, as much as possible, by considering only the recorded data from comparable areas in the individual life cycles of each GT i.e. the interval between services. These performance trends were then compared; along with cost-benefit analysis to show the economic benefits that could be associated with on-line compressor washing.

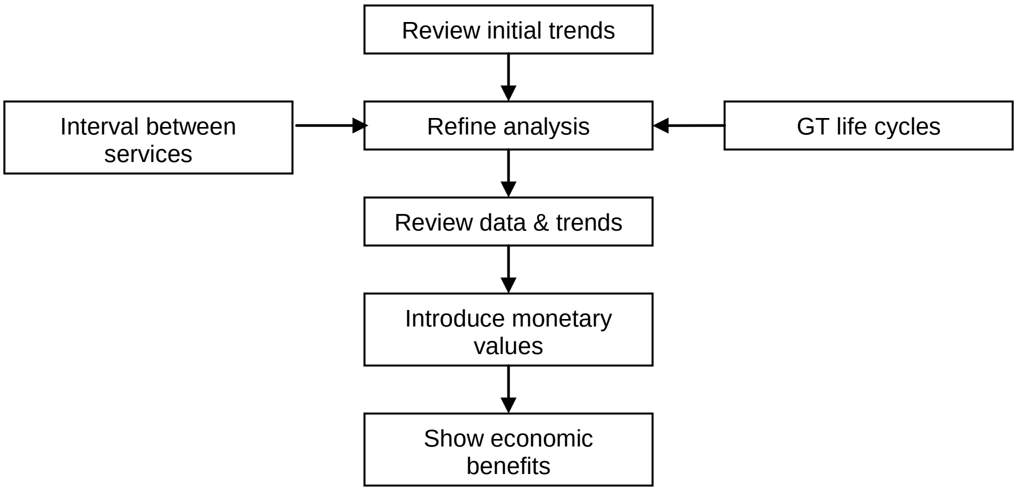

Figure 3-3: Review & refinement flow diagram

3.2 Calculations

3.2.1 Corrections to ISO conditions

Regardless of which method is utilised to define the performance of the GT there is a necessity to correct the values to what would be expected at ISO conditions, i.e. $15^{o}C$, 101.3 kPa & 60% humidity, as previously stated, so that the daily/seasonal fluctuations caused by the differing ambient temperatures, atmospheric pressures, and relative humidity were taken into account.

To enable this, the following calculations were used firstly to take into account for ambient temperature and relative humidity secondly for variations in the atmospheric pressure.

Correction factor for changes in ambient temperature and relative humidity [49].

$$CF_{T+RH} = 2.7048 * 10^{-7} * T_{amb}^{3} + 1.4032 * 10^{-7} T_{amb}^{2} * RH - 1.0725 * 10^{-6} * T_{amb}^{2} - 1.0729 * 10^{-8} * T_{amb} * RH^{2} + 3.7352 * 10^{-6} * T_{amb} * RH - 0.007 * T_{amb} - 1.5464 * 10^{-10} * RH^{3} + 1.1605 * 10^{-7} * RH^{2} + 2.683 * 10^{-5} * RH + 1.0971 \tag{3-1}$$

Correction factor for changes in atmospheric pressure [49].

$$CF_p = 1.4461 * \left(\frac{P}{101325}\right) - 0.4456 \tag{3-2}$$

3.2.2 Heat rate calculation

The heat rate, sometimes known as specific fuel consumption, is a means of establishing the fuel used per unit of power output, in this case, expressed as kJ/kWh, and require not only the fuel flow but also the calorific value of the fuel, usually the lower calorific value is used [50].

$$Heat\ rate = fuel\ flow * fuel\ calorific\ value/power\ output \tag{3-3}$$

3.2.3 Isentropic compressor efficiency calculation

The calculation for compressor efficiency [51] compares the actual difference between the temperature of the air at the compressor inlet and the outlet with the expected difference under 'ideal conditions', i.e. a clean compressor.

$$Comp\ eff = (T2i - T1)/(T2 - T1) \tag{3-4}$$

Before this calculation can be made the 'ideal' outlet temperature has to be established which can be achieved using the compressor inlet temperature, the pressure ratio of the compressor and a constant in the equation below [51]. This constant refers to the ratio of specific heat at constant pressure and that at constant volume which is '1.4' for diatomic gases such as those that make up the majority of air.

$$T2i = T1 * ((P2/P1)\hat{}((1.4 - 1)/1.4)) \tag{3-5}$$

3.3 Data handling & data filtering

A revised way of monitoring the performance of gas turbines must be able to take into account the various different operating regimes and the percentage of time at different gas turbine settings; this should then illustrate both the pro’s and con’s of each, any advantages of compressor washing or even change in operating regime. Gas turbines are more efficient when operating at baseload conditions, if they are not being utilised at their most efficient setting then the reason for this needs to be identified; this may, of course, be beyond the control of the operator.

Under ideal conditions and if the site was consistently operating at base-load, the simplest way to analyse the performance of a GT would be to establish a ‘baseline’ set of values after the GT has just been installed, undergone an 'A' level service or the compressor overhaul has just been completed; this could then be used to compare with the GT's performance at a later date, with any deviation being easily noticed. It must be noted that due to seasonal variations in ambient conditions and demand from the grid the trends of some recorded parameter may fluctuate in a similar fashion to that of a ‘sine wave’.

To simplify the data and remove the lines which could be considered erroneous, that related to transient points of the gas turbines operations or from times when a viable power output was not being produced, a number of data filters would need to be introduced, they related to shaft speed, inlet guide vane angle and generator output above a certain level. The remaining data could then be categorised by GT status to understand the breakdown of the actual operations of each gas turbine recorded data for the different load conditions when the gas turbine was producing electricity.

Comparing the performance of a gas turbine when operating at baseload conditions is a relatively simple one, the power output data has been corrected for ISO conditions, in terms of ambient temperature, atmospheric pressure and relative humidity, then observing the rate of change. Whilst at base-load the gas turbine can be considered to be operating at its optimal conditions thus enabling ‘like-for-like’ comparisons to be made in terms of the different parameters available. However, when operating at part-load this is not the case as there could be a number of different reasons for the gas turbine not meeting the base-load criteria? Therefore ‘like-for-like’ comparisons are no longer possible [52]; e.g. drop in electricity demand, gas turbine operating parameter limitations, site restrictions etc. It is not practicable to compare base-load operations with operation at a different load such as part-load because, both the efficiency and heat rate will be adversely affected by anything below base-load [47].

Once the relative performances for the gas turbines, at base-load conditions, have been established, the time spent at part-load will be included in the calculations to provide an indication of the overall differences. This can then be used as the format for compiling figures for the annual losses and extra cost associated with difference compressor washing regimes.

4 Gas Turbine Engines under Investigation

4.1 Site details and operations

The site study was carried out on data from a combined cycle plant that operated GE frame 7FA type gas turbines, each with its own steam turbine that supplied power to the national grid. The on and off-line washes were all carried out using a centrally positioned, dual high-pressure, wash system, which is an ‘aftermarket’ system that initially replaced the OEM wash equipment on two gas turbines near the turn of the century; at this time the site operated at base-load conditions for the majority of the time and after the first 15 months of operating the replacement system they were able to extend the off-line washes interval and make significant improvements in efficiency and power output. This success was the key to extending the operations using the Atomax wash system onto the two remaining gas turbines in the block; which subsequently led to further wash systems being installed on similar gas turbines within the operator's company.

The site operated the gas turbines under load sharing condition which is when the demand placed upon the company is shared equally between all available machines. On this site, each gas turbine is coupled directly to its own steam turbine by a single shaft. Generally, steam turbines produce approximately 50% of the power output of the gas turbine.

The Atomax dual high-pressure wash system, supplied by R-MC Power Recovery Ltd, utilises high-pressure injection to accurately control the range of droplets produced and ensure that they penetrate the airflow to reach the compressor blades. The following Figure, 4-1, shows that with conventional low & medium pressure systems, with a pressure of no more than 10 bar, the range of the droplet sizes produced is quite wide; a large proportion of these droplets are non-effective because they are either too large or too small. The use of high pressures, along with heating the fluid, allows the distribution of droplet sizes can be narrowed to produce accurately sizes effective droplets. Altering the pressure part way through the injection cycle then targets either the blades at the front or the rear half of the compressor by shifting the size of the droplets to allow for the flashing off of the demineralised water part way through the compressor.

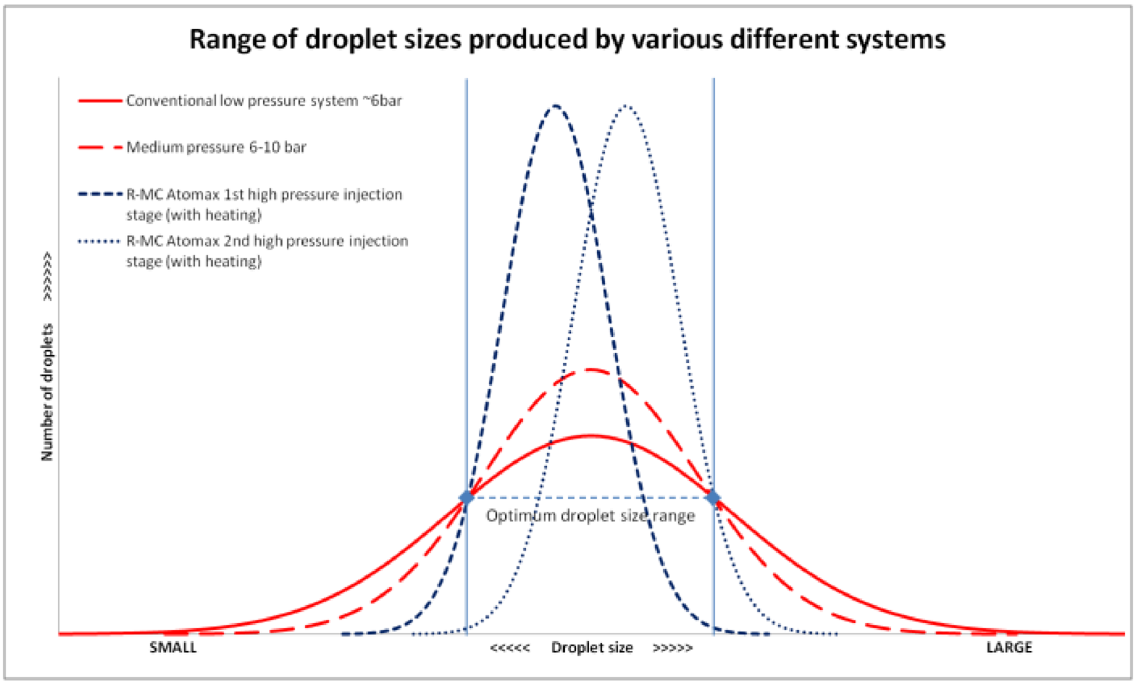

Figure 4-1: Droplet size management (Courtesy of R-MC Power Recovery Ltd)

The system comprises a high-pressure pump injecting heated wash fluid through 9 ‘twin tipped’ nozzles. These nozzles had been installed into the redundant locations originally designed for the OEM off-line wash nozzles which had been previously removed. The use of these locations provided the nozzles with a direct line of sight of the variable inlet guide vanes, VIGV's or IGV's. The photograph in Figure 4-2 shows the atomised droplets being injected between the individual bearing supports during an off-line wash.

Figure 4-2: High-pressure injection (Courtesy of R-MC Power Recovery Ltd)

4.2 Evaluation

During recent years, due to constraints imposed on the company by government policies and the shift away from the production of electricity from fossil fuels to other means previously described, meant that the gas turbines, which usually load share, resulted in the base-load periods of operations being spasmodic, to say the least, and also frequently being shut down when demand fell. The operators then decided to investigate possible ways of reducing operating costs and question the financial benefits of compressor washing which instigated the trial detailed below.

The selection of gas turbines used for the trial was dictated by the operators who were also responsible for the various differences in the wash regimes that were employed and monitoring the adherence to the plan.

The plan split the four gas turbines, into two pairs by matching as far as possible their life cycles and service histories and then compared their relative performances. Whilst this method of comparing the operational performances of one gas turbine against another is not ideal due to the number of variables and tolerances that exist between ‘identical’ machines, in this instance, it was considered to be the most effective way of demonstrating to the customer. Each of the pairs would have one GT that would follow the recommended wash regime and wash fluid mix ratio and act as a ‘control’ GT to compare the benefits if any.

One gas turbine of each pair would follow an on & off-line wash regime every 50 hours +/- 4 using a wash fluid in the recommended dilution ratio with demineralised water of 1:4, would provide a ‘standard’ with which to compare the trial regimes of the remaining gas turbines. The second gas turbine of each pair would follow either an on & off-line wash regime every 50 hours +/- 4 using a wash fluid in the weakened dilution ratio with demineralised water of 1:9 or off-line washing only.

The aftermarket compressor washing system that was utilised during the trial was a dual high-pressure injection system connected to all four gas turbines in a particular block. It consisted of a mixing tank to combine the wash fluid, antifreeze when necessary, with demineralised water automatically in a preset mix ratio; the fluid mixture was then heated prior to injection to ease the production of the correct size of droplets. Once the wash system had reached the correct temperature and permission to inject had been confirmed by the control room operators the injection cycle was initiated, part way through the injection cycle the size of the droplets was altered to enable them to be effective at the rear stages of the compressor by automatically changing the pressure. On completion of the injection cycle, the system switched to divert air to the delivery line to purge it of any remaining fluid.

4.3 Details of trial

The sequence of events for the trial seen in the previous 3 flow diagrams, in Chapter 3, the selection and allocation of each GT was the sole decision of the operators; however, there was a full discussion when it came to selecting the parameters required, the frequency of recording and data filter criteria.

Under ideal circumstances the trial would have commenced immediately after the installation as the condition of the gas turbines would have been perfect but unfortunately, this was not possible. The four gas turbines numbered 21, 22, 23 & 24 were split into the two pairs, A & B, according to their life cycles so reduce any differences between each machine. The first pair consisted of GT’s 23 and 24 that underwent ‘C’ level services* with a month of each other, ‘A’ level services* were then carried out after operating for 15 months. Similarly the gas turbines of Pair B, GT’s 21 and 22, had ‘C’ services within one month of each other, however, the duration of the inter-service period differed before the shut down for the ‘A’ level services with GT21 operating for 23 months whilst GT 22 was off-line almost 13% earlier.

NOTE: The different service interventions nomenclatures, ‘A’, ‘B’ & ‘C’ were provided by the operator, however, the OEM also refers to them as inspections. These vary in depths and cover but are not limited to items in the following summary [3] the work required in each subsequent level is included in the preceding one, Figure 4-3 graphically shows what sections of the gas turbines are covered in the various levels of inspections.

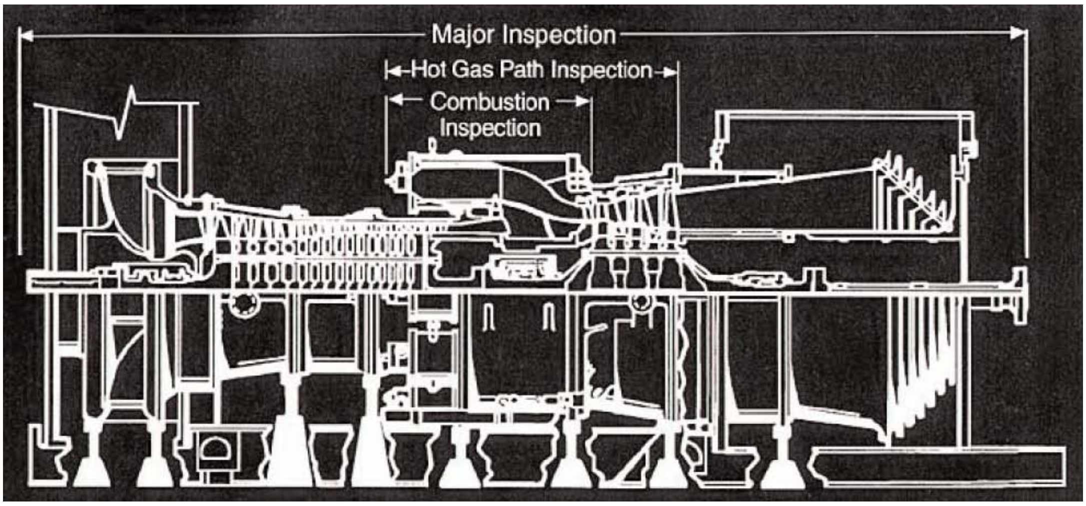

Figure 4-3: Major inspection work scope [1]

- 'A' level is the ‘Major Inspection’ and the most ‘in-depth’; it involves the examination of all the internal components, both stationary and rotating, of the gas turbine.
- 'B' level or ‘Hot Gas Path Inspection’ as the title suggests encompasses parts of the GT that are exposed to high temperatures primarily the combustion and turbine sections, although the compressor blades will be checked using boroscopic equipment and checks for wear and damage on the IGV’s.
- 'C' level is the ‘Combustion Inspection’ and covers the combustion liners and fuel nozzles etc.

The different wash regimes were then assigned by the site operators to the individual gas turbines with GT23 being the only gas turbine that did not undergo any on-line washes:

- Pair A:
    - GT23: OFF-line washes ONLY.
    - GT24: ON & OFF-line washes using designed mix ratio of 1:4 with demineralised water.
- Pair B:
    - GT21: ON & OFF-line washes using designed mix ratio of 1:4 with demineralised water.
    - GT22: ON & OFF-line washes using a weakened mix ratio of 1:9 with demineralised water.

As previously stated under ideal conditions and if the site was consistently operating at base-load, the simplest way to analyse the performance of a gas turbine would be to establish a ‘baseline’ set of values after the gas turbine has just been installed, undergone a major overhaul or the compressor overhaul has just been completed; this could then be used to compare with the gas turbine's performance at a later date, with any deviation being easily noticed provided that the data had been corrected to ISO conditions.

The data collected by the operators on site from the GT control system was saved in ‘Microsoft Excel’ format which enabled it to be arranged and collated into a standard format for each of the 4 gas turbines. The units of measurement were standardised into the following units, pressures in kilopascals (kPa), temperatures in Kelvin (K) and the fuel flow in cubic metres per hour (Nm^3/h). The data, in an MS Excel spreadsheet, received for the entire recording period of 3 years 8 months and the breakdown by GT status is shown in Table 3-1, to an insight into the main areas where the gas turbines were operating.

Initially, the recorded data was broken down by GT status in an effort to understand how the GT's were being operated. What this confirmed was that for the largest proportion of the time they were operated at part-load, in the region of 50%, this was to be expected given that they were load sharing; however, there was a significant difference in the amount of time spent at base-load between the gas turbines.

To rationalise the large amount of data and ease its handling, a number of steps were taken to remove unwanted and/or erroneous entries where there was an incomplete set or line of all the parameters in the form of faults, failures, shutdowns etc. The introduction of a series of data filters were used to ensure that the GT was in a state that could be considered to be producing a viable supply of electricity for export, these were a shaft speed of 3600rpm +/- 0-1%, the speed necessary to produce a 60Hz supply, variable inlet guide vanes, VIGV, angle of $>84.0^o$ indicative of base-load operation; the remaining data could then be grouped by GT status. However it was found that there were three categories of gas turbine status that remained, which are determined by the gas turbine controlling computer, are namely ‘base-load’, ‘part-load’ and the third which encompassed various transient conditions which have been entitled ‘other’.

- Base-load: This is when the gas turbine is operating at its thermal limit, usually the exhaust gas temperature limit.
- Part-load: When the gas turbine is operating outside base-load condition.
- Other: These are all data points that could be considered to be ‘transient’ while the gas turbine transited from one position in its operating range to another like during the process of ‘loading’ or ‘unloading’ etc. It also

included occurrences when there was no recorded GT status and therefore could not be attributed to any other group.

The power output of each gas turbine was corrected to ISO conditions, (15°C, 101.3 kPa & 60% humidity) as previously stated so that the fluctuations caused by the differing ambient temperatures, atmospheric pressures, and relative humidity were taken into account.

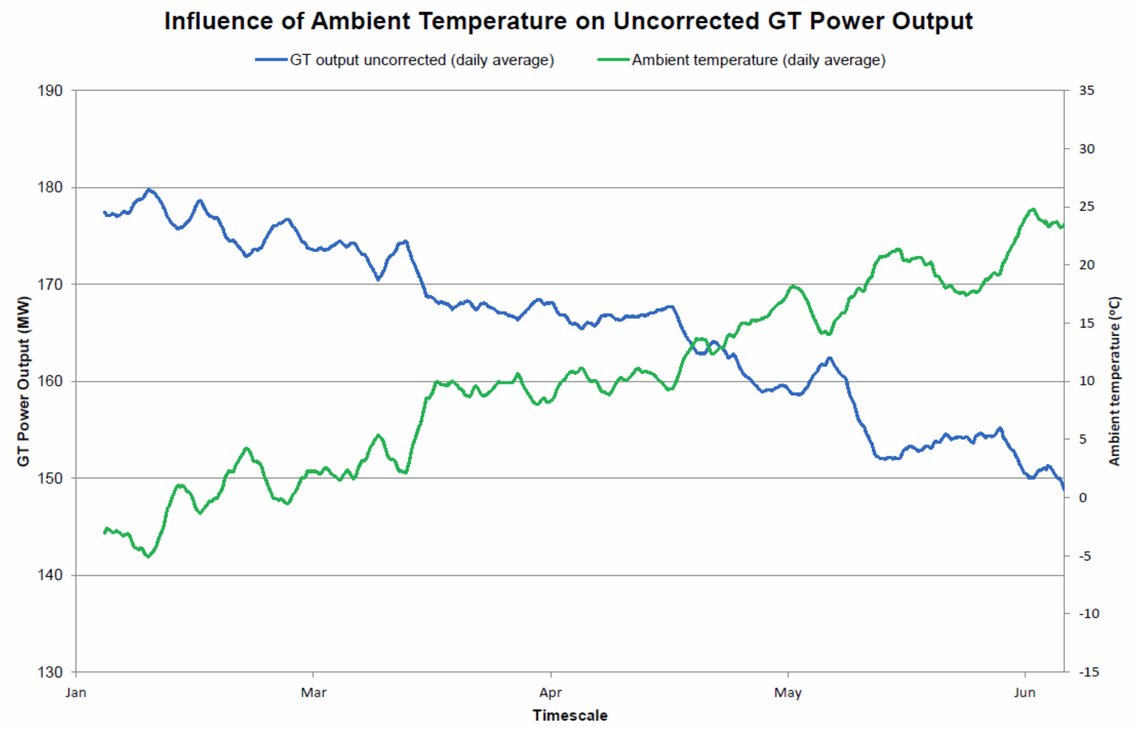

Figure 4-4: Influence of Ambient Temperature on Uncorrected GT Power Output

The graph above, Figure 4-4, illustrates that an increase in the ambient temperature has a negative effect upon the uncorrected power output value this can be explained using the following equation [51], where: ρ is the density, C is the fluid velocity & A is the cross sectional area.

$$Mass\ flow = \rho C A \tag{4-1}$$

This means that if the gas turbine is in a steady state with both the rotational speed and cross-sectional area, ‘C’ & ‘A’, remaining constant, as the ambient air temperature increases the density of the air falls, which results in a reduction in uncorrected power output. Additionally, because of the reduced density of the air, the pressure ratio of the compressor will also fall as is shown in Figure 4-5 where both trends follow similar lines.

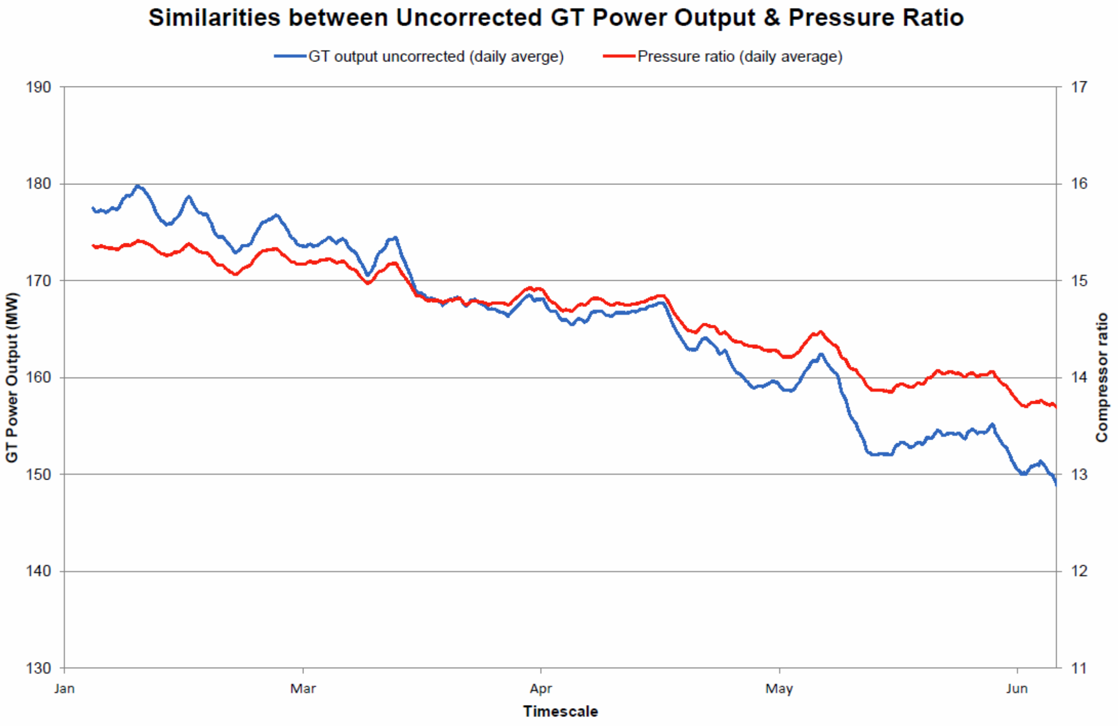

Figure 4-5: Similarities between Uncorrected GT Power Output & Pressure Ratio

Similarly, with differing atmospheric pressures the air density also changes, lower pressures will decrease the air density; therefore with the same steady state conditions as before the mass flow will decrease along with the uncorrected power output. The magnitude of the influence that changes in atmospheric pressure have on the GT power output is secondary to that of the ambient temperature but it is still significant. It can be seen in Figure 4-6 that when the changes in atmospheric pressure are plotted against the same power output trend used in the last 2 Figures, the slight increase in atmospheric pressure does not dramatically affect the output.

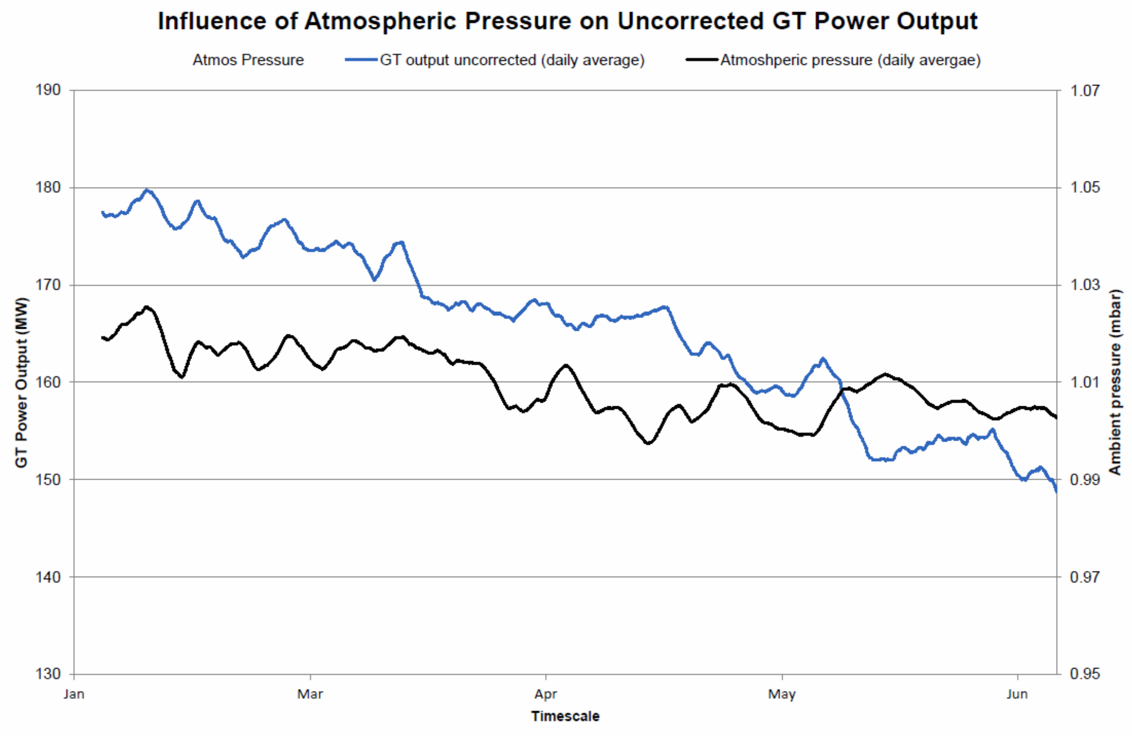

Figure 4-6: Influence of Atmospheric Pressure on Uncorrected GT Power Output

The third and least influencing factor of changes in ambient conditions is that of the relative humidity of the air, which is highly dependent on the ambient temperature and the way in which that alters the capacity of the air to hold water. Increases in the ambient air temperature will increase its capacity to hold water vapour for a given volume, reducing the density of the air.

The results of correcting the power output to take into account these changes in ambient conditions, temperature, pressure and relative humidity are visible in Figure 4-7.

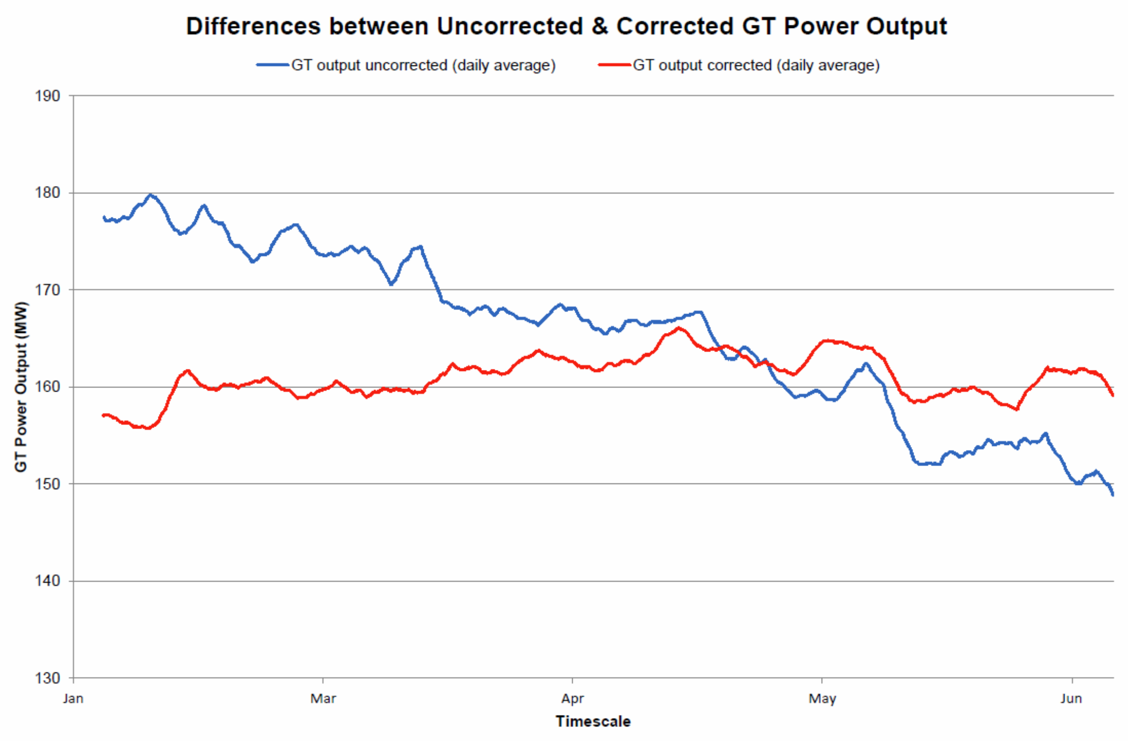

Figure 4-7: Differences between Uncorrected & Corrected GT Power Output

Having calculated the corrected power output figures, a number of data filters were applied to the data as a whole to remove any lines where specific criteria were not met along with the heat rate was calculated kilojoules per kilowatt-hour (kJ/kWh) to determine how well the gas turbine is performing.

To focus the point of investigation still further in an effort to produce more robust results the selection of data was then taken from within a narrower area of GT operations. This involved the period of operations between service interventions of the same level and it was hoped that this would significantly increase the likelihood of the conditions within the GT's being comparable.

5 Results

5.1 Pair A (GT’s 23 & 24): Data split and GT status

As stated in the previous chapter the split of data for the whole period illustrated that the majority of the time was spent at 'part-load' conditions. Although this proportion varied slightly between GT's it was in the region of 50%, the exact figures are displayed in the following pie charts, Figure 5-1 & 5-2. The GT statuses that contributed most in percentage terms have been labeled on the main section of the charts. While many of these could be considered to be transient and therefore not the main area of electricity production, the volume of their occurrence means that they must be considered in order to understand the whole picture of operations.

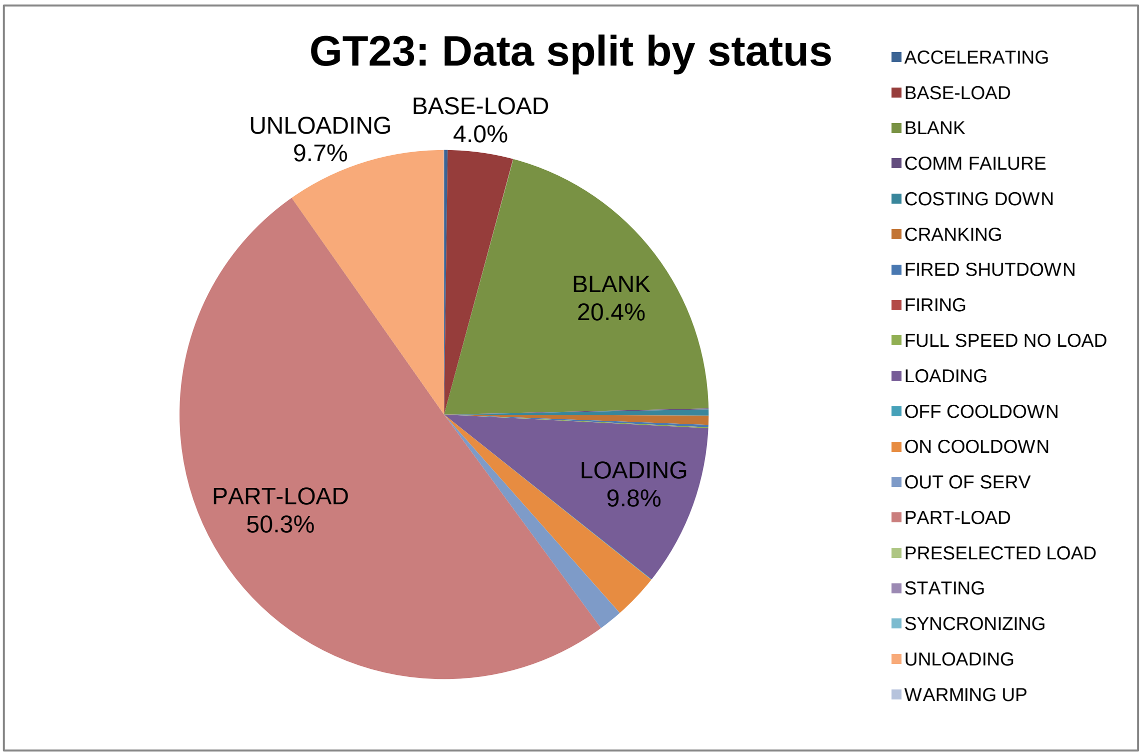

Figure 5-1: GT23 data split by status

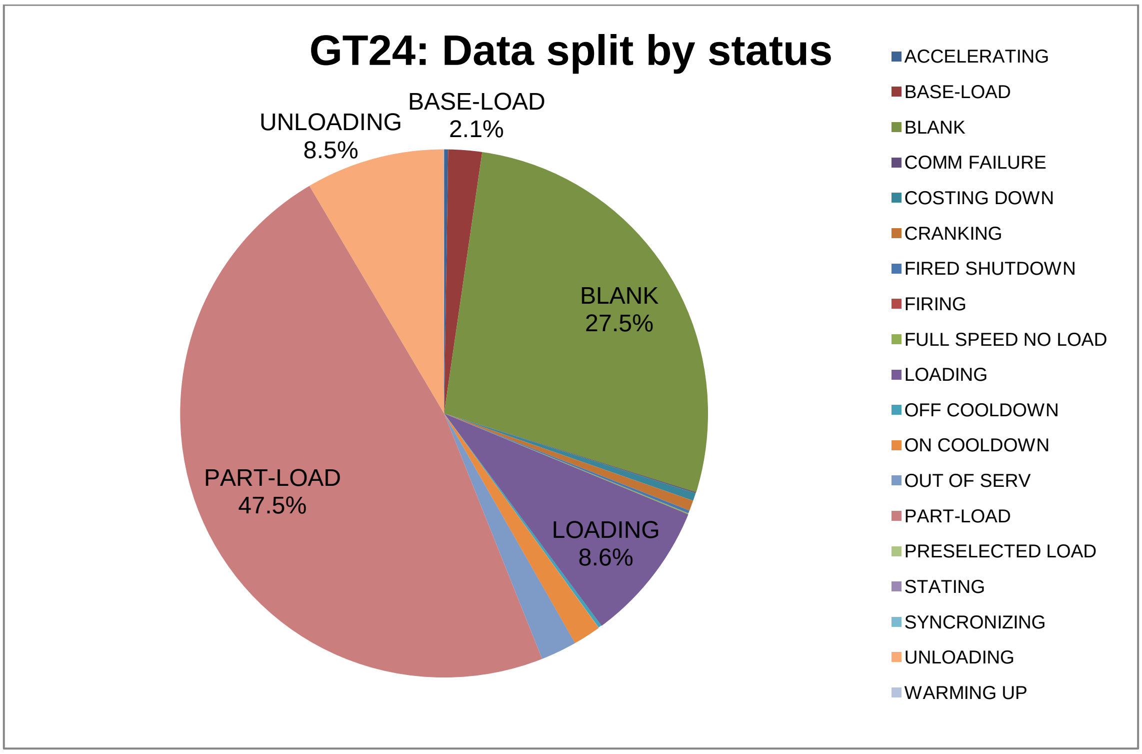

Figure 5-2: GT24 data split by status

Initial observation of the comparison of data split between GT's 23 & 24 shows that there is twice the amount of base-load data for GT23 than GT24; this is despite the fact that the gas turbines were load sharing. This indicates that GT23 was working harder to remain on parity with GT24 in terms of power output.

Although there were indicators of the various statuses at which the gas turbines operated there was a need to identify times of productive operations. The introduction of the data filters as previously stated, to identify occasions when the gas turbines were producing an exportable product, that is:

- a shaft speed of 3600rpm +/- 0.1%, the speed necessary to produce a 60Hz supply.
- a variable inlet guide vane angle, or VIGV angle, of $>84.0^{o}$ indicative of base-load operation, as defined by the site operators.

With these data filters in place, the quantity of usable data was reduced by more than 80%, as shown in the following table and charts.

Table 5-1: Data split following the use of data filters on GT's in Pair A

GT status	GT23		GT24	
	Quantity	%	Quantity	%
Base-load	13223	3.4	7667	2.0
Part-load	35488	9.2	50264	13.1
Loading	3936	1.0	5182	1.3
Unloading	4726	1.2	6553	1.7
Blank	329	0.1	535	0.1
Removed by data filters	326202	85.0	313703	81.7
Total lines of data recorded for each gas turbines = 383904				

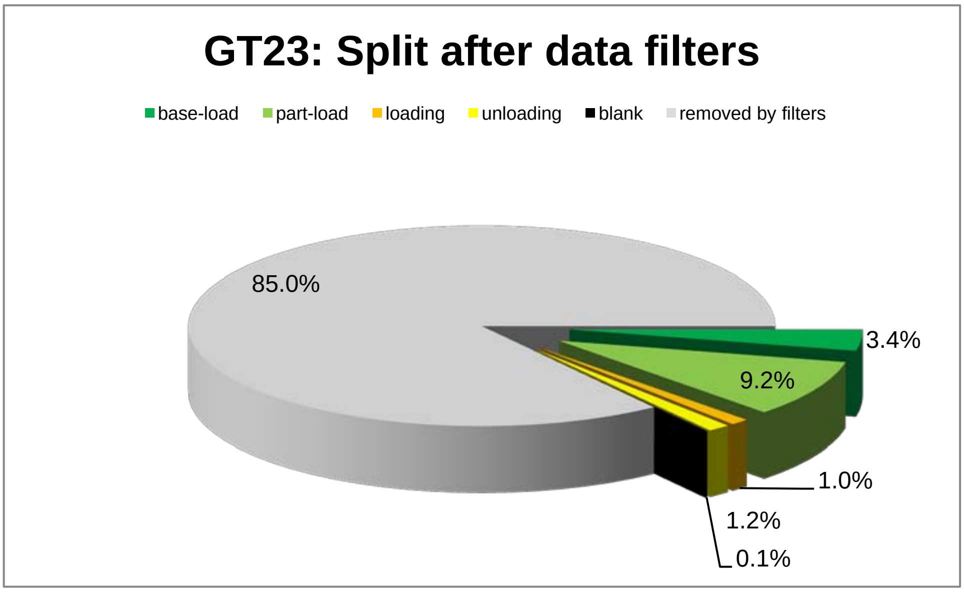

Figure 5-3: GT23 data split after data filters

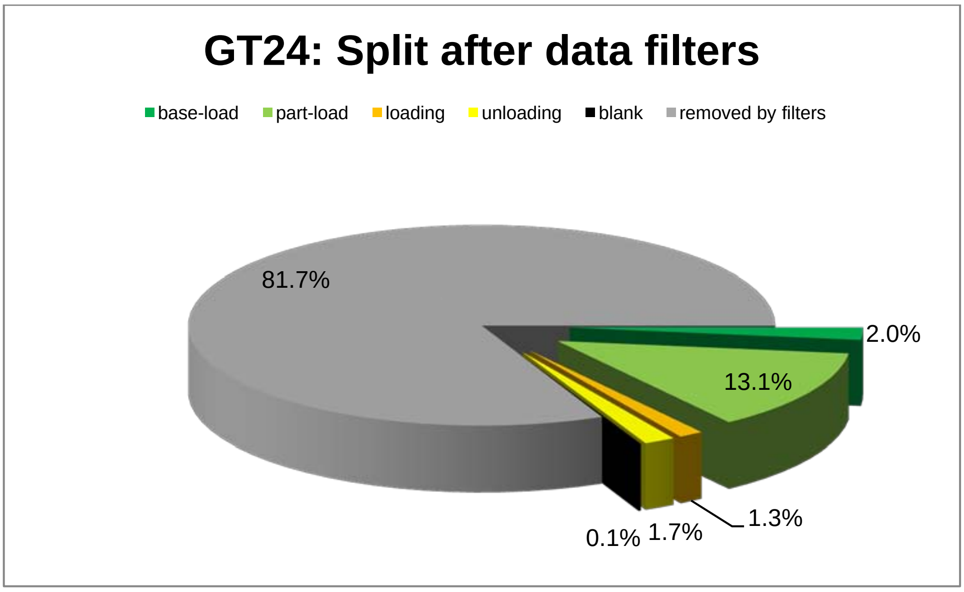

Figure 5-4: GT24 data split after data filters

The data from the transient GT statuses remaining after the introduction of the data filters, 'loading' and 'unloading', along with the non-specified data entitled 'blank' were ignored due to their nature as they were not considered to be relevant. Cumulatively these 3 groups accounted for little of the total data, only 2.3% & 3.1% for each of the gas turbines respectively. Their removal from the analysis produced only a small difference to the overall average values as shown in the following table. These figures showed that GT23 had produced less power output, less economically and at a higher operating temperature than GT24.

Table 5-2: Average values comparisons (total data vs. base & part-load only)

	GT23			GT24		
	Total data	Base & Part-load only	Difference	All data	Base & Part-load only	Difference
GT power output corrected (MW)	157.7	157.7	**Nil**	158.2	158.2	**Nil**
Heat Rate (kJ/kWh)	11413	11399	**14**	11396	11383	**13**
EGT (^{o}C)	627.6	628.3	**0.7**	615.4	616.0	**0.6**

The way of displaying the recorded data from the gas turbine will influence the view and how it could be interpreted. Below are listed a number of the options available with the respective advantages and disadvantages including the ways that this can change as the analysis proceeds. This can be split into three parts, different units for the ‘X’ axis, different ranges of data included in the study and finally selecting either actual data values or the daily average.

Firstly the use of different units for the ‘X’ axis, two examples of this are either based on the date, Figure 5-5, or on the occurrence of recorded data, as shown in Figure 5-6. Both these figures use exactly the same data, from GT24 only in the period from January to March the following year when the ‘C’ service took place and the differences are obvious.

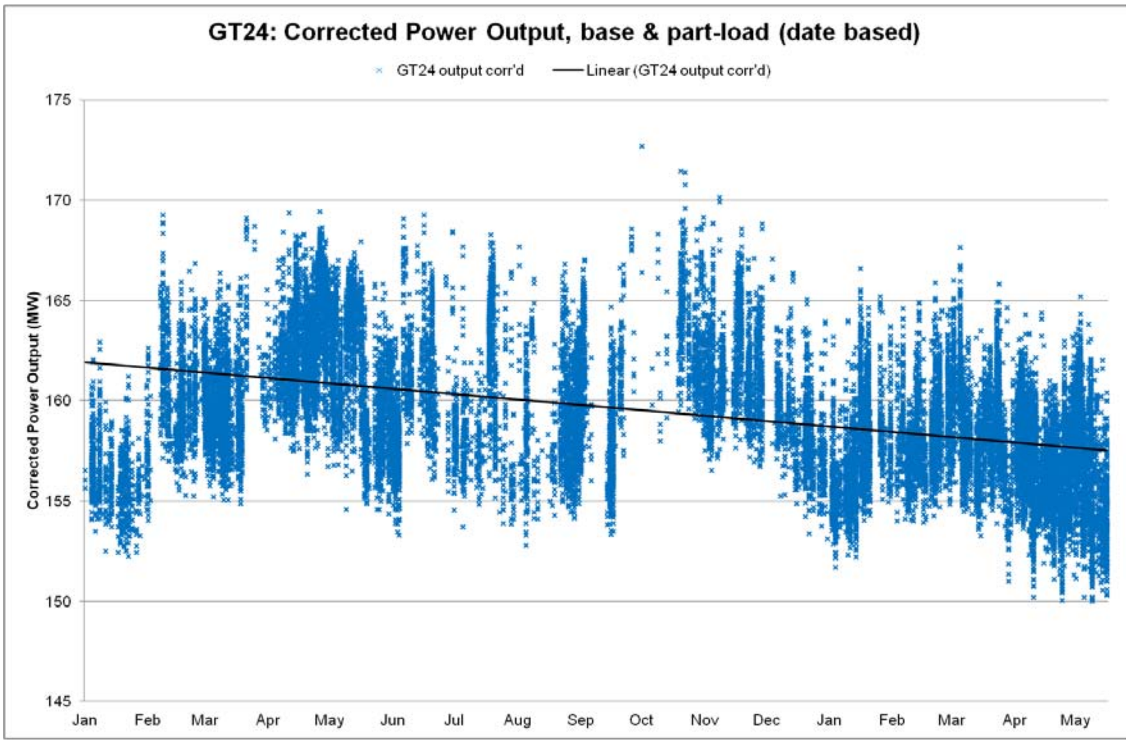

Figure 5-5: GT24, Corrected Power Output, base & part-load (date based graph)

In the date based graph above, there are gaps in the recorded data in places whilst elsewhere a number points of recorded data appear for the same point on the ‘X’ axis. As the ‘X’ axis is linear, there were occurrences when no valid data was available, also others when numerous points were recorded for the same date. Comparing this with the valid data based trend below the opposite is true, as this has a continuous trace of recorded data. This can bias the results one way or another depending upon the amount of recorded data and when it occurred, these differences affect any trend line that is introduced. The solid black trend line in Figure 5-5 has a shallower angle than the ‘dashed’ trend line on Figure 5-6 which indicates a slower rate of degradation. The most straightforward option to provide an easily understood overview of operations and performance that can easily be related to time is the ‘date’ based format.

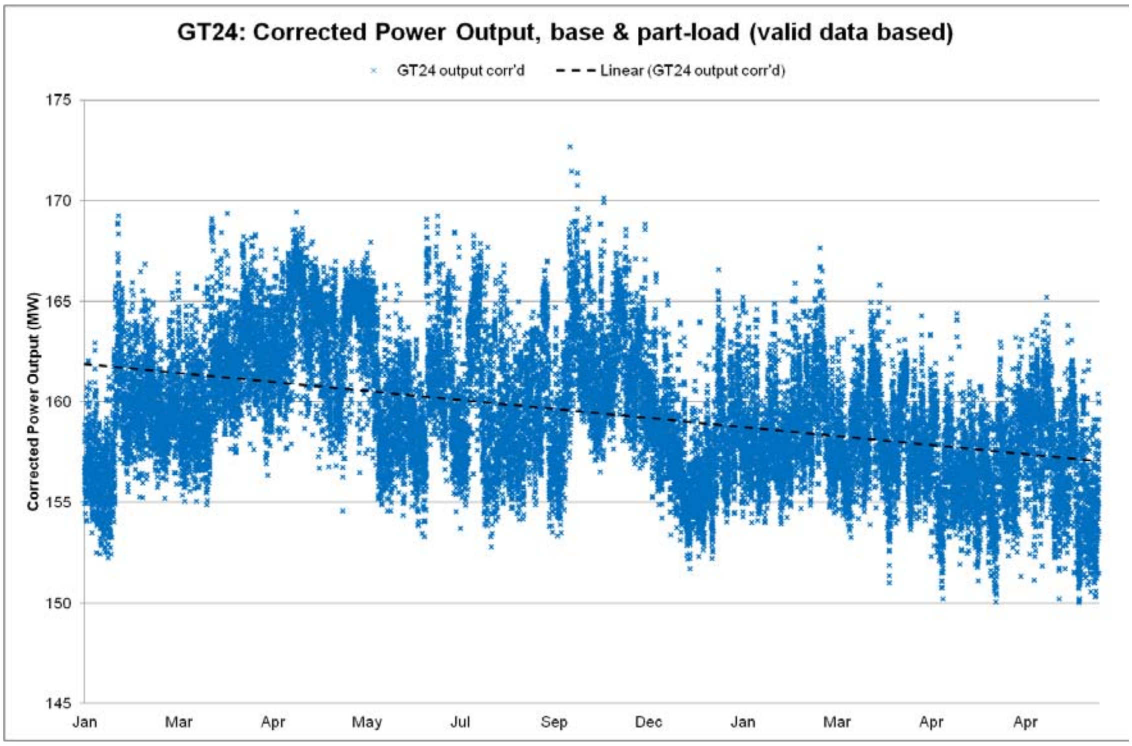

Figure 5-6: GT24, Corrected Power Output base & part-load (valid data based graph)

Secondly, the range of data that is included can have a huge effect on the results because of its scope, having already stated that the data from transient periods of operation have been ignored. The inclusion of both part-load and base-load data will give an overview of performance as shown in Figure 5-5 and help pinpoint areas of points of concern within the operation. If a detailed perspective is required then the relatively small amount of data points at base-load is best suited because of the ability for ‘like-for-like’ comparisons between

GT's as shown in Figure 5-7 below. This provides the clearest evidence as to the gas turbines performance when operating at its optimum setting.

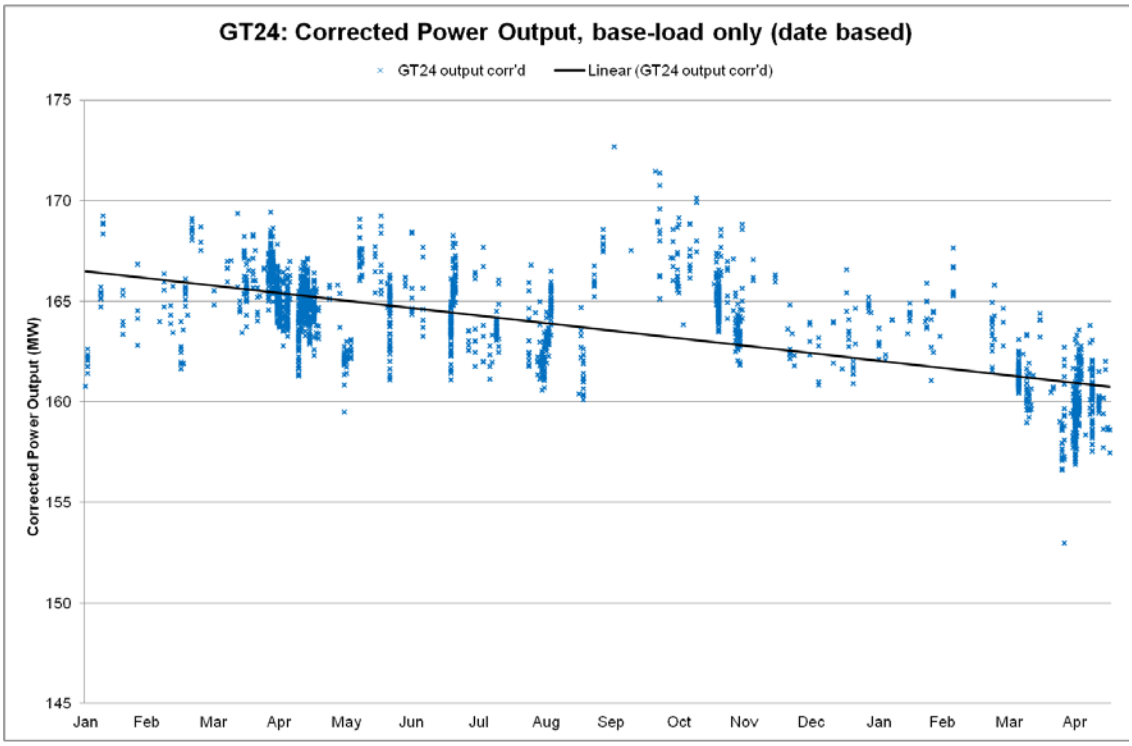

Figure 5-7: GT24, Corrected Power Output, base-load only (date based graph)

Thirdly, the selection of actual data will provide a detailed picture to which values can be applied or if the daily average is chosen, a simple overview.

Taking these statements into consideration the methodology for the progression of the subsequent 'date' based graphs will be to provide an overview of the use of the daily average figures using both part and base-load data. Following this when there is a need to establish monetary values on the gas turbine performance the graph will only utilise actual base-load data, not daily averages, and retain the 'date' based format.

The daily average of the remaining data, base and part-load operations, for the entire recording period, were then compared in an effort to understand the overall performance of each GT. The following graph shows the variation in the daily average for the corrected power output for GT's 23 & 24 along with the overall trend line and periods when the service interventions occurred.

The trend for the corrected power output of GT24 is not only of a higher value than that GT23 but also the degradation rate is slower, see Figure 5-8. Both gas turbines operated with similar heat rates see Table 5-2, with GT23 returning a slightly better rate of degradation, however, this could in part be due to the effects of seasonal ambient temperature changes and that the ‘A’ service took place a month earlier on GT23.

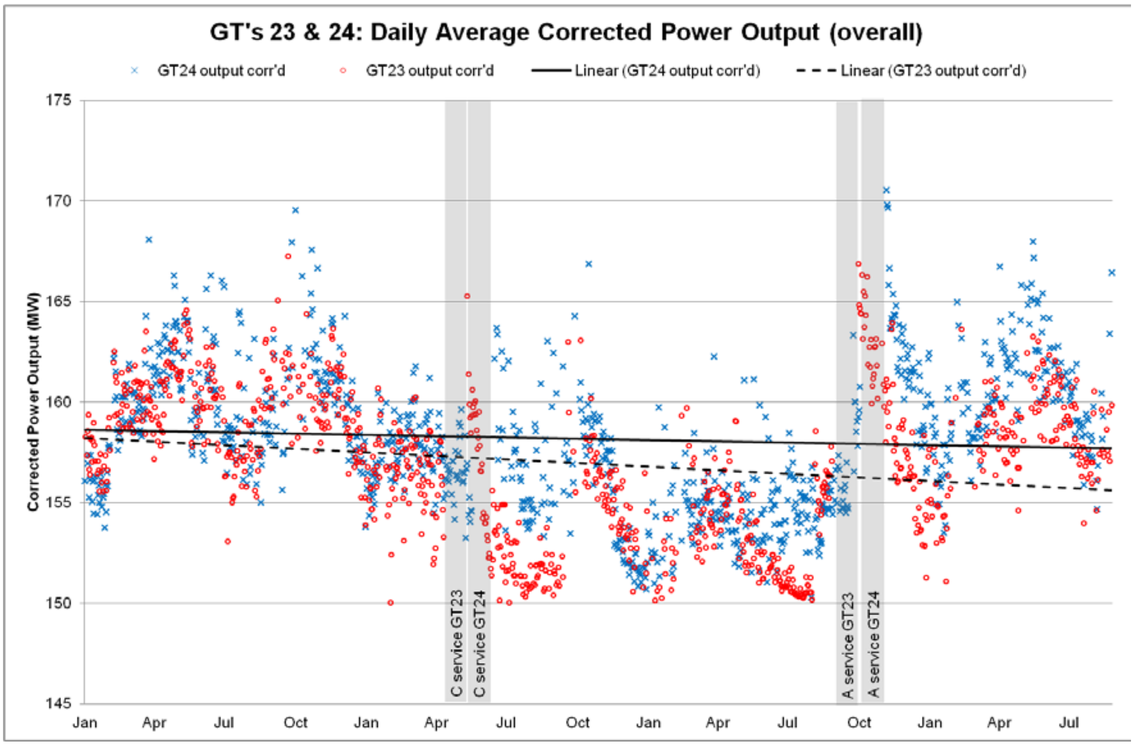

Figure 5-8: GT's 23 & 24 Daily Average Corrected Power Output (overall)

During this operating period, both gas turbines had undergone both a ‘C’ level servicing of the combustion section and a major ‘A’ level servicing of the entire unit, these interventions part way through the recording period should have affected the GT performance in a positive way and therefore the trends may have been also affected and given incorrect results. For this reason, the overall recording period was broken down into three sections, pre-C service, inter-service period (C to A) and post ‘A’ service, with the main focus being on the inter-service period.

5.1.1 Pair A: Inter-service period (‘C’ to ‘A’ service)

Although the dates of the ‘C’ and ‘A’ services of GT’s 23 & 24 were different the duration of the intervening periods was remarkably similar and so permits an even comparison to be made, the details of this data can be seen in Table 5-3 below.

Table 5-3: Inter-service period: data breakdown

	GT23		**GT24**	
	Quantity	%	Quantity	%
Base-load	4325	3.2	3300	2.4
Part-load	10613	7.8	18979	13.9
Total	14938	11.0	22279	16.3
Maximum available	136302		136533	
Duration (days)	473		474	

Whilst the duration may have been similar what is clearly evident from the above table is that both the distribution and quantity of data available differs. These differences of both, base and part-load data have a dramatic impact on any overall trends as illustrated in the following graphs. Figure 5-9, compiled from the total data for GT’s 23 & 24 incorporates the 50% more readings for GT24 than GT23: however, in Figure 5-10 when only base-load data is used, there is 31% less base-load data for GT24.

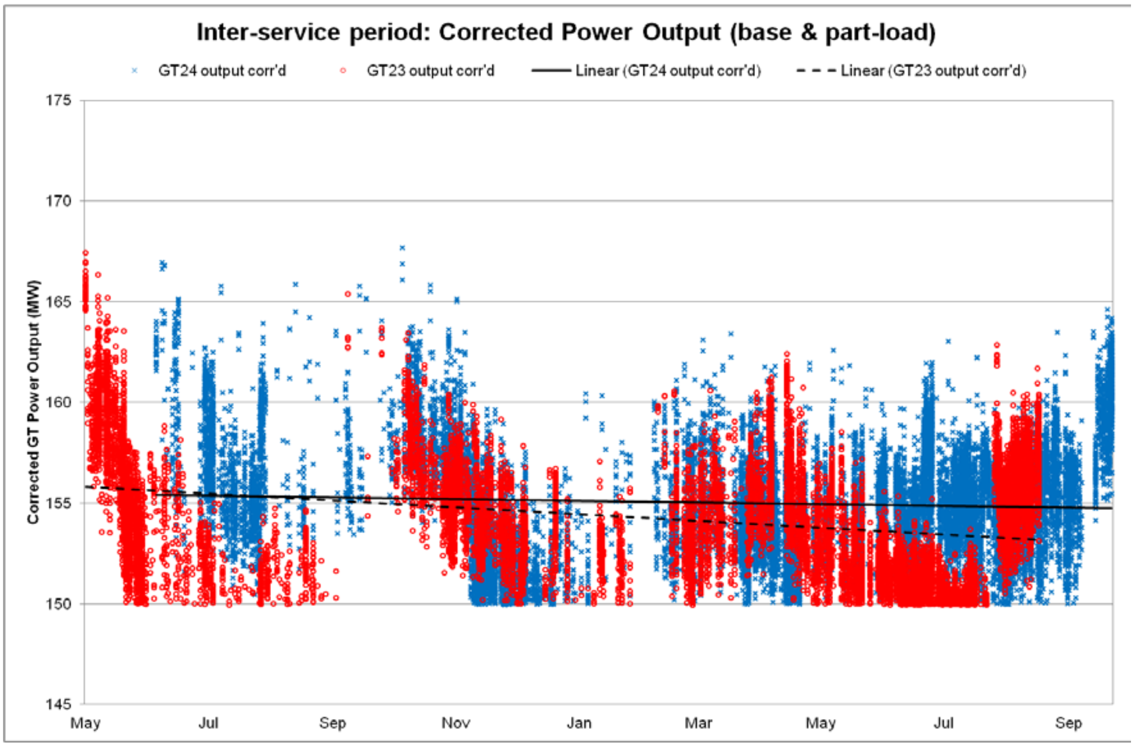

Figure 5-9: Inter-service period: Corrected Power Output (base & part load)

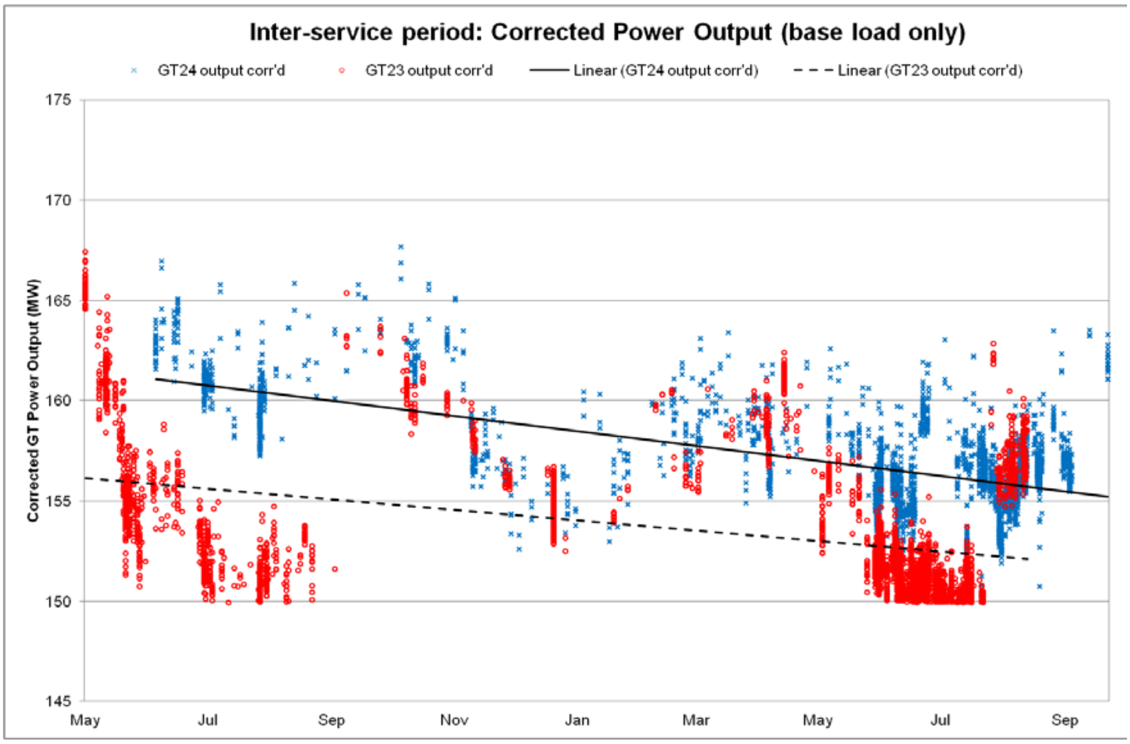

Figure 5-10: Inter-service period: Corrected Power Output (base-load only)

The influence of the large percentage of part-load data is clearly evident in Figure 5-9, along with the split in the data between base and part-load. The number of base-load data points amounted to less than 15% when compared to the more than 85% of part-load readings. Clearly, this had a major influence on the trend line of GT24, both in magnitude and rate of degradation. Looking at only this trend, an observer could draw inaccurate conclusions as to which GT was the most efficient or at the very least the size of the inefficiencies.

Operating at base-load, there are fewer variables to affect the recorded parameters and this is the point at which gas turbines are at their most efficient. The same source data that was used to compile Figure 5-10 can now be used to calculate the daily average of the base-load only data to produce trends. The difference between the performances of the 2 GT's is again evident, see Figure 5-11, which is a representation of the best possible performances available at the time. The start and end values of the trend lines can be established along with the rate of power degradation that will assist in the investigation as to the overall 'health' of the GT's with the use of some additional parameters.

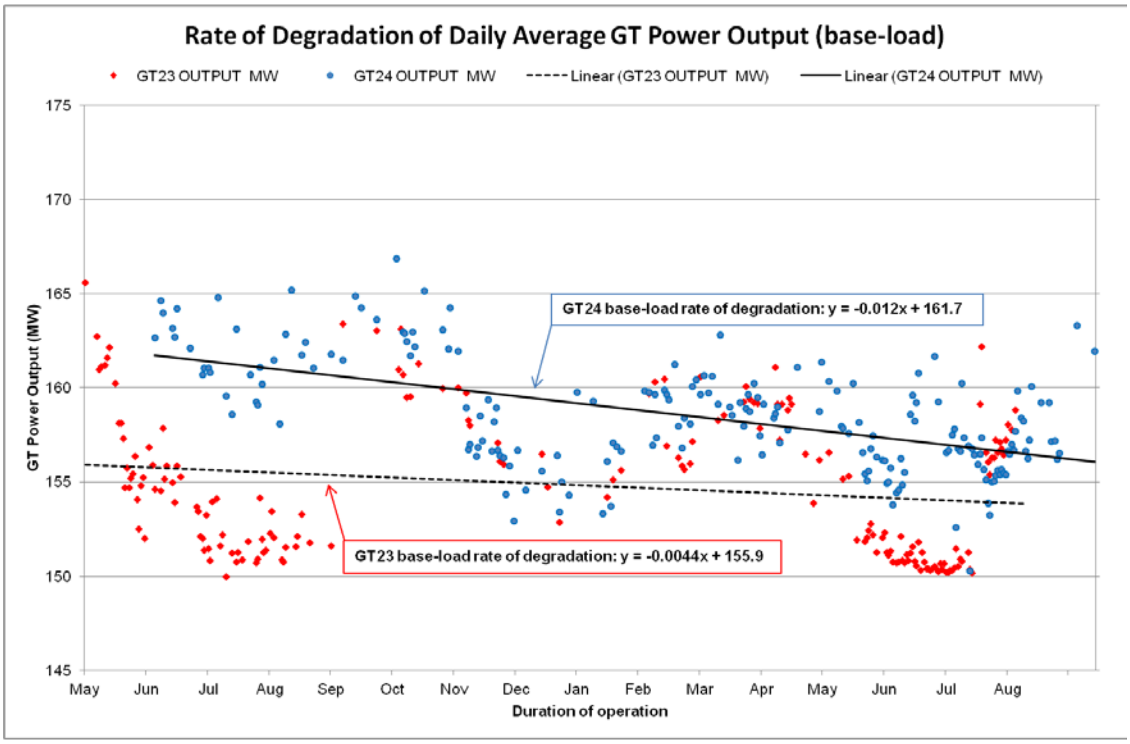

Figure 5-11: Rate of Degradation of Daily Average GT Power Output (base-load only)

Comparing the 2 base-load trend lines in Figure 5-11 reveals that the performances of GT's 23 & 24 deteriorate at different rates and the amount of lost power output. The fact that GT24's total loss of power output is almost 2.5 times greater than that of GT23, see Table 5-4, a number of factors must be taken into consideration to fully understand the relative performances.

- At the start of the trial, the power output level of GT24 was 3.7% higher than that of GT23.
- On completion of the trial GT24's power output level was still greater than the initial value produced by GT23.
- The degradation due to compressor fouling is not a linear process; the initial losses are high, with the rate slowing down as time progresses. Eventually, the losses due to fouling will be minimal; this is when no further deposits are able to adhere to the internal surfaces of the compressor.

Table 5-4: Inter-service period corrected power output (daily average)

	GT23		**GT24**	
Load setting	Base-load	Part-load	Base-load	Part-load
Initial power output (MW)	155.9	154.5	161.7	155.7
Final power output (MW)	153.8	152.8	156.0	153.9
Total loss (MW)	2.1	1.7	5.7	1.8
Mean daily loss (kW/day)	4.4	3.6	12.0	3.7
Duration (days)	473		474	

Once this level of fouling is reached it becomes the limiting factor for any further losses in performance as displayed by GT23 in Figure 5-11; subsequent losses are likely to be attributable to non-recoverable causes as previously described.

The situation is different when comparing the production at part-load conditions, as displayed below; Figure 5-12; whilst the trends of each of the gas turbines are similar in terms of the rate of degradation, GT24 remains more productive in power output terms. The reason for the part-load rates of degradation being very similar is due to the fact that both gas turbines are operating to meet the demand placed upon them; once again this shows that GT24 outperforms GT23.

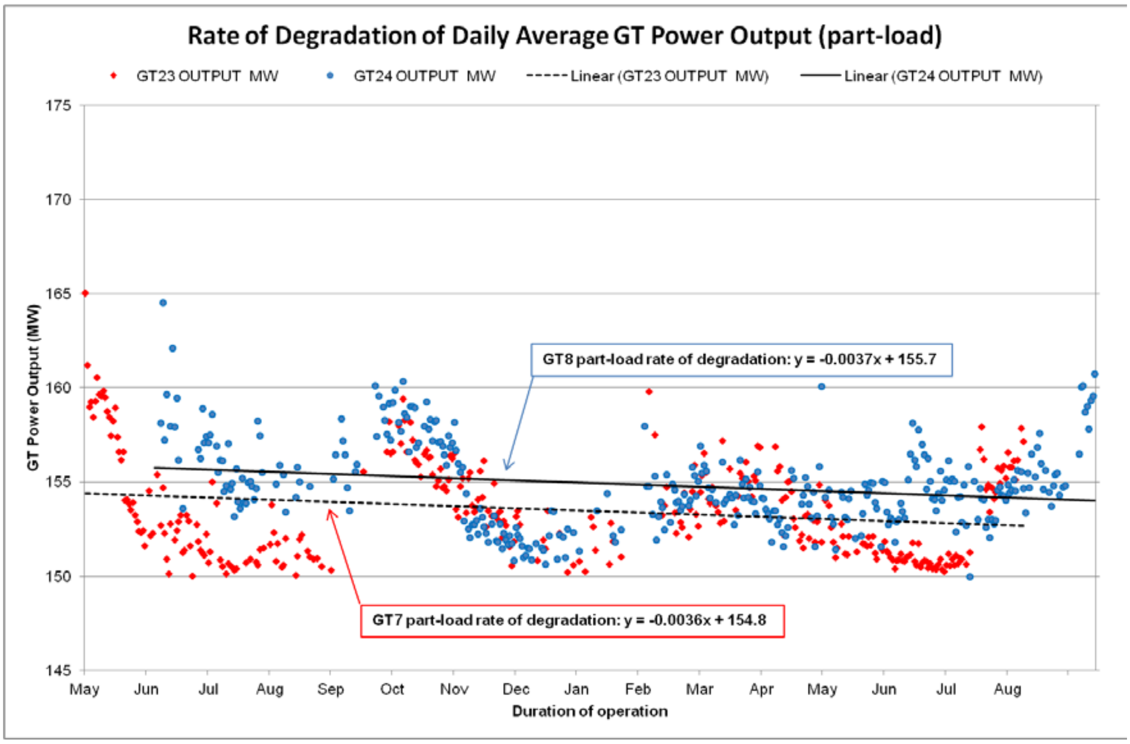

Figure 5-12: Rate of Degradation of Daily Average GT Power Output (part-load only)

Given the above facts about the difference in power outputs and rate of degradation, all of the total base-load data of the heat rate and corrected exhaust gas temperature data were included to fully understand how the GT's are operating. Base-load data only was selected, as this is the point at which the gas turbine is operating at its optimum and is less affected by outside influences. This data produced the following cloud graphs, Figures 5-13 & 5-14, illustrating the respective performance of GT's 23 & 24, with the average values of corrected GT power output, heat rate and EGT displayed in the following table, Table 5-5.

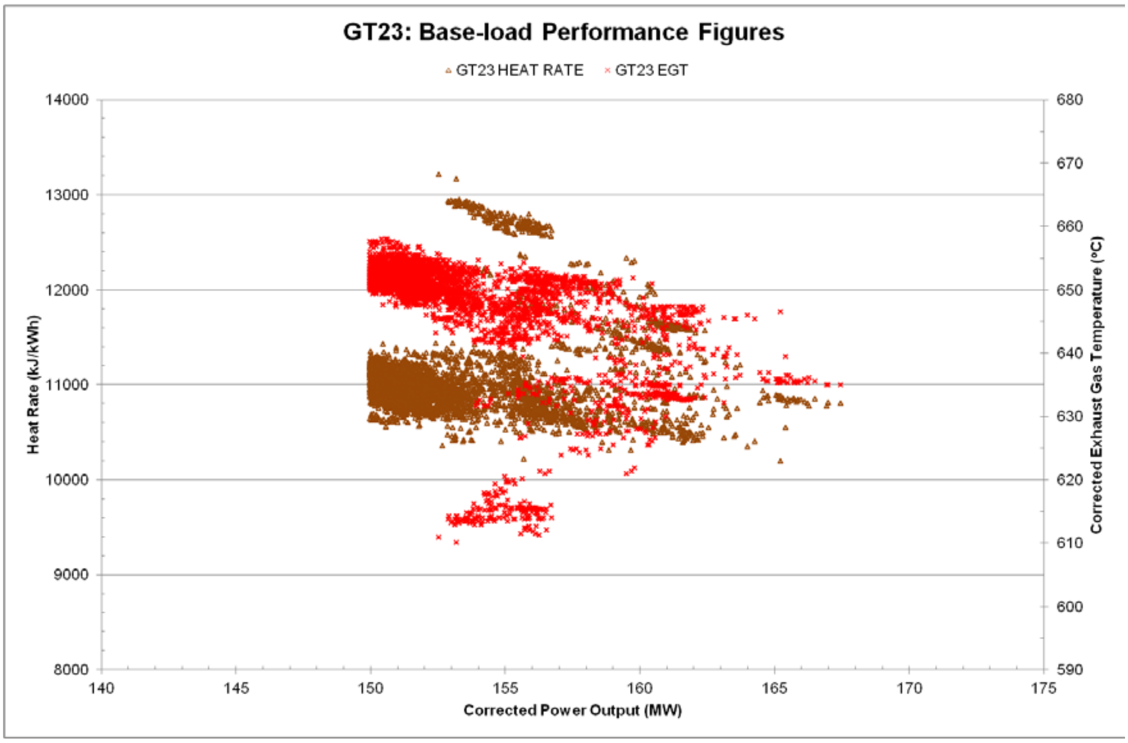

Figure 5-13: GT23 Base-load Performance Figures

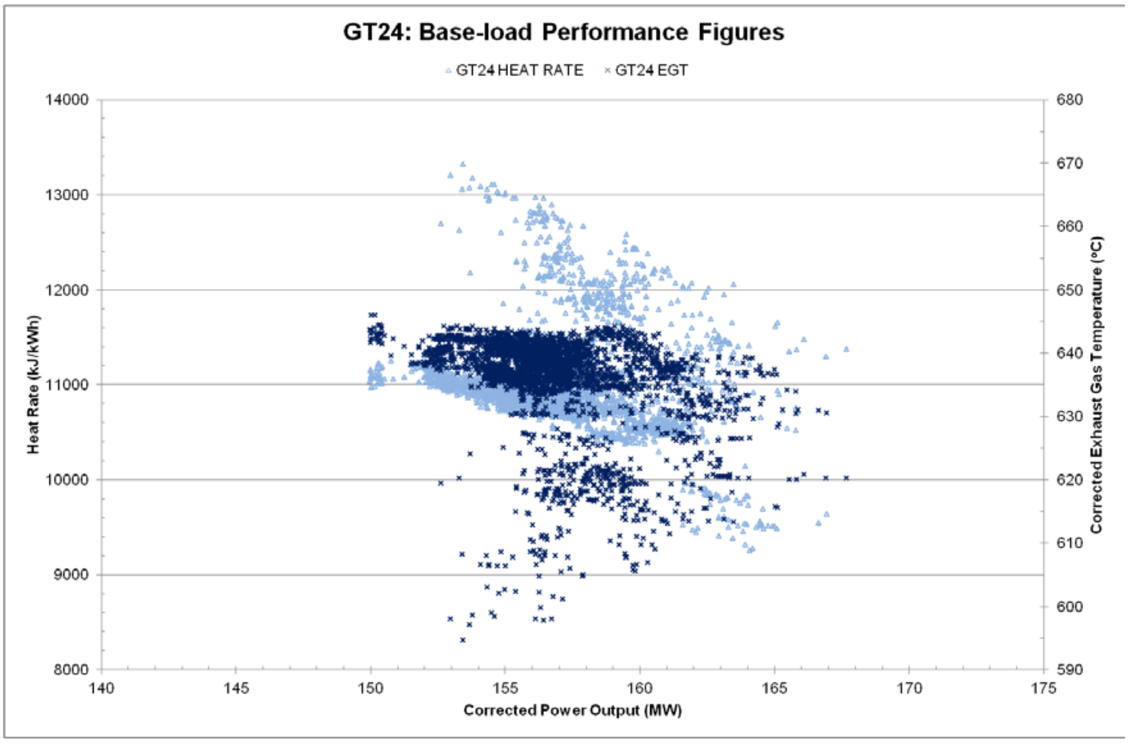

Figure 5-14: GT24 Base-load Performance Figures

Table 5-5: Base-load average values

	GT23	GT24	DIFFERENCE
Corrected power output (MW)	154.9	158.9	4.0
Heat rate (kJ/kWh)	11069	11019	50
Corrected EGT (^{o}C)	647.6	635.7	11.9
Base-load data (qty)	4325	3300	1025
Base-load data (%)	3.2	2.4	
Base-load hours	360.4	275.0	85.4

It can be seen that GT24 produces more power output at a lower corrected exhaust gas temperature than GT23 which means more revenue but also lower maintenance costs. The average heat rates are fairly close in value but this can be explained by the fact that GT23 operated for more time at base-load, closer to its design point, than GT24 and therefore had an advantage in lowering its trend. This was due to the fact that GT23 was only being washed off-line which if not totally successful would not return the GT power output to the maximum possible.

Examination of the records for compressor washing showed that the frequency of off-line washing was similar, a total of 6 being performed during the inter-service period, averaging out to 1 every 79 days. For the same period, the frequency of on-line washes performed on GT24 averaged out to every 68 hours, 36% more than the 50 hours recommended by the OEM of the wash fluid and equipment.

5.1.2 Pair A: Cost-benefit analysis for inter-service period

The values from the performance of the gas turbines, at both base & part-load, were then used in a series of calculations to form a cost-benefit analysis, or CBA, to determine the financial implications of the differing wash regimes; the electricity export price, the relative cost of fuel and compressor wash fluid cost were also included. This was broken down into 3 parts:

- Revenue from the generated electricity exported to the grid.
- Fuel costs incurred.
- Wash fluid costs associated with the different wash regimes.

The duration of the inter-service period of the 2 gas turbines was also considered as a wide variation between the 2 could have affected the results. The introduction of a level of standardisation into the analysis would then have been necessary to allow for a direct comparison in performance. In this case, the 1-day difference in the respective durations of the inter-service period was insufficient to have unduly affected the results.

5.1.2.1 Pair A: Revenue from inter-service period

The first step was to calculate the total power produced for the inter-service period for each gas turbine, both at base and part-load, whilst also taking into account the percentage of time at each load setting.

Table 5-6: Base & part-load average values

	GT23		**GT24**	
Load setting	Base-load	Part-load	Base-load	Part-load
Average power output (MW)	154.9	153.7	158.9	154.8
Average heat rate (kJ/kWh)	11069	11353	11019	11450
Percentage of data at each load setting	3.2%	7.8%	2.4%	13.9%
Duration (days)	473		474	

The average daily output had been calculated using the linear rate of degradation for both gas turbines from Figure 5-11 & 5-12; it was then possible, using Eq. (5-1), to calculate the total possible number of megawatts that could be produced at both base & part-load conditions.

$$MWh\ (possible) = MW\ (mean\ daily\ average) *\ hours \tag{5-1}$$

However as the production was at various different power settings, and not consistently at either base or part-load, the percentage of exporting hours from Table 5-6, had to be applied for each case as per Eq. (5-2).

$$MWh\ (actual) = MWh(possible)\ *\ \%(exporting\ hours) \quad \textbf{(5-2)}$$

The combination of these production totals for base & part-load provided a figure that could be used with the electricity export value, £30 per MWh at the time of the trial, to give the revenue for the inter-service period using Eq. (5-3).

$$Revenue\ = [MWh\ (base\ load) + MWh\ (part\ load)]\ * \frac{price}{MW} \quad \textbf{(5-3)}$$

Table 5-7: Revenue from electricity generated

	GT23	GT24
Base-load average output (MW)	154.9	158.9
Percentage of time operated at base-load	3.2%	2.4%
Base-load production (MW)	56251	43370
Part-load average output (MW)	153.7	154.8
Percentage of time operated at part-load	7.8%	13.9%
Part-load production (MW)	136,050	244,780
Total revenue*	**£5,769,052**	**£8,644,486**

* Electricity export value £30/MWh at the time of the trial

Table 5-7 shows that despite the fact that GT24 operated for 33% less time at base-load the difference in base-load output was only 23%; an indication of operating more efficiently. At part-load conditions, where GT24 operated for 78% more than GT23, it produced 80% more revenue; this can be accounted for in the relative rates of degradation of both GT whilst at part-load being similar due for the most part in purely meeting the demand placed upon them.

5.1.2.2 Pair A: Associated fuel cost for the inter-service period

The next stage was to calculate the cost of the fuel used by each gas turbine using the value provided at the time of the trial, £22/kWh. This factor was applied to the production figures and the average heat rate for each gas turbine in Eq. (5-4).

$$Basic\ fuel\ costs\ = MWh\ (actual) * \frac{price}{MWh} \tag{5-4}$$

However as both GT's had different average heat rates, as shown in Table 5-6, these had to be taken into account. The percentage difference was then factored into the calculation, where appropriate, to calculate any additional costs that one of the gas turbines would incur Eq. (5-5).

$$Adjusted\ fuel\ costs\ = MWh\ (actual) * \frac{(price + heat\ rate\ difference)}{MWh} \tag{5-5}$$

Table 5-8: Associated fuel cost

	GT23	**GT24**
Average base-load heat rate (kJ/kWh)	11069	11019
Difference of base-load heat rate from GT24	+0.45%	Nil
Base-load production (MW)	56251	43370
Base-load fuel costs	£1,243,147	£954,137
Average part-load heat rate (kJ/kWh)	11353	11450
Difference of part-load heat rate from GT24	-0.85%	Nil
Part-load production (MW)	136,050	244,780
Part-load fuel costs	£2,967,750	£5,385,153
Total fuel costs**	**£4,210,897**	**£6,339,290**

** Fuel costs £22/kWh at the time of the trial

5.1.2.3 Pair A: Wash fluid cost for the inter-service period

To calculate the costs of wash fluid used for both on and off-line washing the following facts had to be established.

- On-line wash frequency.
- Off-line wash frequency.
- Quantity of litres per on-line wash.
- Quantity of litres per off-line wash.
- Cost of wash fluid per litre.
- Number of operating hours of the inter-service period.

As previously stated in Chap 4.3, the details of the trial, GT23's wash regimes was off-line washing only, whilst GT24 had both on & off-line washes using the recommended mix ratio of 1:4 with demineralised water. The records from the site showed that the average off-line wash frequency for both gas turbines was every 79 days, using 140 litres per off-line wash. The on-line wash frequency for GT24 average every 68 running hours and used 60 litres per wash. Using the Eq. (5-6) the costs for off-line wash fluid wash calculated by including the cost of the wash fluid, which at the time of the trial was £9 per litre.

$$Offline\ fluid\ costs\ = \frac{duration}{offline\ wash\ frequency} * \frac{litres}{wash} * cost\ of\ fluid \tag{5-6}$$

As the gas turbines operations for the inter-service period were not continuous there was a requirement to ascertain the actual number of operating hours. This was calculated by studying the initial 'raw' data and noting whenever there was a positive fuel flow recorded; this percentage was then applied to the total number of hours of the inter-service period. This number of operating hours was then used in Eq. (5-7) to establish the on-line wash fluid costs.

$$Online\ fluid\ costs\ = \frac{operating\ hours}{online\ wash\ frequency} * \frac{litres}{wash} * cost\ of\ fluid \tag{5-7}$$

Table 5-9: Wash fluid costs

	GT23	GT24
Percentage of operating hours	86.3%	78.9%
Quantity of off-line wash fluid (litres)	838	840
Cost of off-line wash fluid (£9/litre)	£7,544	£7,560
Quantity of on-line wash fluid (litres)	Nil	7920
Cost of on-line wash fluid (£9/litre)	Nil	£71,277
Total wash fluid costs***	**£7,544**	**£78,837**

*** Wash fluid costs £9/litre at the time of the trial

Combining the above calculations for the revenue from electricity generated, Table 5-7, associated fuel cost, Table 5-8 and wash fluid cost, Table 5-9, enabled the profit for each gas turbine to be calculated using Eq. 5-8.

$$Profit \ = Total\ revenue - Total\ fuel\ costs - Total\ wash\ fluid\ costs \qquad \textbf{(5-8)}$$

Table 5-10: CBA for inter-service period for GT23 & GT24

	GT23	GT24
Total revenue	£5,769,052	£8,644,486
Total fuel costs	£4,210,897	£6,339,290
Total wash fluid costs	£7,544	£78,837
Profit for individual GT's	**£1,550,611**	**£2,226,359**
Greater profit for GT24		**£675,748**

Table 5-10 is the CBA for the entire inter-service period and demonstrates that GT24 generated 50% more revenue than GT23 whilst using 51% more fuel in the process. The extra wash fluid cost due to the differences in the 2 compressor wash regimes employed meant that the expenditure associated with compressor washing for GT23 was 85% less. After taking into account these 3 factors, the result was that GT24 profit for the inter-service period was 44% greater.

5.1.3 Pair A: Cost-benefit analysis for 365 day period

The procedure carried out in Chap 5.1.2.1 was then repeated using data from after 365 days of operation and the same equations, in an effort to provide values that were more easily related to the annual usage. The resulting values are shown in Table 5.11; despite the reduced timescale, shortened by approximately 108 days, the differences in revenue and fuel cost percentages were remarkably similar; this was due to the fact that the overall degradation had also been reduced.

Table 5-11: CBA for 365 days (GT23 & GT24)

	GT23	**GT24**
Total revenue	£4,458,008	£6,668,024
Total fuel costs	£3,244,373	£4,889,885
Total wash fluid costs	£5,822	£60,708
Profit for individual GT's	**£1,207,813**	**£1,717,432**
Greater profit for GT24		**£509,619**

There are other factors that would affect the profitability of the gas turbines namely, the electricity export price and the cost of the fuel. Figure 5-15, shows how these variables affect the extra profitability achieved by GT24 and the employment of an effective on & off-line compressor wash regime.

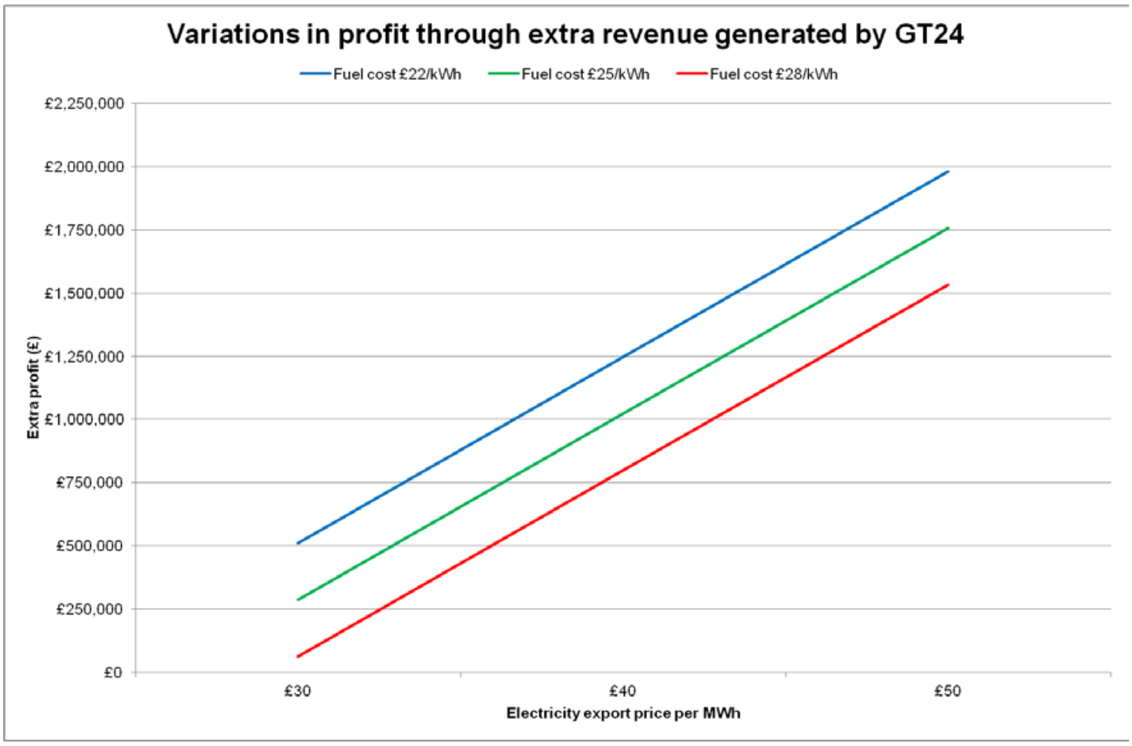

Figure 5-15: Variations in profit through extra revenue generated by GT24

The cost of wash fluid was not included in the examination of the variable costs because the basic wash fluid costs for a year's operations equated to only 1.6% of the fuel cost expended or 7.6% of the extra revenue generated during the trial.

5.1.4 Pair A: Supporting evidence of additional benefits

Having provided a positive financial case for an on-line wash regime, there was also supporting evidence for additional benefits, in terms of reduced servicing cost due to the lower operating temperatures. The costs associated with these are beyond the scope of this paper and therefore cannot be quantified. However, by plotting the daily average of the corrected exhaust gas temperature, for all of the readings of the entire recording period of more than 3½ years, a significant difference in corrected EGT can be seen, as shown in Figure 5-16, which displays the actual daily average points. In an effort to determine what the difference between the corrected EGT of the 2 gas turbines was a ’14-day moving average’ trend line was included to assist with the clarity.

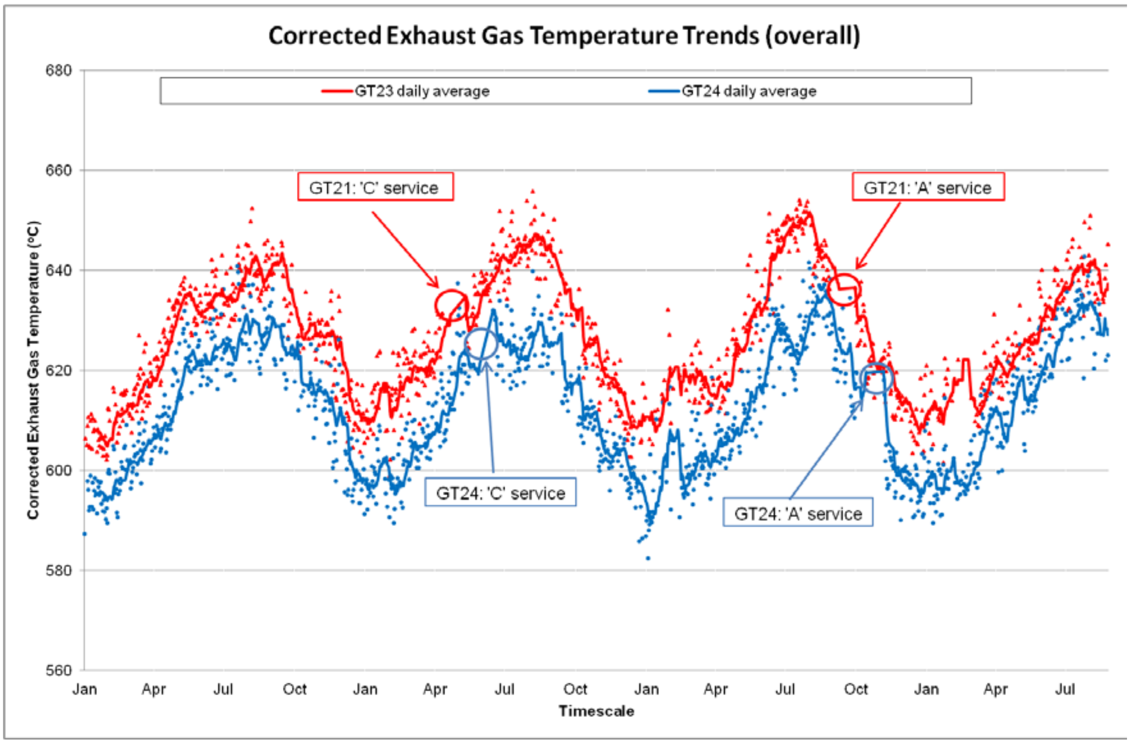

Figure 5-16: Corrected Exhaust Gas Temperature Trends (overall)

The difference between the corrected EGT of the GT's 23 & 24, ranged from 4°C to 24°C with the vast majority being approximately 15°C.

Whilst this may not be at a critical level it will have an impact on the operational regime and could even impose restrictions under certain circumstances. When operating under EGT control could explain why GT23 operated at base-load more often than GT24. Additionally, it lends weight as to why the heat rates of the gas turbines are not too dissimilar despite large variations in the level power output. This could be attributed to the higher firing temperature of GT23 that masked the inefficiency in terms of power output.

The frequency of off-line washes was also examined to determine their effectiveness during the trial. Previously stated in Chap 5.1.1, the off-line wash interval for the inter-service periods for both GT's was every 79 days, however, when the entire recording period, was taken into account the difference was more significant. The average of both had increased, GT23 by an extra 5% to 83 days but more significantly that of GT24 had been extended to 103 days, an increase of almost 30%. These additional off-line washes would have increased the fluid costs for GT23 but would have only a minor financial impact when compared to the overall loss of revenue and additional fuel cost previously calculated. They are nevertheless, important factors that need to be considered in the relative performances of the gas turbines and indicates that despite the more frequent off-line washing of GT23, their effectiveness was no better. The conclusion drawn from this is that due to the fact that no on-line washing was carried out, the compressor was fouled to such a degree that regular off-line washing was no longer enough to completely remove the deposits and return it to a fully clean state. Furthermore, fouling would then have been easier due to the partially clean state of the compressor because of the increased surface roughness.

5.1.5 Pair A: Summary of relative performances

To summarise the facts that have been established in this trial regarding the relative performance figures of these gas turbines it was found that an on and off-line wash regime was more effective in maintaining the performance levels than off-line only.

When considering all the data, before the introduction of the data filters, GT23 had almost twice as much base-load data than GT24, see Table 3-1, which proves that GT23 is attaining the parameters that match base-load status before GT24. This trend was repeated after the data filters were introduced, although the difference was reduced slightly, there was still 70% variation in the quantity of base-load data recorded as shown in Table 5-1. This is due to the fouling that has been allowed to accumulate in the compressor forcing GT23 to work harder to produce an equivalent amount of power under load sharing conditions. GT24 operated more at part-load for the reason stated above, not yet at the limits that determine what is classed as base-load status.

During the inter-service period, similar splits in the distribution of recorded data were noted, as per Table 5-4; however, the rate of loss of power output of GT24 was more than 2.5 times that of GT23. This can be explained by the fact that GT23 was operating closer to the limits that determine base-load operating status. Additionally, the starting point for the power output trend was almost

6MW lower than that of GT24; meaning that there was already a loss of potential range because it was not capable of any more power output. Operating in this degraded state meant that any potential losses would less than for those experienced on a cleaner gas turbine, in this case, GT24, and therefore less noticeable.

The relative performance figures, Table 5-5, calculated using the base-load data from the inter-service period, demonstrated that a gas turbine that operated with both and on and off-line compressor wash regime performed better than one which only had off-line washes. Firstly, in terms of power output, GT23 produced less because the compressor was fouled and therefore unable to deliver the maximum mass air flow, which reduced the potential power output. Secondly, due to the reduced airflow caused by the compressor fouling the firing temperature was lower as a result of maintaining the correct fuel/air ratio which resulted in less efficient fuel usage. Finally to maximise the possible power output and as the gas turbine will be controlled by exhaust gas temperature more fuel can be injected to increase the firing temperature closer to the expected which then raises the EGT.

Throughout the entire recording period, when comparing the quantity of base-load data in Table 3-1 showed, that GT23 consistently operated almost twice as often at base-load than GT24. This was the case, both before and after the introduction of the data filters, as well as during the inter-service period. This reinforces the point that GT23 is working harder to provide its share of the demand when load sharing.

5.2 Pair B (GT’s 21 & 22): Data split and GT status

The second part of the trial that ran concurrently on adjacent gas turbines was to establish the effectiveness of using a weakened wash solution in an effort to reduce costs. The analysis of the information from the second pair of gas turbines, GT’s 21 & 22, was handled in a similar way to those used on GT’s 23 & 24, Chapter 5.1.

The data was split between the various GT statuses as before, with the most time spent at part-load; after excluding the transient statuses as carried out with the gas turbines of Pair A, the percentage of base and part-load records of GT22 is 8% more than GT21. On further examination, the data split shows that GT21 had 1.9% fewer operations at base-load despite the fact that the GT's were operated under load sharing conditions.

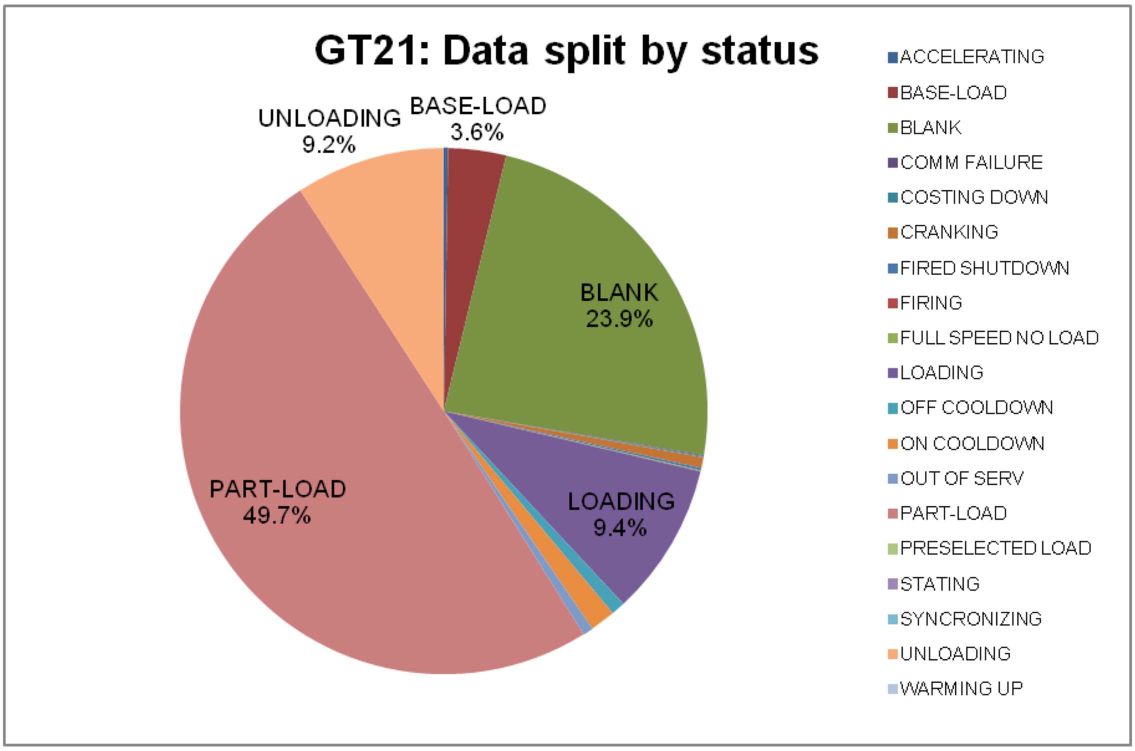

Figure 5-17: GT21 data split by status

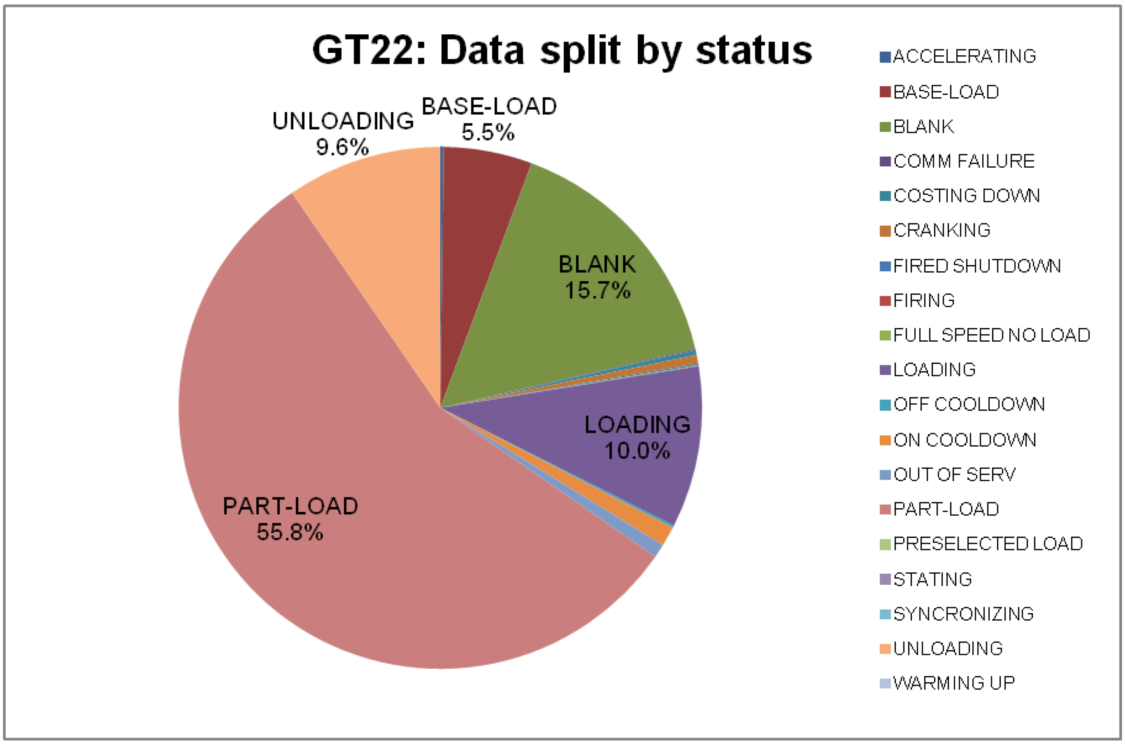

Figure 5-18: GT22 data split by status

Applying the same data filters previously applied to the data from the first pair of gas turbines a similar reduction in the quantity of remaining data was achieved, approximately 20% of the initial data.

Table 5-12: Data split following the use of data filters on GT's in Pair B

GT status	GT21		GT22	
	Quantity	%	Quantity	%
Base-load	13363	3.5	20753	5.4
Part-load	50400	13.1	40973	10.7
Loading	5367	1.4	3870	1.0
Unloading	6395	1.6	4421	1.2
Blank	1451	0.4	1757	0.5
Removed by data filters	306928	80.0	312130	81.3
Total lines of data recorded for each gas turbines = 383904				

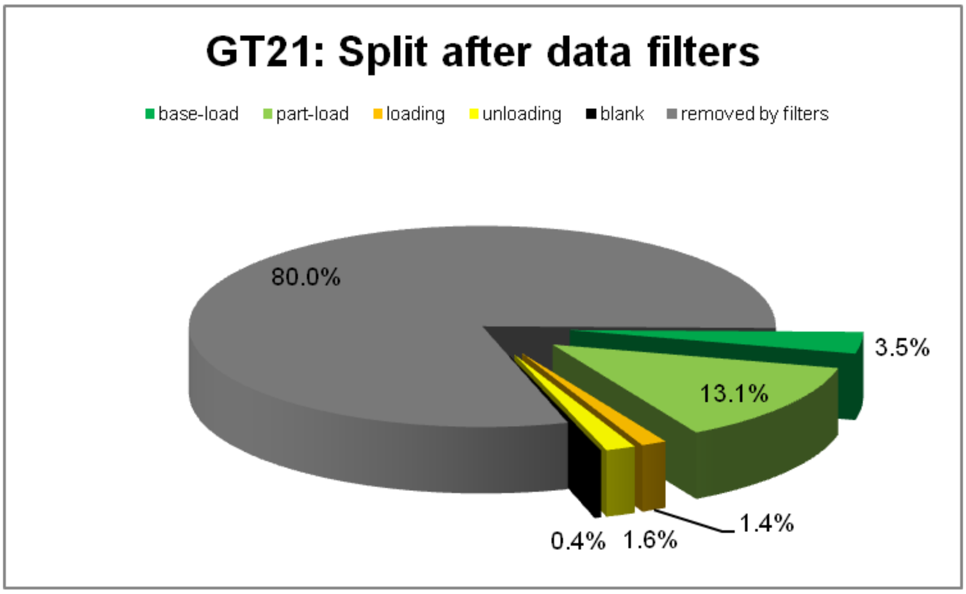

Figure 5-19: GT21 data split after data filters

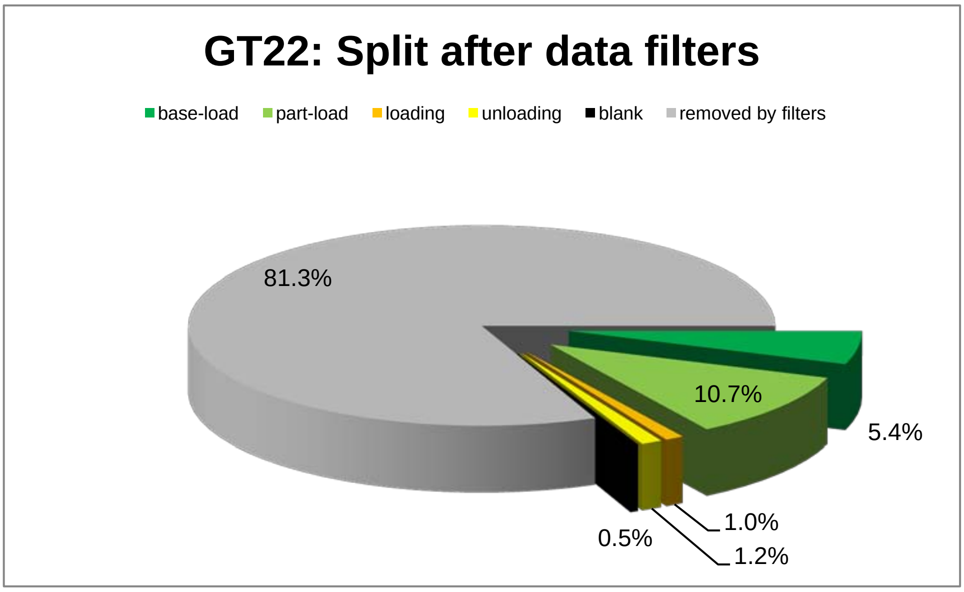

Figure 5-20: GT22 data split after data filters

As before the data from the transient GT statuses, ‘loading’ and ‘unloading’, along with the non-specified data entitled ‘blank’ were ignored due to their nature as they were not considered to be relevant. Cumulatively these 3 groups accounted for little of the total data, only 3.4% & 2.7% respectively, and their removal from the analysis produced a slight difference to the overall average values as shown in the following table.

Table 5-13: Average values comparisons (total data vs. base & part-load only)

	GT21			GT22		
	Total data	Base & Part-load only	Difference	All data	Base & Part-load only	Difference
GT power output corrected (MW)	160.7	160.8	**0.1**	159.5	159.6	**0.1**
Heat Rate (kJ/kWh)	11276	11257	**19**	11616	11599	**17**
EGT (^oC)	625.2	625.9	**0.7**	627.2	627.7	**0.5**

The daily average of the remaining data, base and part-load operations, for the entire recording period, Jan 11 – Aug 14, were then compared in an effort to understand the overall performance of each GT. The following graph shows the variation in the daily average for the corrected power output for GT's 21 & 22 along with the overall trend line and periods when the service interventions happened with similar results as with the gas turbines of Pair 'A'.

It can be seen that the corrected power output trend of GT21 has a slower degradation rate and is a greater value than GT22, see Figure 5-21 whilst the difference in heat rates between the two GT's is of a significant value. Once again during this period of operation, both gas turbines had undergone both 'C' and 'A' level services and therefore the main focus moved to the inter-service period.

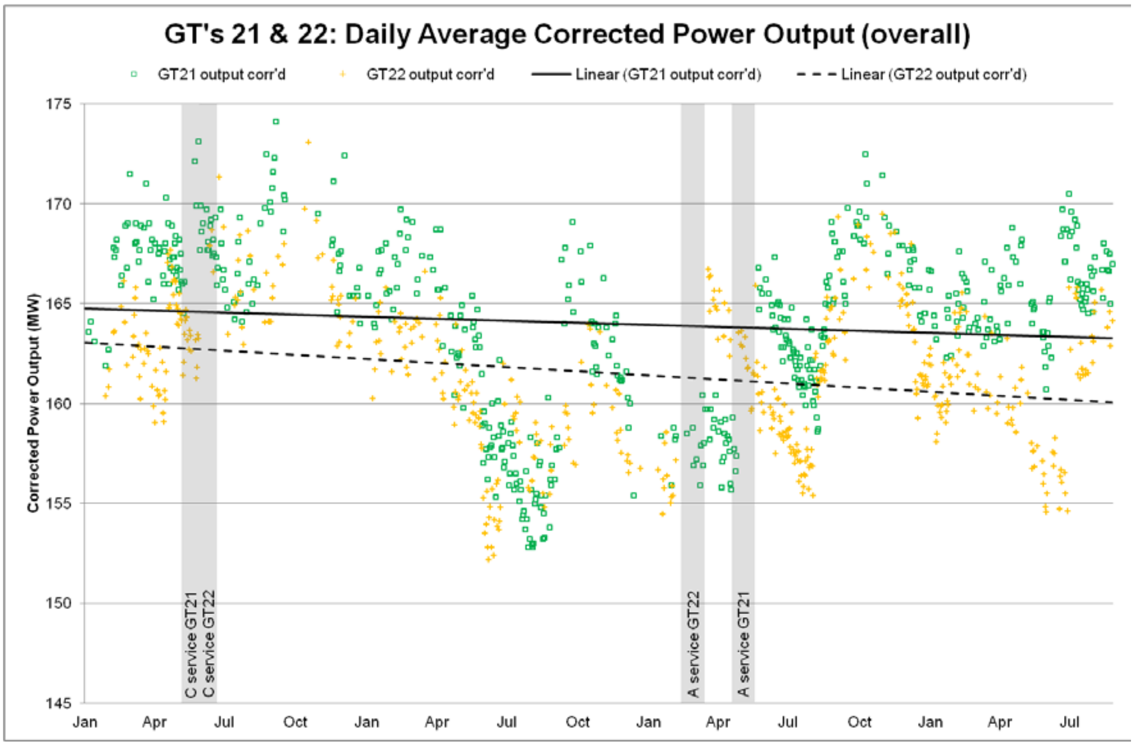

Figure 5-21: GT's 21 & 22, Daily Average Corrected Power Output (overall)

5.2.1 Pair B: Inter-service period (‘C’ to ‘A’ service)

In this comparison, the interval between the ‘C’ and ‘A’ services of GT’s 21 & 22 was not only considerably longer than that of the previous pair of gas turbines but of different duration from each other and with a far larger split in percentages of total data available. Table 5-14 below shows that despite GT21 having almost 33% more usable data from a longer recording period, the percentage of base-load data is less than that of GT22.

Table 5-14: Inter-service period: data breakdown

	GT21		GT22	
	Quantity	%	Quantity	%
Base-load	3920	1.9	5693	3.2
Part-load	26427	13.1	17210	9.7
Total	30347	15.0	22903	12.9
Maximum available	202275		176997	
Duration (days)	702		614	

The difference in both data quantity and percentage, between base and part-load, on GT's 21 & 22 and the influence of including part-load data is evident in the following graphs, Figures 5-22 & 5-23.

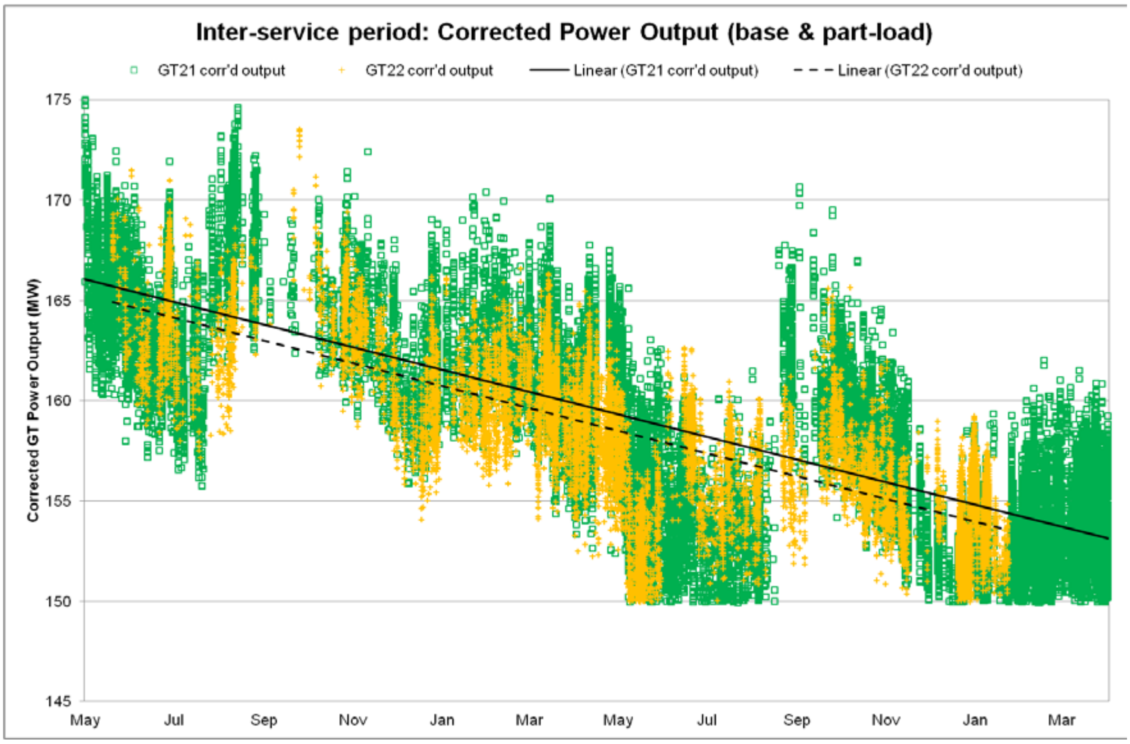

Figure 5-22: Inter-service period: Corrected Power Output (base & part-load)

This is not only in the range of recorded values but also the quantity of data and its distribution in the operational cycle. Whilst the effect that this has on the gas turbines of Pair B appears to be less significant than those observed in the trends of Pair A, it cannot be ignored and must be considered in order to gain a clear understanding of relative efficiencies.

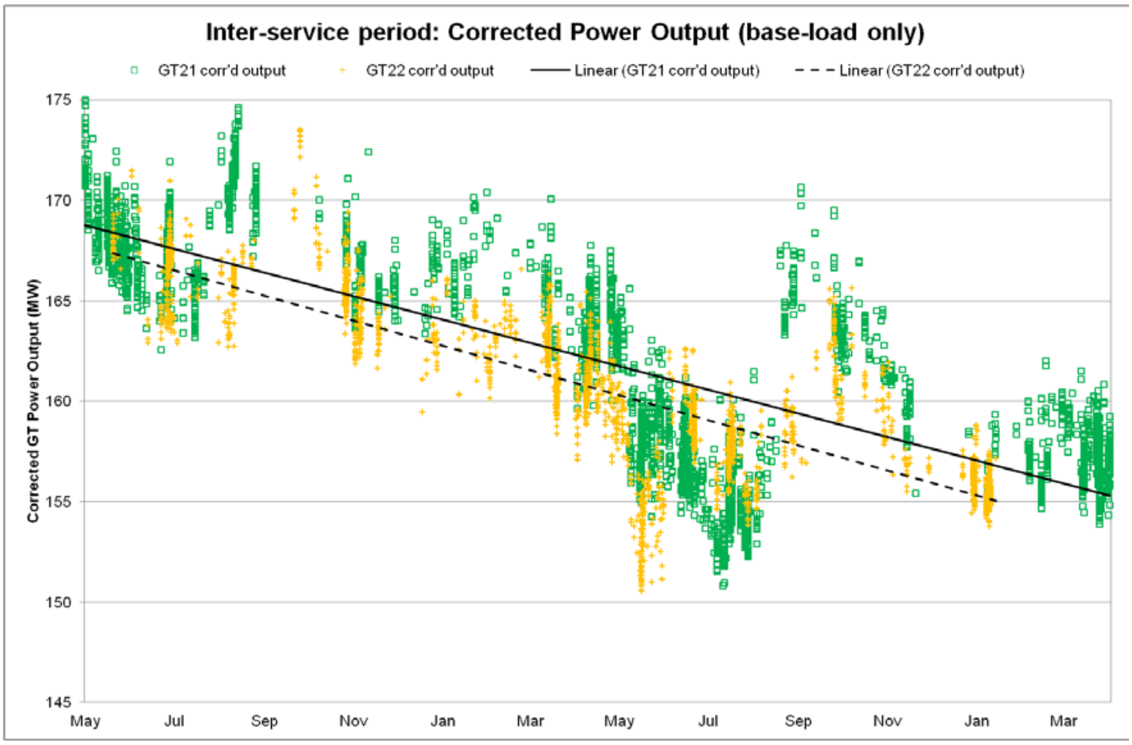

Figure 5-23: Inter-service period: Corrected Power Output (base-load only)

By taking the same approach that was adopted with the gas turbines in Pair A, and focusing on the daily average of the base-load data only, allowed any differences in the relative gas turbine performances to be more obvious; this can be seen in Figures 5-24 & 5-25. GT21 produced more in terms of power output, both at the start and end of the recording period than GT22 despite being similarly rated; it also operated for more than 14% longer with a better rate of degradation. This lack of performance could be, in part at least, because the compressor was not being washed effectively with the weakened wash fluid solution.

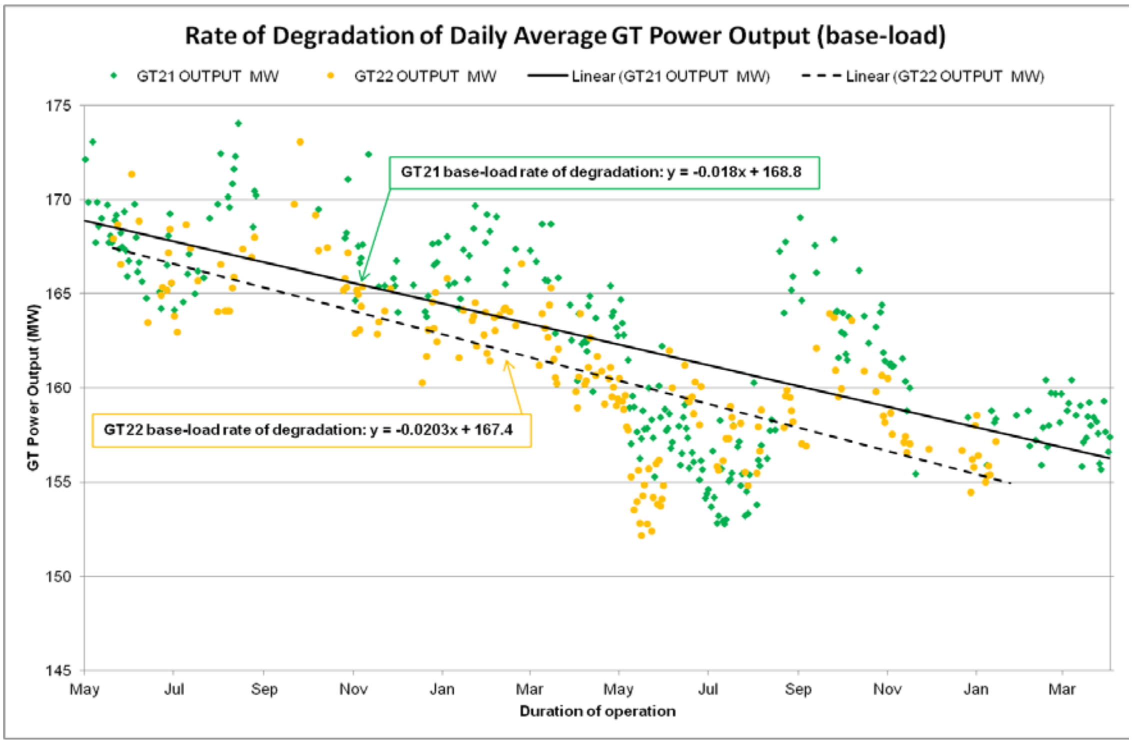

Figure 5-24: Rate of Degradation of Daily Average GT Power Output (base-load only)

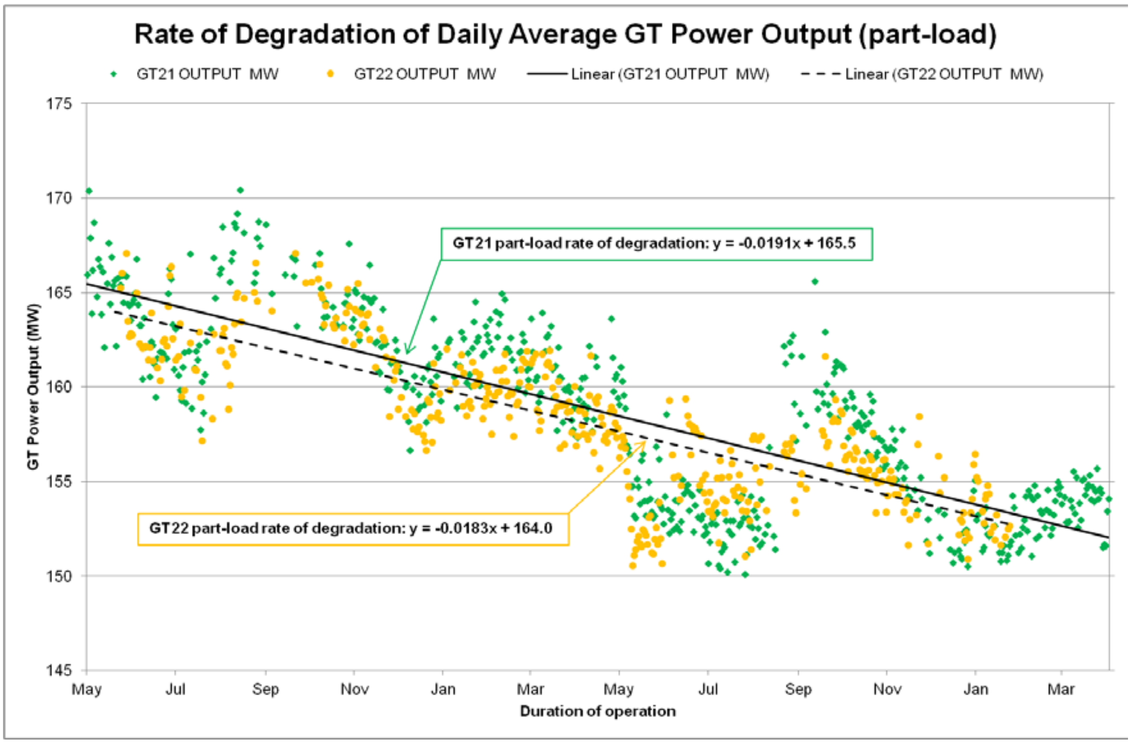

Figure 5-25: Rate of Degradation of Daily Average GT Power Output (part-load only)

Table 5-15: Inter-service period corrected power output (daily average)

	GT21		GT22	
Load setting	Base-load	Part-load	Base-load	Part-load
Initial power output (MW)	168.8	165.5	167.4	164.0
Final power output (MW)	156.2	152.1	154.9	152.8
Total loss (MW)	12.6	13.4	12.5	11.2
Mean daily loss (kW/day)	18.0	19.1	20.3	18.3
Duration (days)	702		614	

Repeating the steps carried out with the first pair of gas turbines using the total base-load data, in terms of the heat rate and corrected exhaust gas temperature data, Figures 5-26 & 5-27 were produced for GT's 21 & 22.

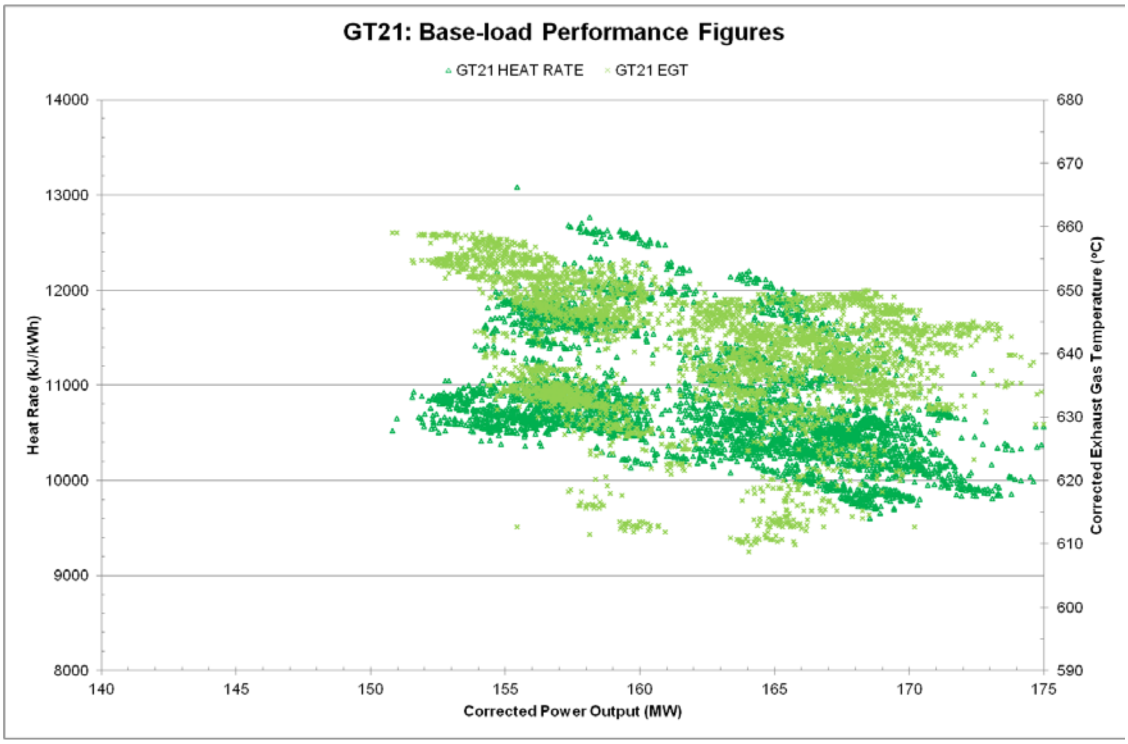

Figure 5-26: GT21 Base-load Performance Figures

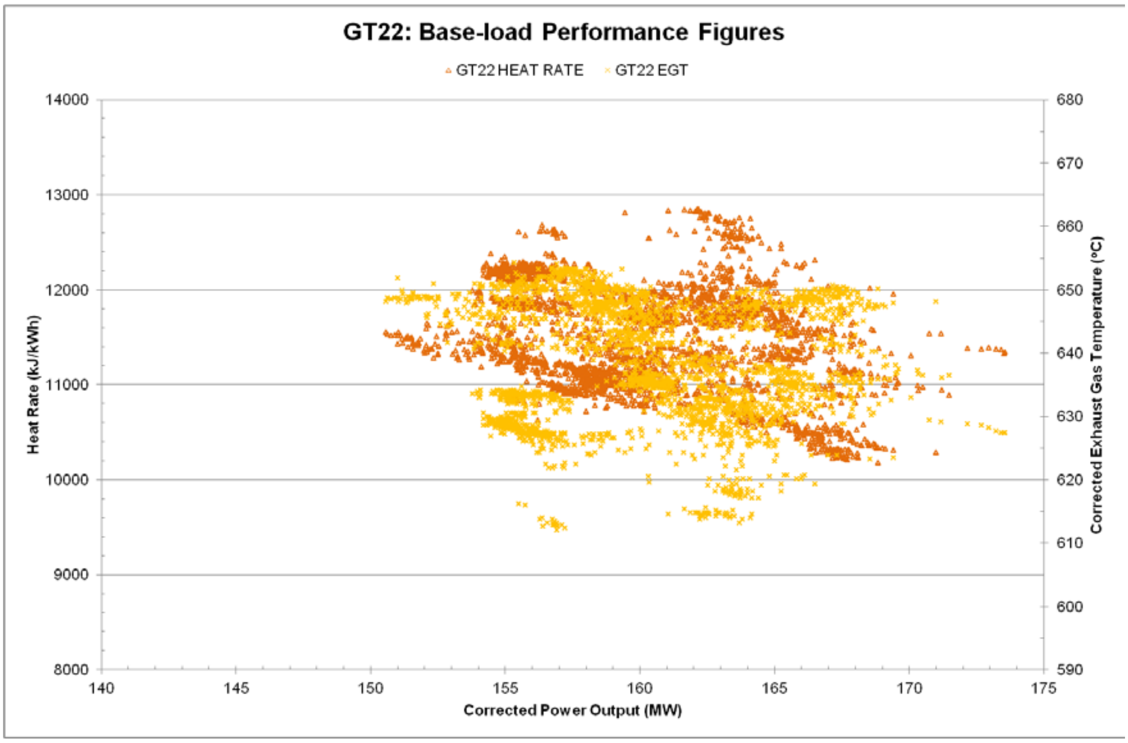

Figure 5-27: GT22 Base-load Performance Figures

Table 5-16 tabulates the average values to provide a clear indication of the relative performances.

Table 5-16: Base-load average values

	GT21	GT22	DIFFERENCE
Corrected power output (MW)	162.5	161.2	1.3
Heat rate (kJ/kWh)	10841	11496	655
Corrected EGT (^{o}C)	640.4	638.2	2.2
Base-load data (qty)	3920	5693	1773
Base-load data (%)	1.9	3.2	
Base-load hours	326.7	230.1	96.6

The values above show that GT21 produced more power output albeit with a marginally higher corrected exhaust gas temperature than GT22 but with a far superior heat rate and for a longer period of time. The on-line washing frequencies employed on this pair of gas turbines were remarkably similar with only 2 hours difference; however, this was not the case when it came to the off-line wash interval. There was almost a 15% difference in the frequencies of off-line washes between the 2 gas turbines, GT21 every 95 days but only 83 days for GT22, a variation of 12 days.

5.2.2 Pair B: Cost-benefit analysis for inter-service period

Repeating the same method and calculations used with the first pair of gas turbines, CBA's were compiled for GT's 21 & 22, to determine the financial implications of the differing wash regimes.

The breakdown of these calculations into 3 parts was the same, revenue from electricity generated, associated fuel costs incurred and wash fluid costs, however, due to the substantial difference in the duration of the trial period this was also included. The disparity in the duration of the inter-service periods can be seen in Table 5-15, GT21 being 88 days, more than 14%, longer; this extra period of operations would have led to additional degradation. This fact must be taken into account when considering the results of the CBA’s.

5.2.2.1 Pair B: Revenue from inter-service period

Having calculated the average daily output using the linear rate of degradation and average daily power output from Figures 5-24 & 5-25, the maximum possible power produced for the inter-service period was calculated using Eq. (5-1) for both gas turbines at both base & part-load conditions.

Table 5-17: Base & part-load average values

	GT21		GT22	
Load setting	Base-load	Part-load	Base-load	Part-load
Average power output (MW)	162.5	158.8	161.2	158.4
Average heat rate (kJ/kWh)	10841	11468	11496	11850
Percentage of data at each load setting	1.9%	13.1%	3.2%	9.7%
Duration (days)	702		614	

Accounting for the various durations at the different power settings necessitated the inclusion of the percentage of exporting hours, base & part-load, within the Eq. (5-2).

Table 5-18: Revenue from electricity generated

	GT21	GT22
Base-load average output (MW)	162.5	161.2
Percentage of time operated at base-load	1.9%	3.2%
Base-load production (MW)	52018	75999
Part-load average output (MW)	158.8	158.4
Percentage of time operated at part-load	13.1%	9.7%
Part-load production (MW)	350,477	226,390
Total revenue*	**£12,074,842**	**£9,071,666**

* Electricity export value £30/MWh at the time of the trial

Applying the electricity export price to the combined production totals for base & part-load from the previous calculations, provided the revenue for the inter-service period using Eq. (5-3), with the results displayed in Figure 5-18.

5.2.2.2 Pair B: Associated fuel cost for the inter-service period

Using Eq. (5-4) and the same electricity export price as before, the fuel cost was calculated which took into account that the 2 gas turbines had been operating with different heat rates. The heat rate difference between that of GT21 and GT22 was over 6%, at base-load conditions and more than 3% for part-load conditions; this was very different from the first pair of gas turbines. These percentage differences were then factored into the calculations to establish the additional costs that the less efficient gas turbine would incur using Eq. (5-5) and are detailed in Table 5-19.

Table 5-19: Associated fuel cost

	GT21	GT22
Average base-load heat rate (kJ/kWh)	10841	11496
Difference of base-load heat rate from GT21	Nil	+6.04%
Base-load production (MW)	52018	75999
Base-load fuel costs	£1,144,400	£1,772,998
Average part-load heat rate (kJ/kWh)	11468	11850
Difference of part-load heat rate from GT21	Nil	3.33%
Part-load production (MW)	350,477	226,390
Part-load fuel costs	£7,710,484	£5,146,479
Total fuel costs**	**£8,854,884**	**£6,919,477**

** Fuel costs £22/kWh at the time of the trial

5.2.2.3 Pair B: Wash fluid cost for the inter-service period

The wash fluid costs associated with GT22, in this part of the trial, were going to be approximately 50% that of GT21 due to the difference in wash regimes; GT22 using a dilution ration that was twice that of the recommended being used on GT21. There would be variation due to the different wash frequencies, mainly caused by the more frequent off-line washing of GT22.

Once again the following facts were established prior to calculating the costs of wash fluid using Eq. (5-6) for both on and off-line, with the cost of the wash fluid set at £9 per litre.

- On-line wash frequency:
- Off-line wash frequency
- Quantity of litres per on-line wash
- Quantity of litres per off-line wash
- Cost of wash fluid per litre
- Number of operating hours of the inter-service period

As previously stated in Chap 4.3, the details of the trial, both gas turbines followed a wash regime that consisted of on & off-line washes. GT21 using the recommended mix ratio of 1:4 with demineralised water, whilst GT22 had the weaker mix ratio of 1:9. The records from the site showed that the average on-line wash frequencies were similar, GT21 every 68 hours with 60 litres of undiluted wash fluid and GT22's interval being 2 hours shorter with only 30 litres of undiluted wash fluid. The total on-line wash quantity, on both GT's, was 300 litres. There was however almost a 15% difference in the frequencies of off-line washes between the 2 gas turbines, GT21 every 95 days but only 83 days for GT22, a variation of 12 days. The total wash quantity for the off-line washes, on both GT's, was 700 litres with GT21 using 140 litres of wash fluid and GT22 only 70 litres.

As the inter-service period were not continuous operations at either base or part-load the actual number of operating hours had to be quantified? The initial 'raw' data was analysed to identify all the occurrences where there was a positive fuel flow recorded; applying this percentage to the total number of hours of the inter-service period produce the number of operating hours. Using Eq. (5-7) and this number of operating hours the on-line wash fluid costs were calculated.

Table 5-20: Wash fluid costs

	GT21	**GT22**
Percentage of operating hours	81.8%	88.2%
Quantity of off-line wash fluid (litres)	1035	888
Cost of off-line wash fluid (£9/litre)	£9,311	£7,989
Quantity of on-line wash fluid (litres)	12,160	5908
Cost of on-line wash fluid (£9/litre)	£109,443	£53,170
Total wash fluid costs***	**£118,753**	**£61,160**

*** Wash fluid costs £9/litre at the time of the trial

The CBA then combined the above calculations, for the revenue, associated fuel costs and wash fluid costs to enable the overall profits for each gas turbine to be calculated. Table 5-21 below is the completed CBA using the duration actually recorded for the inter-service period.

Table 5-21: CBA for inter-service period for GT21 & GT22

	GT21	**GT22**
Total revenue	£12,074,842	£9,071,666
Total fuel costs	£8,854,884	£6,919,477
Total wash fluid costs	£118,753	£61,160
Profit for individual GT's	**£3,101,204**	**£2,091,029**
Greater profit for GT21	**£1,010,175**	

This showed that GT21 returned a profit 48% greater than that of GT22, even though the expenditure, on both fuel and wash fluid was higher, 28% and 94% respectively, the 33% extra revenue outweighed these increased costs. As previously stated, GT21 operated for 88 days longer and therefore the above results not only include additional revenue but also extra fuel and wash fluid costs which do not permit a direct comparison. This was addressed by the next step which recalculated the profits on an annual basis.

5.2.3 Pair B: Cost-benefit analysis for 365 day period

This analysis was repeated using 365 days of operation, to provide annual values and Eqs. (5-1) to (5-7) inclusively and in a similar way as previously stated in Chap 5.1.3. The outcome understandably produced smaller values for revenue and incurred costs, fuel and wash fluid, but in percentage terms, the results were close to those in the previous chapter. This was due to the fact that the overall degradation had been reduced as the timescale was shortened. Table 5-22 displays the actual value of the extra profit produced by GT21 and the benefits of using the correct dilution ratio for the wash fluid.

Table 5-22: CBA for 365 days for GT21 & GT22

	GT21	**GT22**
Total revenue	£6,403,516	£5,471,877
Total fuel costs	£4,695,912	£4,317,825
Total wash fluid costs	£61,745	£36,357
Profit for individual GT's	**£1,645,859**	**£1,117,695**
Greater profit for GT21	**£528,165**	

As discussed previously the profitability of the gas turbines is affected by fluctuations in the following, the electricity export price and the cost of the fuel. The impact on the profit margin is displayed in Figure 5-28, as the extra profitability achieved by GT21 and the employment of a more effective on & off-line compressor wash regime. The compressor washing regime of GT21 & GT22 consisted of on & off-line washes, albeit with different wash fluid concentrations. This differential in the profit margins between them, whilst smaller, is none the less significant and worthwhile calculating, to understand how fluctuations affect the profitability.

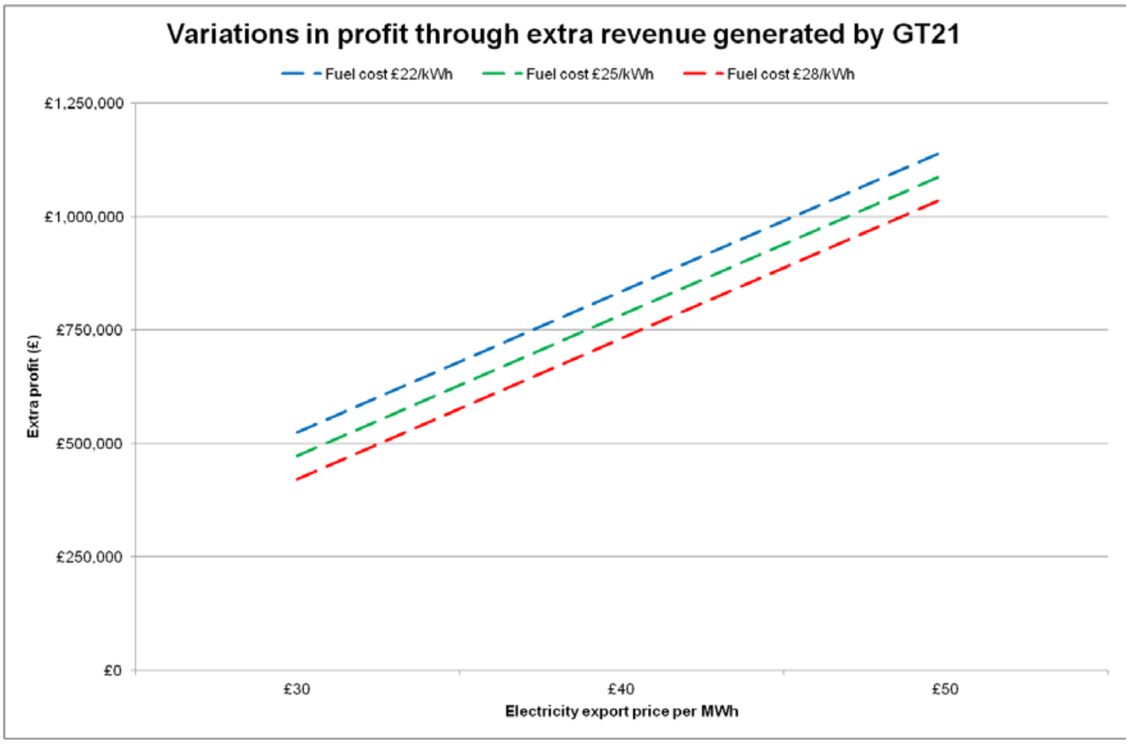

Figure 5-28: Variations in profit through extra revenue generated by GT21

5.2.4 Pair B: Supporting evidence of additional benefits

In much the same way as for the first pair of GT's, there is supporting evidence of additional benefits of on-line compressor washing using the recommended mix ratio in terms of lower operating temperatures. Whilst the magnitude may not be of the scale witnessed previously it is still significant, especially when both gas turbines have been operated with an on & off-line wash regime.

It can be seen in Figure 5-29 that for the majority of the time the difference in the corrected EGT is approximately 5^{o}C, with the maximum reaching over 12^{o}C. There were some occasions when this was reversed with GT21 displaying a fractionally higher corrected EGT than GT22 but they numbered less than 6 and of a short duration and with a difference in temperature of less than 6^{o}C. These differences are even smaller than those shown by the GT's in the first pair, but still need to be taken into consideration when assessing the performances of each gas turbine.

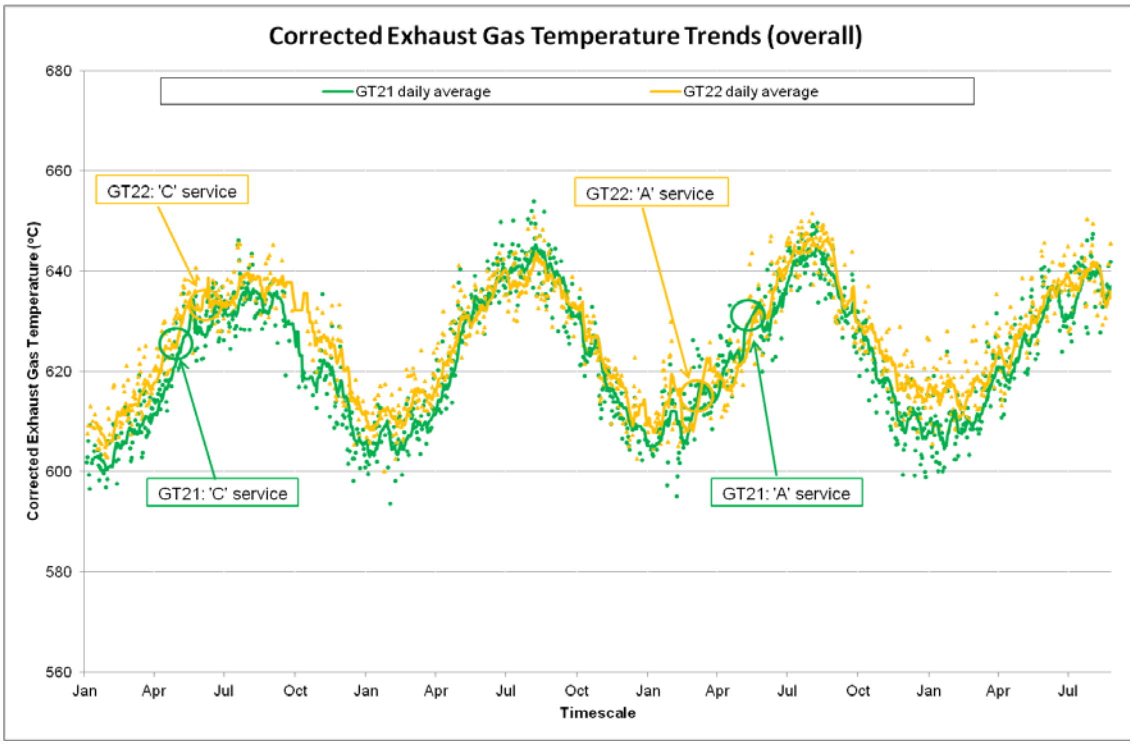

Figure 5-29: Corrected Exhaust Gas Temperature Trends (overall)

Despite GT22 being washed both, on & off-line, more frequently; there were additional wash fluid costs for GT21 due to the difference in dilution ratios. Whilst the financial impact of these additional litres of wash fluid on GT21 were small when compared to the increased revenue and reduced fuel cost previously calculated; they are important factors that need to be considered in the relative performances of the gas turbines. This indicated that despite GT22 being washed more often, their effectiveness was no better. The conclusion drawn from this is that the over diluted wash fluid was not as effective at cleaning the fouling off the blades etc. As a result, the compressor was fouled to such a degree that regular compressor washing was no longer enough to completely remove the deposits and return it to a fully clean state. Further fouling would then have been made easier due to the partially clean state of the compressor.

5.2.5 Pair B: Summary of relative performances

In summary, this part of the trial showed that compressor washing with an over-diluted wash fluid was not as effective at maintaining the cleanliness of the compressor while following similar washing regimes.

The recorded data, 3 years 8 months for the total period, before the introduction of the data filters, showed that GT22 had 54% more recorded occasions at base-load than GT21, see Table 3-1. This is due to GT22 meeting the parameters, that match base-load conditions, ahead of and more often than GT21: as they were operated under load sharing conditions this can be attributed to the more degraded state of the compressor.

After the introduction of the data filters, to remove any erroneous data, the differential between the base-load occurrences remained fairly constant, despite the fact that there were 7% more records of ‘valid’ data for GT21 available. This proved that GT21 was unable to attain base-load conditions and remained operating at part-load, Table 5-12. This situation is repeated when focusing in on the data from the inter-service period even though GT21 operated for 88 days longer than GT22, see Table 5-14.

Despite the facts above it was shown that GT22, at base-load conditions, not only produces 1.3MW less power but also recorded a substantially poorer heat rate, 655kJ/kWh worse than GT21, throughout the inter-service period, as displayed in Table 5-16. This had a double impact in financial terms that demonstrated the underperformance of the compressor washing regime.

The performance difference in monetary terms between GT21 & GT22 was similar to that recorded for the gas turbines in Pair A, as shown by using the figures from the CBA’s for 365 days, Tables 5-11 & 5-22. An indication that profitability can be affected by not only revenue from increased exported electricity but also by the efficient use of fuel required to produce it.

As with the first pair of gas turbines when studying the split in the total data, see Table 3-1, it was found when comparing the quantity of base-load data for each gas turbine, that GT22 had 54% more than GT21. Whilst not on the same scale as the difference between the GT in Pair A, it is an indication that when producing an exportable product, GT22 works harder to keep pace with the other gas turbines with which it is load sharing.

6 Conclusions & recommendation for future work

Firstly, the efficiency of a gas turbine can be demonstrated in various ways and by looking at certain parameters. In this case, they were the corrected power output of the gas turbine, the corrected exhaust gas temperature and the heat rate, both at base & part-load conditions, which have been highlighted throughout this study. A combination of these parameters is able to provide a comprehensive indication as to the actual gas turbine efficiency as discussed below.

The parameter, where differences in the respective GT was most evident, is the level of power output generated when operated at base-load; available as a direct reading from the control system, although correction was required to account for the fluctuations in atmospheric conditions. It became immediately apparent when studying the base-load conditions during the inter service period, of the GT's in Pair A, that this had a direct impact on the revenue from the plant, as the average power output for GT24 was 4MW or 2.6% more than GT23. The situation was not so clear when studying the power outputs from GT’s 21 & 22 where there was only 1.3MW or 0.8% difference and therefore its importance could have been overlooked.

The next most obvious indicator of efficiency was the corrected exhaust gas temperature difference between two identical GT’s. It was found that the EGT of GT23 was consistently higher than GT24, by ~12^{o}C throughout the trial which would have been caused by the reduction in mass flow that the compressor section of the gas turbine was able to handle. The corrected exhaust gas temperatures recorded on the gas turbines from Pair B were within 2^{o}C, which was not considered significant.

Maybe the least readily available is the heat rate, as there is a need to calculate it rather than obtain a direct reading from the control system. Once established, however, it provides a direct value as to some of the operating costs of the gas turbines. The heat rates for the GT’s in Pair A, only varied by 50kJ/kWh, a relatively small difference when compared to that of GT’s 21 & 22 which was

655kJ/kWh, over 6%. Whilst the variations in heat rate recorded at base-load conditions cannot be directly applied to other power settings on the GT operating range; it is never the less a valuable indicator of the GT fuel efficiency at its optimum point.

It can be seen that the only way to identify the true efficiency of a gas turbine is to examine the performance from more than one aspect to achieve a complete picture of the situation. The fact that the gas turbines in the first pair operated with similar heat rates but widely different power outputs and exhaust gas temperatures, whilst the opposite was true for the second pair. The 2 gas turbines which did not follow the recommended on-line wash frequency and dilution ratio, as laid down by the OEM for the high-pressure wash system and fluid, both exhibited signs of inefficient operation. This manifested itself in the higher exhaust gas temperatures, an indication that the compressor performance is degraded and therefore reducing the potential mass flow of the gas turbine. These are clear indications that there is a requirement for on and off-line compressor washing using the recommended dilution ratio.

The second conclusion drawn from the data analysis of this 2-part trial is that the gas turbines are not being operated at their most efficient, with less than 6% of the time is spent at base-load. Unfortunately, this has been driven by governmental constraints and changes in generating policy; however, with enhanced monitoring of the gas turbine operation and performance, this could be improved. This information could provide reasons for the operators to look at different operating regimes to maximise the benefits from their plant.

Thirdly, the difference in time spent at base-load of the gas turbines of Pair A indicate that GT23, that is only washed off-line, operated at base-load 70% more often than GT24; an indication that when load sharing, it was having to work harder to produce its proportion of the demand. This would suggest that a wash regime that includes both on and off-line washing is effectively maintaining performance as demonstrated with GT24.

A similar difference, albeit smaller, was also observed when comparing the time spent at base-load of the gas turbines from Pair B, where GT22, washed with a weaker solution of wash fluid but the same frequency as GT21 recorded almost 55% more occurrences. Suggesting that the over dilution of the wash fluid reduces the effectiveness of any wash regime.

At the site in question, there are multiple gas turbines which were for the majority of the time operated at part-load conditions, not the most efficient. If there were a way to manage their operation in such a way as to permit a number of gas turbines at base-load for prolonged periods then it would be beneficial, both in economic and engineering terms. Instead of operating all the gas turbines at base-load for a small percentage of the time, it would be prudent to select one or more for base-load operations continually with the minimum number at part-load generating the remainder of the demand. This would allow the operator to achieve the maximum benefit from the base-load operation in terms of power output revenue and fuel efficiency. For the gas turbines not running at base-load, there would be a requirement to ensure that they remained above the minimum stable load. Having the most gas turbines at base-load and those that were not, kept to a minimum would provide maximum efficiency and minimum losses whilst still maintaining a degree of flexibility.

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