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Performance Degradation Effects in Modern Industrial Gas Turbines

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ABSTRACT

Like any machinery, industrial gas turbines exhibit the effects of wear and tear over time. A detailed analysis and simulation of the effect of component deterioration (or degradation) on overall engine performance is presented. The emphasis of this paper is showing recoverable and non-recoverable degradation on specific components resulting in an overall effect on gas turbine system performance and operation. The interaction of degraded components is studied in detail. An engine model is subjected to various types of degradation, and the effect on operating parameters is studied. The focus is on three areas associated with component degradation: impact on gas turbine compressor operating line, full load and part load gas turbine performance characteristics, and measurable engine operating parameters. Example test data is provided to support conclusions from the model simulations.

INTRODUCTION

The purpose of this paper is to provide well documented data from gas turbines operating in the field. This data is carefully analysed and conclusions are drawn that provide insight into some of the open questions in this field [1,2,3,4]. These include the preventability of fouling, the level of non-recoverable degradation, as well as data on component degradation, and the level of power and heat rate degradation.

The paper contains degradation examples of an installed Mercury 50 engine exhibiting significant compressor fouling rates, data trends from a Titan 250 engine, and an evaluation of a Mars 100 overhaul return. Simulation data and field data are shown on a compressor map, and a hypothetical scenario shows component contributions to power and heat rate degradation.

Degradation of industrial gas turbines over their service life can be classified as recoverable and non-recoverable. Recoverable degradation can be defined as performance loss that can be recovered by operational procedures without the need of hardware replacement. Typical measures to recover degradation include conducting a water wash of the compressor to restore flow and efficiency to as commissioned levels. Non recoverable degradation is performance loss that cannot be recovered without replacement or repair of affected components.

DEGRADATION MECHANISMS

Several mechanisms cause the degradation of gas turbines [1]:

Fouling is caused by the adherence of particles to airfoils and annulus surfaces. Oil or water mists on the surface significantly increase the amount of particles that are captured, and typically only small particles (up to 10 µm) stick to the surface. Smoke, oil mists, carbon, and sea salt particles are typical examples. The build-up of dirt particles increases surface roughness and may change the shape of the airfoil. Fouling can be controlled by appropriate air filtration system, and often reversed to some degree by detergent washing of components.

Hot corrosion is the loss or deterioration of material from flow path components caused by chemical reactions between the component and certain contaminants, such as salts (for example sodium and potassium), mineral acids or reactive gases (such as hydrogen sulfide or sulfur oxides). Since many industrial gas turbines are located near the sea, sea salt (sodium chloride) is often a potential offender. Sodium sulfate is often the result of the combination of sulfur in the fuel and sodium chloride in the air.

Corrosion is caused both by inlet air contaminants and by fuel and combustion derived contaminants. Fuel side corrosion is typically more noted and severe with heavy fuel oils and distillates than with natural gas because of impurities and additives in the liquid fuels that leave aggressive deposits after combustion. Corrosion is often produced by salts such as sodium and potassium, but lead and vanadium are also common contributors.

Erosion is the abrasive removal of material from the flow path by hard or incompressible particles or droplets impinging on flow surfaces. These particles typically have to be larger than 10µm in diameter to cause erosion by impact. State of the art filtration systems used for industrial applications can keep these these larger particles from entering the engine. Erosion can become a problem for engines using water droplets for inlet cooling or water washing.

Abrasion is caused when a rotating surface rubs on a stationary surface. Many engines use abradable surfaces, where a certain amount of rubbing is allowed during the run-in of the engine, in order to establish proper clearances. Bearings tend to become softer (reduction in stiffness) due to an increase in clearance over time that causes an increase in journal orbital amplitude. The larger orbit can result in material removal at blade tips and seals , which will increase seal or tip gaps.

Damage may also be caused by *foreign objects* striking the flow path components. These objects may enter the engine with the inlet air, or are the result of broken off pieces of the engine itself. Pieces of ice breaking off the inlet, or carbon build up breaking off from fuel nozzles can also cause damage.

Fouling, Corrosion, Hot Corrosion and Erosion can to some degree controlled by appropriate inlet air filtration.

While fouling effects can be reversed by cleaning or washing the engine, other effects require the adjustment, repair or replacement of components. It is thus common to distinguish between recoverable and non-recoverable degradation. Any degradation mechanisms that can be reversed by on-line and off-line water washing are considered recoverable degradation. Degradation mechanisms that require the replacement of parts are considered non-recoverable, because they usually require an engine overhaul.

The determination of the exact amount of performance degradation in the field is rather difficult, due to ubiquitous test uncertainties. Even trending involves some uncertainties, in particular when data from transient operating conditions has to be identified [5].

Few publications exist that indicate the rate of gas turbine degradation. In many instances it seems that the initial degradation on a new engine is seen as more rapid than the degradation after several thousand hours of operation. One cause for this might lie in different performance test practices of different manufacturers. If the engine, as a part of the factory test process, is subjected to a hot restart (i.e. the engine is shut down, and almost immediately restarted. This will normally cause the smallest possible clearances. Therefore, during later operation of the engine, clearances will not open up further) prior to the performance test, the performance data will already reflect the clearances that will likely not deteriorate during the later engine operation. In this case, the early sharp drop in degradation may be reduced. Another design feature that can slow degradation is the effort to thermally match stationary and rotating parts of the engine. This means, that the thermal growth of components is matched such that the running clearance remain constant during thermal cycles (i.e. change of load or start and stop).

Three major effects determine the performance deterioration of the gas turbine compressor: Increased tip clearances, changes in airfoil geometry, and changes in airfoil surface quality [1].

While the first two effects typically lead to non-recoverable degradation, the latter effect can at least partially reversed by washing the compressor (Stalder [6]). Stage degradation also has a cumulative effect: A degraded stage will create different exit conditions than a new stage, and each subsequent stage will operate further away from its design point. While in the new machine all stages were working at their optimum efficiency point at design surge margins, the degradation will force all stages after the first one to work at off optimum surge margins and lower than design efficiency. This will not only lower the overall efficiency and the pressure ratio that can be achieved, but also the operating range. Furthermore, increased tip clearances will effectively reduce the flow capacity of the compressor. Careful readjusting variable geometry, where available, could be used to counteract some of the mismatching effects of degradation.

Typically, a degraded compressor also will have a reduced surge or stall margin (Spakovszki et al[7], Brun, et al [8]). While the reduced surge margin may not directly affect the steady state operation, it may reduce transient capabilities (e.g. block loads or dropped loads for generator sets), and could cause damages if other actions are taken that further reduce the surge margin. Examples are the use of overspraying (i.e the spraying water in the engine inlet to reduce the engine inlet temperature, to the extent that some the water does not complete evaporate before entering the compressor) for performance enhancement, or if a fuel with a very high content of dilutants is used (Brun et al, [8]).

Graf et al [9] discuss an axial compressor with increased clearances causing reduced surge margin and reduced efficiency. In this case, the clearance was increased from 2.9% (design value) to 4.3%. This led to an increase in surge flow coefficient of about 20%, a reduction in design pressure coefficient of 12% and a loss of design point efficiency of 2.5 points.

The compressor pressure ratio and the compressor flow are not independent, and the compressor efficiency is determined by the resulting compressor operating point. Increases in tip clearance as well as deteriorated airfoils will shift the pressure ratio-flow relationship for a given operating speed to lower flow rates, as well as to lower efficiencies [1].

Just as for the compressor section, the turbine section experiences the following issues as a result of degradation: Increased tip clearances, changes in airfoil geometry, and changes in airfoil surface quality. Maintenance of tip clearances is in particular a problem in the turbine section, due to the extreme changes in temperatures between a cold engine and an engine accelerating to full load. In many designs the stationary components expand at a different rate than rotating components. Many new turbine designs use abradable seals to minimize these clearances. However, the most severe case, which is usually after a hot restart, will determine the minimum clearance for the engine.

In addition to a reduced efficiency, added clearances will also increase the axial flow blockage, and thus will cause reduced through flow, and increased velocities in the main flow. Radtke and Dibelius [10] report a reduction in efficiency of a multistage turbine by 0.6% when they increased the radial clearances from 0.5% of the blade height at the rotors and 0.4% of the blade height at the stators to 0.8% of the blade height at rotors and stators.

Corrosion tends to alter the flow path in two regards: It increases the surface roughness, but it may also remove material, in particular at the leading edges and the trailing edge of the airfoils. Especially the turbine nozzles, operating at or near choked conditions, are very sensitive to changes in flow area. Furthermore, changes in the flow capacity of the turbine section will subsequently alter the operating points for the engine compressor. Increased surface roughness causes thicker boundary layers on the blades and sidewalls, and thus may reduce the flow capacity, especially near choking conditions. Boyle[11] found for a two stage turbine efficiency losses of 2.5% for a 10.2 μm surface roughness when compared to smooth blades. He also found, that the most pronounced differences appear at the optimum operating point at the turbine, whereas the far off-optimum efficiency was almost the same for rough and smooth blades. It should be noted, that the losses due to clearances were in the same order of magnitude as the profile losses.

However, if the degradation of the turbine section leads to material removal, especially in the nozzle area, we will see the opposite effect: The flow capacity increases for any given pressure ratio. Because the flow capacity of any nozzle is limited by the effective throat area, erosion of the trailing edge causes the throat area to increase and the exit flow angle to become more axial. This means a reduction of turning in the stator and the rotor, which will lead to reduced work extraction for this stage and to an increased flow capacity. Since the turbine nozzles constitute a flow restriction, any change in the flow capacity of the turbine section will also impact the operating points that the engine compressor will see.

In summary, data exists on the impact of specific component damage. Degradation of engine components has a compounded effect on engine performance, because the change in component performance characteristics leads to a mismatch of these components on the engine level, as well as on the component level [1]. The impact of individual component degradation is also influenced by the control system and the control modes of the engine. Single shaft engines, operating at constant speed will show different degradation behavior than two shaft engines. The impact of degradation on two shaft engines depends on the control mode they are in, i.e. whether the gas generator speed or the firing temperature are the limiting factors. Additional, the method and location of measuring the control temperature will determine the behavior of the engine in degraded conditions.

INLET AIR FILTRATION SYSTEMS

Industrial gas turbines can afford very effective inlet filtration systems. Modern systems can virtually eliminate the ingestion of particles into the engine compressor that can cause erosion (Figure 1). The trade-off for filtration systems lies in size , weight and cost on one side versus filtration efficiency versus low pressure loss [12,13].

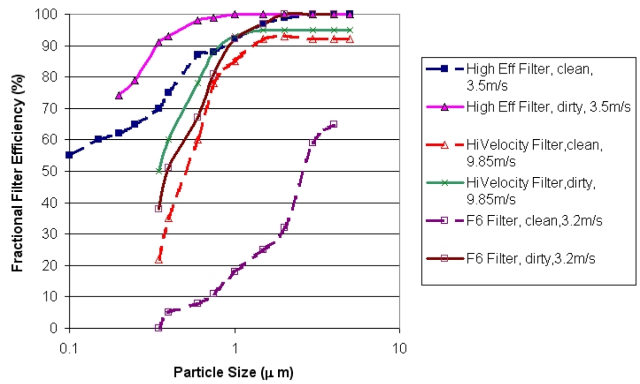

Figure 1: Comparison of fractional efficiency for filter elements from different suppliers and different face velocities in new and dirty conditions [12].

Schroth et al [13] report on a comparison of gas turbine power loss for two different air filtration systems used on 165MW gas turbines. The filtration systems are either a 2 stage or a 3stage system. The 3 stage system causes a significant reduction in finer particles entering the engine. Power loss after 3000 hours of operation was 4% with the 2 stage system and 2% with the 3 stage system.

If an engine ingests 100kg/year of contaminants if there were no filtration system in a typical off shore application, an F5[1] filter would reduce this to about 21kg/year, an F6[1]filter to 6kg/year, a F7/H10[1] filter system to 0.2kg/year and a F7/F9/H10[1] system to as little as 0.05 kg/year.

This yields two conclusions:. The overall contaminant ingestion can be influenced by several orders of magnitude by using an appropriate air filtration system. This, in turn, reduces the rate of degradation significantly. Second, with high efficiency filtration systems mentioned above, there are virtually no particles larger than a micron entering the engine.

DIAGNOSTIC METHODOLOGY

Some Solar engines have extensive standard instrumentation used for health monitoring and diagnostic purposes. Both the Mercury 50 and the Titan 250 have such instrumentation to isolate each component module contributing to overall engine behaviour and to perform model diagnostics to identify engine

[1] Per EN 779

and instrumentation faults. Temperature is measured at the inlet, the compressor exit, recuperator exit (Mercury 50 only), inter turbine, and turbine exhaust. Pressure is measured at the inlet, across the filter to the inlet of the compressor, compressor exit, recuperator exit (Mercury 50 only), turbine inlet, inter turbine (Titan 250 only), and exhaust. Shaft speeds, power, fuel flow, and other more specialized instrumentation may be included for further granularity, such as for secondary flow networks. Inlet airflow is measured with compressor inlet pressure drop measurements calibrated to test cell measured values. All of these measurements are processed for trending and for input into representative engine performance models. By matching the model to the measured data, the model characteristics are scaled. The component scalars can be used to diagnose the engine component or instrumentation faults. Time series, like the ones presented in this paper, can also be used to set up predictive models, as, for example, described in [14].

CASE STUDIES

Case Study 1 - Mercury 50 (1 Shaft Recuperated Gen Set)

Figure 2 shows the compressor efficiency, flow, and site dew point temperature data versus time for a Mercury 50 installation in southern California. The data covers a full year of operation. This particular installation includes an inlet chiller that regulates the inlet airflow to the compressor at 11°C (52°F) year around. The first observation is that there is significant fouling during parts of the year when the dew point temperature is consistently above 11°C. When the dew point temperature drops below 11°C, the fouling rate is notably reduced as shown when late Fall approaches. With the initial filter media, the customer is forced to conduct frequent water washes to sustain a high performing system. In each water wash event, the gas turbine compressor performance is fully recoverable. The second observation is the difference in loss between compressor flow and efficiency when susceptible to significant fouling. The compressor flow is reduced twice as much as compressor efficiency relative to the diagnostic scalar, which is a direct multiplier on the compressor map characteristic. The power loss to the engine at full load can exceed 10% considering this combined decrement alone. The third observation is that once an improved filter media (HEPA Filter) is applied inlet filtration system, all compressor degradation is essentially eliminated despite still being susceptible to a dew point well in excess of 11°C. This suggests that a fouling particulate that got through the original standard filtration system is not proceeding through the inlet. This small fouling particulate builds on the compressor blades and vanes at a significantly higher rate in the presence of condensing water when the dew point temperature is in excess of the chiller set temperature. The author would like to refer to this as the “sand castle” effect. Adhesion of the fouling particles with compressor surfaces and other like particles in the presence of water is notably increased [2,15,16]. This observation of reduced fouling validated this improved filter medium for the customer and for Solar Turbines.

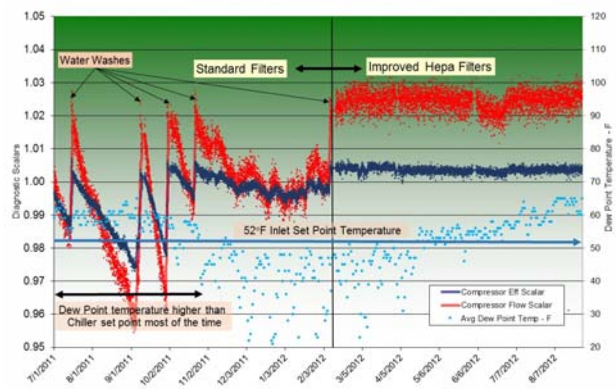

Figure 2: Mercury 50 Field Data Recoverable Compressor Degradation

One of the open questions in a number of publications [2,3,4,17,18,19] was the capability of very fine dust to alter the air foil shape and surface quality sufficiently to affect a performance deterioration. The data shows the performance of an engine with an air filtration system that filters out all but the smallest particles. It thus seems that the data indicates that very fine particles indeed will not cause any fouling at all. This also proves a statement in [2]: The effect of the type of air filtration on fouling far outweighs any effect of engine design, or engine susceptibility [3].

Figure 3 shows the increasing differential pressure across the HEPA filter media over the same time interval for the Mercury 50 installation depicted in figure 2. This indicates the improved filter media captured more of the fouling particulate that previously had made its way to the compressor inlet. The plot indicates an increase of 1.4 inH2O of inlet pressure loss over the initial 3 month period. Then the filter was replaced or cleaned, and the filter continued to show an increase in pressure loss albeit at a slower rate.

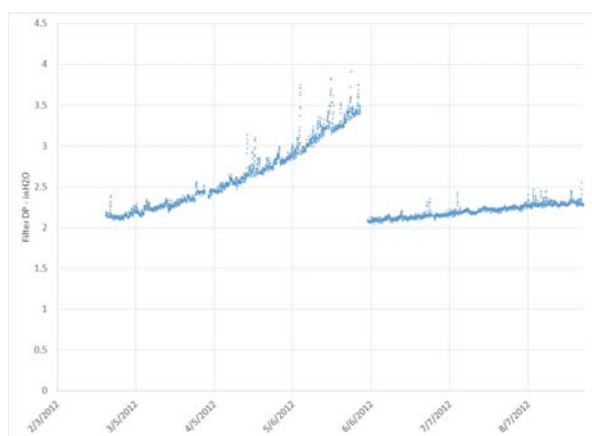

Figure 3: Mercury 50 Field Data Inlet Filter DP

Figure 4 shows power margin versus new engine level performance for the Mercury 50 installation at the same time interval depicted in Figure 2. The power loss and gains are coincident with the water washes over the observation period. The one noticeable exception is the general overall power loss demonstrated over the entire duration despite the full elimination of fouling with the new filter media resulting in a non-degrading compressor. Figure 5 shows the compressor and turbine efficiency diagnostic scalars again at the same time interval. While the compressor parameters show no degradation after the HEPA filters were installed, the turbine efficiency clearly deteriorates, leading to a loss of power over time. Hardware evaluation during overhaul identified the turbine to operate with higher running clearances which in turn results in a lower turbine efficiency. This particular issue explains this set of data. Initially, the effectiveness of the newer filter media was questioned observing only the power, but looking deeper into the diagnostic results, it could be seen that the compressor was performing in an as new state from the point in which the new filter was installed.

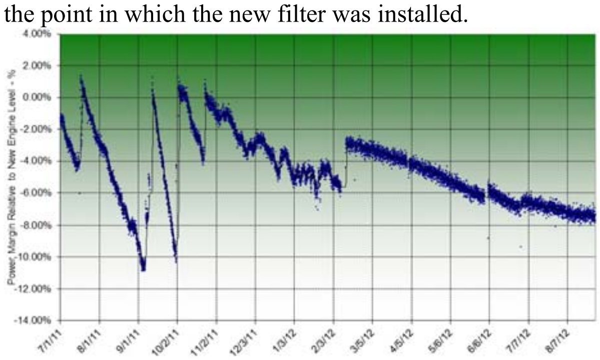

Figure 4: Mercury 50 Field Data Power Margin

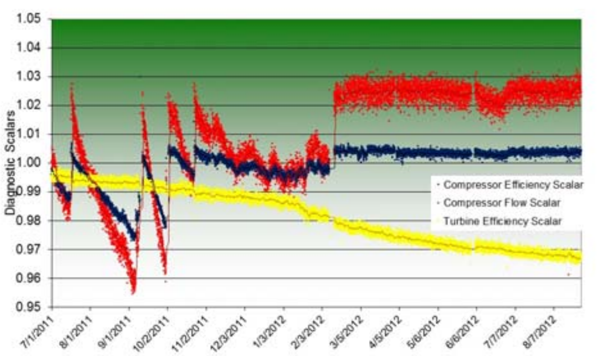

Figure 5: Mercury 50 Field Data Component Diagnostic Scalars

Case Study 2 – Titan 250 (2 Shaft Generator Set)

The next case uses data from a Titan 250 installation in Spain. Figure 6 shows power and heat rate margin relative to new engine acceptable performance for an installed Titan 250 engine plotted versus an equivalent TBO (time between overhaul) interval. A TBO interval may typically be between 30000 and 40000 hours of operation. Zero percent on the y-axis represents the performance level of a new reference engine. The tested engine performed initially slightly better than the reference engine. The data shows water washes mitigating recoverable degradation every 1000 to 2000 hours of operation through most of the first TBO cycle. One notable observation is that the engine would likely pass new performance qualification requirements after reaching the normal TBO interval in the field with one last thorough water wash. It was noted that the fuel flow measurement may have drifted over the duration of operation and probably shows better efficiency than in reality. There is confidence in the output power relative to the model reference and site condition data over the duration of operation.

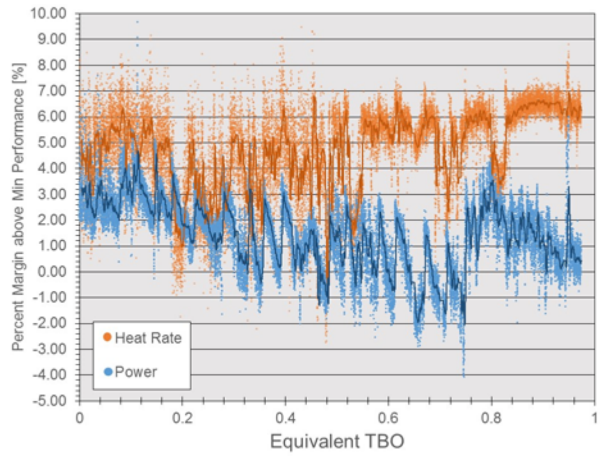

Figure 6: Titan 250 Field Data Heat Rate and Power Margin

Figure 7 shows compressor flow and efficiency scalars relative to the original compressor map characteristic over the duration of operation. The changes in compressor flow and efficiency shown in figure 7 are coincident with the changes in power margin shown in figure 6. Every water wash indicates an improvement in both compressor flow and efficiency and overall performance. There is an indication of an overall non-recoverable drop in compressor flow over the duration of operation. However, it is believed compressor flow did not fall off as much as indicated. The compressor flow measurement may have been biased for the duration. This is evident by observing the trends of the GPT flow capacity (scalar), shown in Figure 8, calculated based on the airflow measurement as well as other parameters. Typically, calculated GPT flow capacity will remain constant unless there is an unaccounted overboard leak, which however, would cause the flow to increase rather than decrease. The overall trend of GPT flow is similar to the trend for compressor flow scalar. Correcting for this trend would bring compressor flow up by about 2% at end of the trend. GPT efficiency is also shown in Figure 8. It is relatively flat and constant within expected uncertainty indicating no loss of efficiency over the duration of operation. Figure 9 shows PT flow and efficiency scalars versus each hourly point analysed. Again, PT flow is shown to be trending down much like GPT flow also indicating a bias in compressor airflow measurement over time. PT efficiency (Figure 9) shows some minor fluctuations, but does not degrade overall through the duration of operation. If the measured compressor airflow data was adjusted to account for the suspected increasing bias, the corrected data would show a slight reduction in the turbine efficiencies over time and the turbine flow capacities would be essentially constant. Overall, the data indicates that this

Titan 250 installation has incurred recoverable degradation, but little non-recoverable degradation over nearly the full TBO interval.

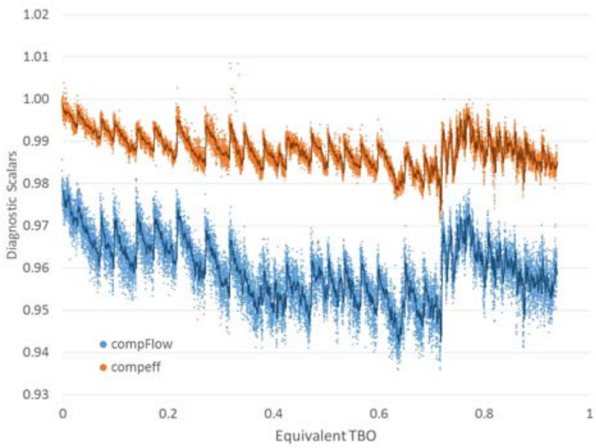

Figure 7: Titan 250 Field Data Compressor Diagnostic Scalars

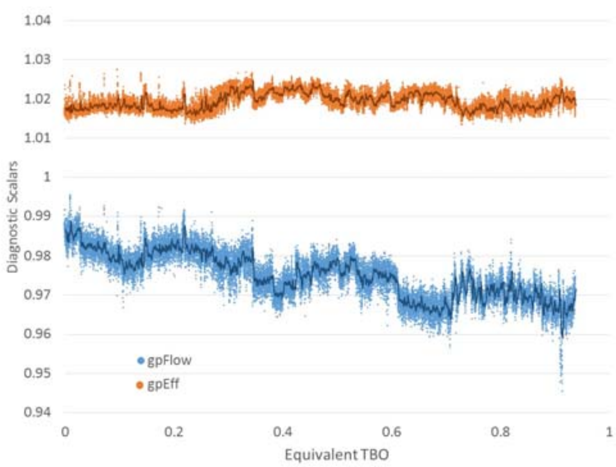

Figure 8: Titan 250 Field Data GP Turbine Diagnostic Scalars

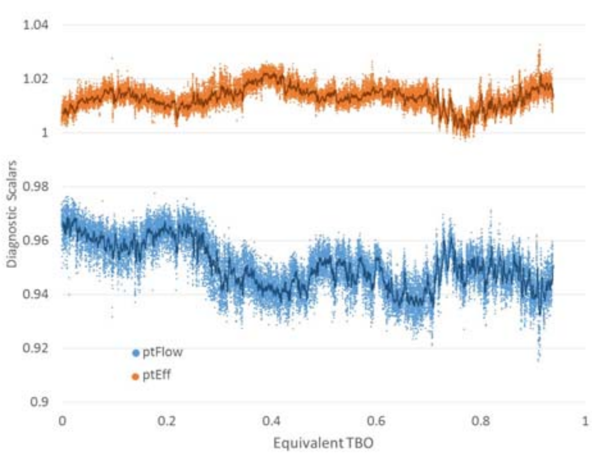

Figure 9: Titan 250 Field Data PT Turbine Diagnostic Scalars

Figure 10 shows a Titan 250 compressor map with pressure ratio versus inlet equivalent flow. The data points show installed field and simulation data. The simulation data shows a compressor operating line for a nominal engine and an engine with a degraded compressor. Sample Titan 250 field data is also provided for reference. The operating line represents a full load simulation from 59°F (15°C) to 131°F (55°C). The simulation assumed about a 2% loss in scaled compressor efficiency and about a 4% loss in scaled compressor flow. It can be observed that as the compressor degrades the op-line will match to a lower corrected flow with a slight increase in pressure ratio at a given corrected flow. The match point represents full load set by a constant TRIT (turbine rotor inlet temperature) or T5 (temperature at inlet to PT). Figure 11 shows how relative full load output power at different ambient temperatures is effected by compressor degradation and rematch on the compressor map at a much lower airflow.

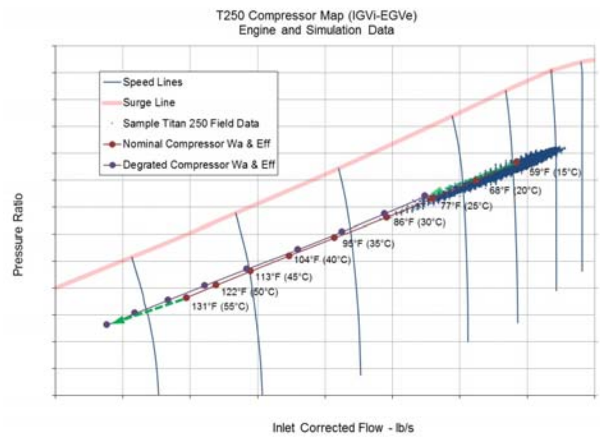

Figure 10: Titan 250 Compressor Map with Field and Simulation Data

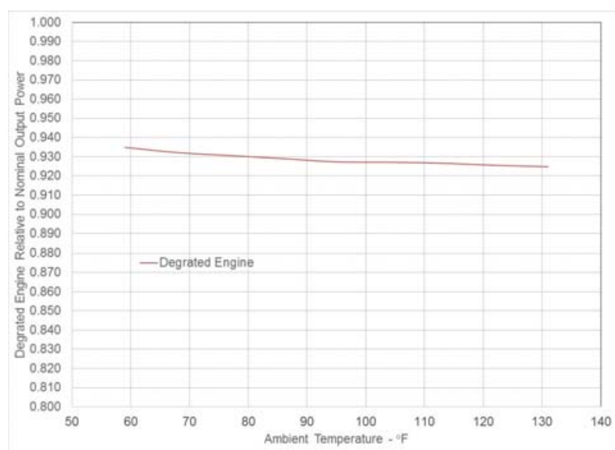

Figure 11: Titan 250 Normalized Power, Effect of Comp Degradation

Case Study 3 – Mars 100 (2 Shaft Mechanical Drive)

The final case study is a thorough evaluation made on a Mars 100 engine with a conventional combustor after an overhaul return reaching the typical service interval. This unit was well maintained and operated at part load while in service at a site in South Africa. Without any significant rubs from the rotating components, there was negligible non-recoverable performance degradation from the new to the as received condition. Figure 12 shows gas producer speed (NGP) at or below 90%, which is well below full load (~100%) speed throughout the nearly 5 years of operation in the field. Since this is an engine with conventional combustion engine, the firing temperature drops significantly at part load operation based on the control methodology. The cooler operating temperature was beneficial to the hot section components. Surface finish data was compiled for all the hot section flow path components. It was found that each component would be compliant to new engine surface finish requirements even after reaching TBO. Figure 13 illustrates where the air foil surface finish measurements were obtained. Tables were created measuring a representative sample of air foils to determine values relative to the drawing requirement. Tables 1,2 and 3 show normalized surface finish data for the Mars 100 1st stage nozzle, 1st stage blade, and 2nd stage nozzle respectively taken after tear down at overhaul. Average values at or below 1 indicate a surface finish that would be acceptable for a new engine.

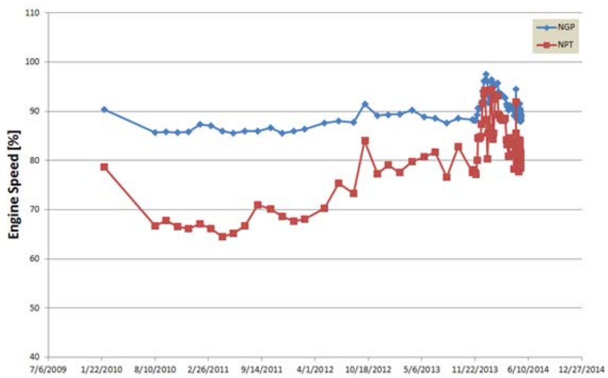

Figure 12: Mars 100 Field Data Engine Speeds to TBO

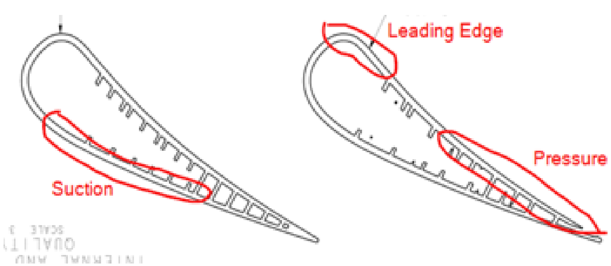

Figure 13: Airfoil Locations of Surface Finish Measurements

Stage 1 Nozzles Surface Finish (Viewed aft looking forward)				
Serial Number	Left Vane Suction Side Airfoil Trailing Edge	Right Vane Pressure Side Airfoil Trailing Edge	Right Vane Leading Edge	Inner Shroud
1	0.889	0.932	1.143	0.843
2	1.029	0.537	1.190	0.803
3	0.937	0.598	1.370	0.878
4	0.683	0.771	1.144	0.598
5	0.719	0.657	1.324	0.776
6	0.633	0.710	1.389	0.813
7	0.984	0.675	0.990	0.556
8	0.860	0.624	0.651	0.562
9	0.671	0.570	1.116	0.595
10	0.644	0.524	1.210	0.643
AVERAGE	0.805	0.660	1.153	0.707

Table 1: Stage 1 Nozzle Normalized Surface Finish Measurements

Stage 1 Turbine Blade Surface Finish (Viewed aft looking forward)				
Serial Number	Pressure Side	Suction Side	Leading Edge	Platform
1	1.137	0.965	0.908	1.024
2	0.952	0.754	0.741	1.008
3	0.954	0.767	0.684	0.879
4	0.910	0.927	0.825	0.894
5	1.095	0.956	0.798	1.073
6	0.922	0.837	0.668	0.722
7	0.989	0.817	0.698	0.752
8	0.983	0.763	0.668	0.779
9	1.016	0.687	0.789	0.890
10	0.973	0.908	0.798	0.878
AVERAGE	0.993	0.838	0.758	0.890

Table 2: Stage 1 Blade Normalized Surface Finish Measurements

Stage 2 Nozzles Surface Finish (Viewed aft looking forward)				
Serial Number	Left Vane Suction Side Airfoil Trailing Edge	Right Vane Pressure Side Airfoil Trailing Edge	Right Vane Leading Edge	Inner Shroud
1	0.638	0.698	0.516	0.540
2	0.903	0.867	0.543	0.721
3	0.660	0.832	0.546	0.975
4	0.648	0.841	0.510	0.759
5	0.733	0.913	0.586	0.786
6	0.610	0.843	0.486	0.803
7	0.637	0.829	0.579	0.843
8	0.686	0.637	0.500	0.889
9	0.492	1.056	0.622	0.856
10	0.851	0.776	0.594	0.805
AVERAGE	0.686	0.829	0.548	0.797

Table 3: Stage 1 Nozzle Normalized Surface Finish Measurements

This information, along with the general good condition all flow path components, seals, cases/shrouds, and bearings helped explain the as received finding of negligible performance loss compared to the as new condition.

PREDICTIONS

Figure 14 shows a rather conservative scenario depicting the power degradation contribution for each of the primary aerodynamic modules that make up a gas turbine made up of a gas producer and free power turbine. Figure 15 shows a similar plot depicting heat rate degradation. Considering service of the unit in-situ, the overall performance is determined with different combinations of refurbished hardware in assumed typical overhaul hour intervals. In every case the gas producer turbine is typically believed to have the potential for the most non-recoverable loss in power and heat rate. The power turbine would lose performance to a lesser extent in a given amount of time and the compressor would lose the least in non-recoverable performance over time.

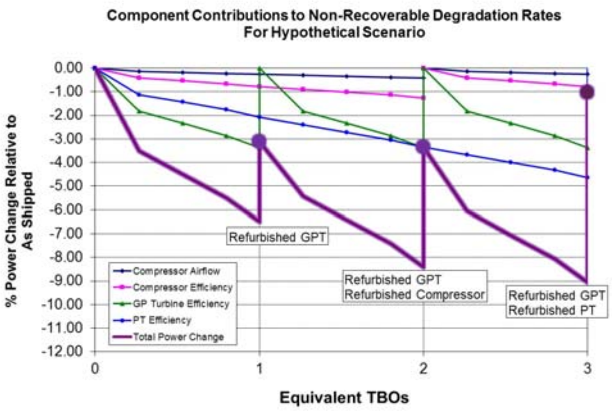

Figure 14: Hypothetical Non-Recoverable Power Degradation

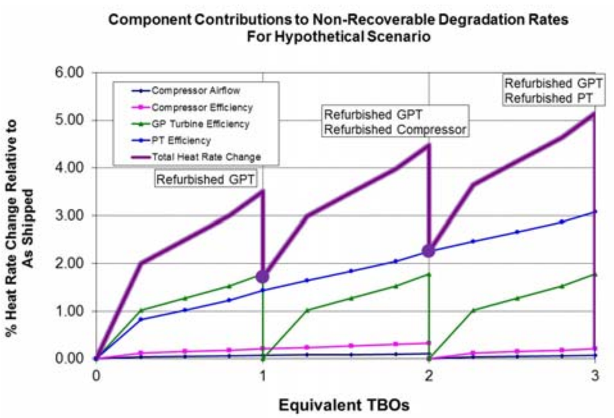

Figure 15: Hypothetical Non-Recoverable Heat Rate Degradation

CONCLUSIONS

The data presented here allows a number of crucial insights and recommendations for the users of gas turbines, as well as for researchers studying the issue of performance degradation:

-Fouling is preventable, if the appropriate filters are used
-The key parameter affecting fouling, and fouling rate is the quality of the air filtration system.
-non-recoverable degradation is well managed if the proper operational measures are taken.
-There is an impact of engine design features on non-recoverable degradation.
-power and heat rate degrade at different rates
-compressor flow and efficiency degradation seem to be closely correlated.
-the gas producer turbine (GPT) section seems to be the biggest contributor to non-recoverable degradation, followed by the power turbine (PT) and the compressor
-Actual degradation rates in well maintained, modern engines can be significantly lower than often found in the literature.

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