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GAS TURBINE PERFORMANCE ANALYSIS AND HOT-SECTION LIFE PREDICTION USING THE GTHM SYSTEM

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ABSTRACT

In the past decade, the Gas Turbine Health Management (GTHM) system has been developed, and put into service, for various engine types, such as LM2500, RB211-24G and 11NMC, for various operators around the world. The system collects real time data from the on-site Programmable Logic Controllers (PLCs) or Human Machine Interfaces (HMIs), stores them in an OSISoft PI historian, and periodically executes performance calculations and factored hours calculations for each unit. The performance calculations are run from within the Gas Turbine Analysis Program (GTAP), one of the core modules of the health management system. The analysis program employs aerodynamic and thermodynamic principles to model each unit. It uses measured data as input and calculate a set of performance indicators, including compressor and turbine degradations, engine load, efficiencies, fuel usage etc. It also calculates inter-stage temperatures and pressures in the hot section. The health management system also includes a component life prediction module that uses the hot section component metal temperatures to calculate factored operating hours actually consumed by the engine, thereby predicting realistic remaining life of the hot section components. The system also includes turbine exhaust temperature spread radial plot, trending, and reporting modules.

INTRODUCTION

Typically, four servers would be installed at the operator's data centre. Two historian servers are used for data collection and storage, hosting a redundant PI Data Archive collective. Two application servers are used to extract data from the data collective and run the analysis program and GTHM factored hour calculations and write the results back into the historian collective. The calculated data is thus stored into the data collective and can be mined for analyses at any time. The performance indicators computed by the analysis program can be used to determine the health of the engine. For example, the engine degradations are indicators for engine wear and fouling, thus can be used to schedule borescope examinations and engine wash. The indicators calculated by the program include the following:

- Compressor efficiency degradation percentage
- Compressor flow degradation percentage
- Turbine efficiency degradation percentage
- Turbine throat area change
- Turbine Inter-stage temperatures

The turbine inter-stage temperatures are used to calculate the hot-section component life. The component life calculations would provide the operator with actual factored hours consumed by the engine which is typically more realistic than the Original Equipment Manufacturer (OEM) prescribed equivalent operating hours, as it is based on the engines actual operating conditions throughout the entire service interval. The accumulated factored hours could be used to help schedule engine overhauls, thereby potentially extend the overhaul cycle.

The health management system is a scalable solution package that has the capacity to be expanded to include various engine models from different manufacturers within one seamless interface.

This paper will focus on engine performance modelling for the analysis program, hot section component life modelling, and how they can be used to assist in turbine operation diagnostics and turbine maintenance scheduling using several case studies from various operators. Figures that include plots of data points are based on operators' data, but have been modified and are for illustrative purposes only.

METHODOLOGY

The implementation of the gas turbine health management system includes the following processes:

- Data gathering including instrumentation, data collection and storage.
- Data analysis to verify data integrity, understand operation behaviour and select appropriate data set for engine modelling.
- Developing aero-thermal engine models and unit specific engine signatures, and computing engine degradations and hot section conditions using actual operation data for engine diagnostics.
- Combining mechanical, metallurgical, aero-thermal dynamic analyses to develop life prediction models for the hot-section component(s) using the calculated hot section conditions to determine their remaining life.
- Create display screens and reports to visualize raw, treated and computed data and aid in their analyses.

The following sections will discuss each of the above topic except for data visualization.

Data Gathering

The first step in implementing the system is to conduct a gap analysis on the existing instrumentation provisions. The gas turbine analysis program's engine performance calculations require a set of measured data as input. (Appendix A) The existing instrumentation list provided by the operator is studied, and a list of additional instruments that would need to be installed is determined. In the case of Termoselva Orazul Energy's power plant in Aguaytia, Peru, operating two 11NMC units, the additional measurements are:

- Differential pressure between the inlet plenum and ambient
- Differential pressure between the inlet bell mouth and the inlet plenum
- Differential pressure between the exhaust duct and ambient

Since these measurements are usually only used for performance analysis and are not crucial for day-to-day operation, the instruments for them are typically not permanent installations. They are installed temporarily onto the unit body during engine performance tests and are removed when the tests are complete. Thus, the sensor ports already exist on the unit body. This is verified by reviewing the engine drawings as well as visual inspection of the engines. **Figure 1** shows an example of how the existing inlet casing differential pressure port is temporarily used for performance analysis.

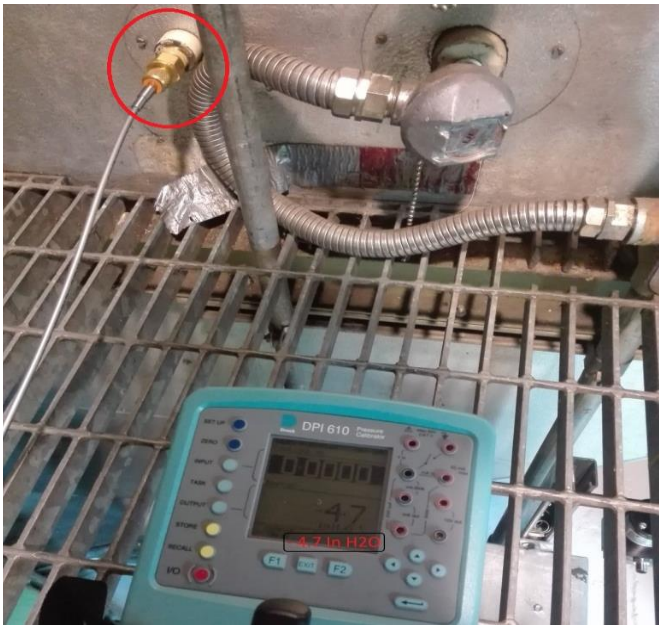

Figure 1 – 11NMC Inlet Casing Differential Pressure port for performance analysis

A set of appropriate instruments to be permanently installed onto the units is then recommended to the operator. After the operator completes the installation of these instruments and augments the control system with the new sensor inputs, their measured data are collected and stored by the management system's data collection module.

In the case of another operator running RB211-24G units, the gap analysis on their gas generator instrumentation shows the following measurements would need to be added:

- Compressor inlet differential pressure
- Low pressure(LP) compressor discharge temperature
- High pressure(HP) compressor discharge pressure
- LP turbine exhaust pressure

These measurements are part of performance packages offered by the OEM that the operator did not include at the time of purchasing the unit. Thus, the sensor ports already exist on the engine body. For LP compressor discharge temperature, the thermocouple is already installed, and is connected to the battery plate by thermocouple wire.

The instruments for these data points as well as the PLCs to digitize the signals for data collection have then been installed. As an example, **Figure 2** shows the installed RB211-24G LP compressor discharge pressure fitting and tubing.

Figure 2 – RB211-24G LP Compressor Discharge Pressure fitting and tubing

Since then, the operator has been recommended to include these performance instruments in its subsequent unit procurements.

Data Analysis

Termoselva Orazul Energy's control system in Aguaytia contains a local data historian. The operator has made available the historical measured operating data prior to the installation of the GTHM system, to assist in the modelling of the 11NMC engines. First, the existing operating data are analysed to determine typical operation environment and typical operation behaviour so to select appropriate data for engine modelling. During this process several anomalies have been revealed.

For example, plotting fuel flow against generator power for an 11NMC unit, as shown in **Figure 3**, reveals that the fuel measurements are capped.

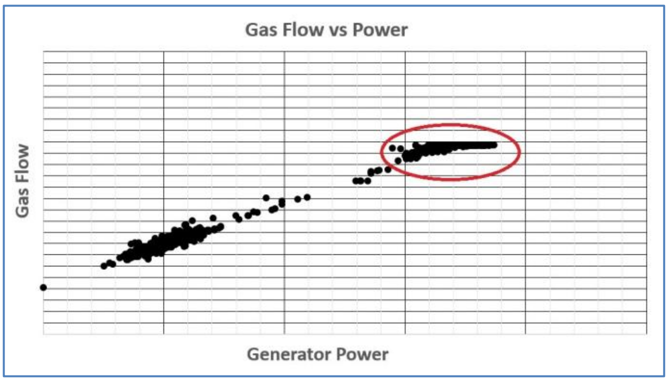

Figure 3 – 11NMC Fuel Flow readings are capped

In 2003 the unit underwent an upgrade from 11NM to 11NMC, with a 6MW guaranteed power gain. It is believed that this anomaly in fuel flow measurement is caused by an error in the on-site FloBoss devices, specifically, the fuel calculation logic in these devices were not updated to reflect the engine upgrades. This anomaly has been reported to the operator. After the operator repaired their FloBoss logic, the fuel flow vs generator power plots became normal. **Figure 4** shows the comparison of the unit fuel flow behaviour before and after the repair.

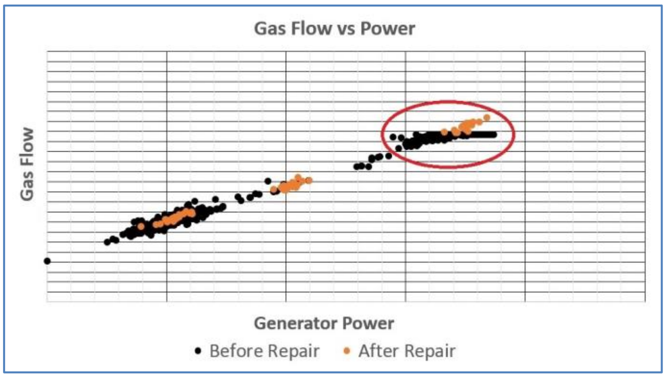

Figure 4 – 11NMC Fuel Flow reading are corrected

Subsequently, a 24-hour period is selected during which both 11NMC units are running at base load. The fuel flow trends of the two units are plotted side by side. Not only do they exhibit high fluctuations during the 24-hour period, the fluctuations also behave very similarly throughout the day. Further plotting the Fuel Stroke Reference (FSR) percentages of the two units confirms this behaviour. **Figure 5** illustrates how fuel flows and FSR percentages for both units fluctuate in synch.

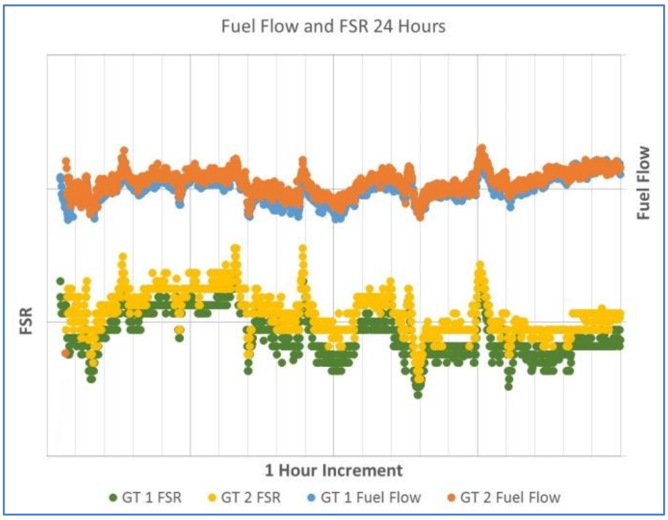

Figure 5 – Fuel Flow and Fuel Stroke Reference of both 11NMC units experience significant fluctuations in synch

Since the fuel gas arrives the power plant via a pipeline, it is believed that the simultaneous fuel fluctuations of both units are caused by pressure variations from the pipeline upstream of the power plant. This fluctuation in fuel readings causes high variances in the calculated compressor flow degradation. While the operator has been informed of this issue, an alternate method is adopted to calculate compressor flow degradation using the inlet bell mouth depression.

Performance Analysis

The GTAP aero-thermal modelling (Weber et al. 2005; Jin et al. 2006; Canteenwalla et al. 2010) process results in a set of engine signatures for each individual engine unit. The engine signature needs to be verified using selected operating data when the unit is running in steady state at baseload under new and clean conditions. Once verified, the engine signature can be used to execute performance calculations for the engine. Typically, the GTHM system would perform hourly calculations on operating data in real time. The calculated performance indicators could be trended over time for analyses.

One morning in October, 2013, the operator running RB211-24G units having one of its sites located in a semi-desert region reporting a sudden 10% increase in compressor degradation for one RB211-24G unit. The operator was recommended an immediate engine shutdown followed by a borescope examination of the compressor, which revealed severe fouling of its foils and annulus. The region in which the compressor station is located is prone to dust storms. Further examination of changes in humidity and barometric pressure in that morning indicated a severe dust storm mixed with humid air causing thick layers of fine dust particles to adhere to the compressor interior. Subsequently, the operator conducted a compressor wash. The unit was back in operation by early November. The compressor degradation indicators started reporting values reflecting unit's clean condition. **Figure 6** illustrates the sudden change in compressor degradation caused by severe fouling, and restoration of degradation after compressor wash.

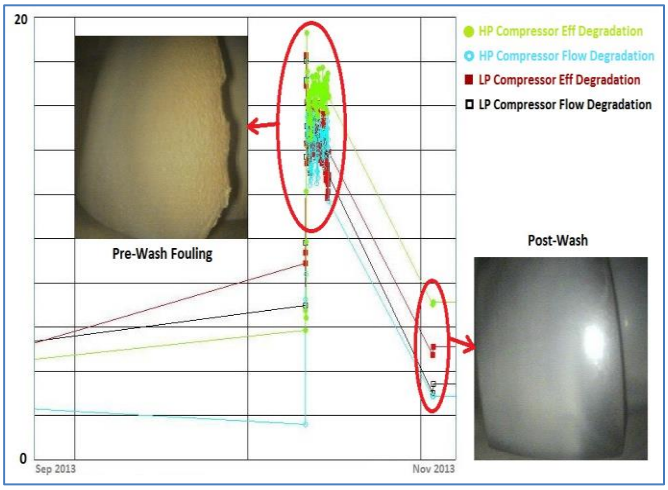

Figure 6 – RB211-24G Severe Compressor Fouling and post wash conditions

The same operator is also running an LM2500 unit in another site. The compressor efficiency degradation values of the LM2500 unit is plotted over a period of 6 months. **Figure 7** clearly shows a 5% drop in compressor efficiency degradation after a regularly scheduled compressor wash.

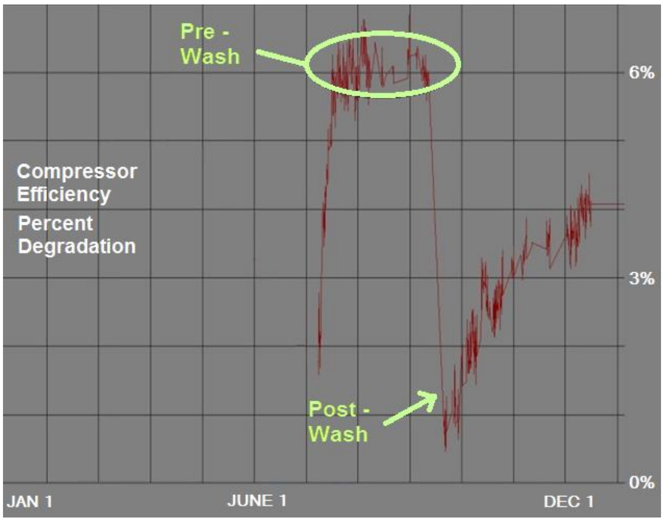

Figure 7 – LM2500 compressor efficiency degradation drop after compressor wash

The LM2500 unit had been operating at 6% compressor efficiency degradation for 2 months before the engine was washed. This happened when the health system was just installed and the operator had not yet adopted the condition-based maintenance methodology. Timely compressor wash when compressor efficiency reaches a certain predefined limit entails significant cost saving on fuel usage.

Hot-Section Life Prediction

Conventional gas turbine maintenance scheduling is typically based on OEMs' guidelines. This approach is generally conservative and does not always take into consideration the operating environment and requirements. The GTHM system offers a hot-section life prediction module that calculates more precise factored operating hours based on each engine's specific operating conditions. This requires the modelling of hot-section component life.

The modelling of gas turbine hot-section components is a multi-disciplinary task requiring expertise in metallurgy, mechanical design, fracture mechanics, aero-thermal dynamics combined with operation and service history. (Jin, 2006) Life limiting factors such as oxidation, hot corrosion, creep, thermal mechanical fatigue and so on need to be examined.

In the case of Termoselva Orazul Energy, having been performing rejuvenation services on the 11NMC stators and rotors for years allows extensive studies to be done on these foils. Computation Fluid Dynamics (CFD) analyses have been conducted on the stators and rotors to model the temperature, pressure and velocity distribution around the foils. (**Figure 8**) Finite Element Analyses (FEA) studies the internal and external heat transfer conditions and model the foils' metal temperature distributions, transient stress from thermal cycling and creep life. (**Figure 9**)

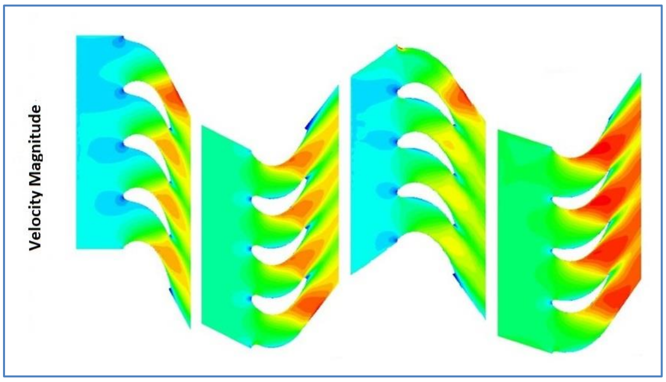

Figure 8 – CFD analysis of mid-stream velocity for stages 1 and 2 of 11NMC

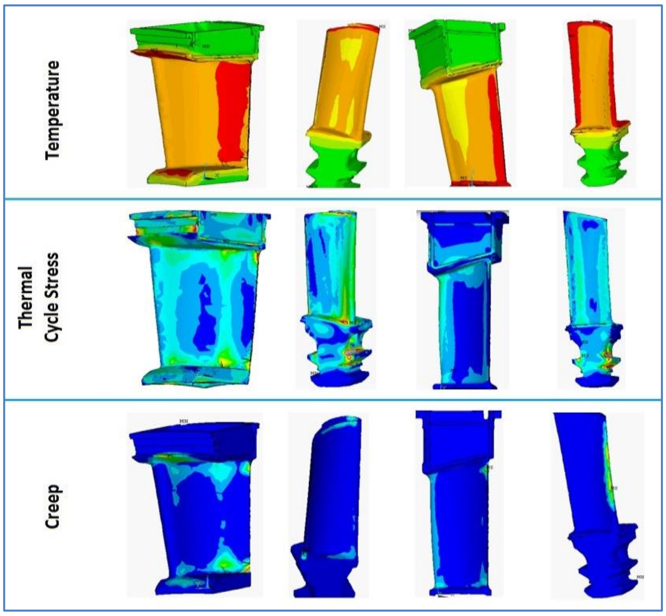

Figure 9 – FEA models of 3D temperature distribution, thermal cycle stress and creep life for stages 1 and 2 of 11NMC

The first stage rotors and stators use ceramic Thermal Barrier Coating (TBC) with MCrAlY bond coat over the substrate. It has been determined that the primary life limiting factor of the first stage foils is the cracking and spallation of the TBC coating caused by growth of Thermally Grown Oxide (TGO) under the TBC and thermal cycling damage accumulated over the engine's service life. **Figure 10** illustrates an example of the formation of the TGO layer between the ceramic top coat and the bond coat. Over time, cracks would start to form within the TBC/bond coat interface region which eventually would cause the spallation of the TBC coating.

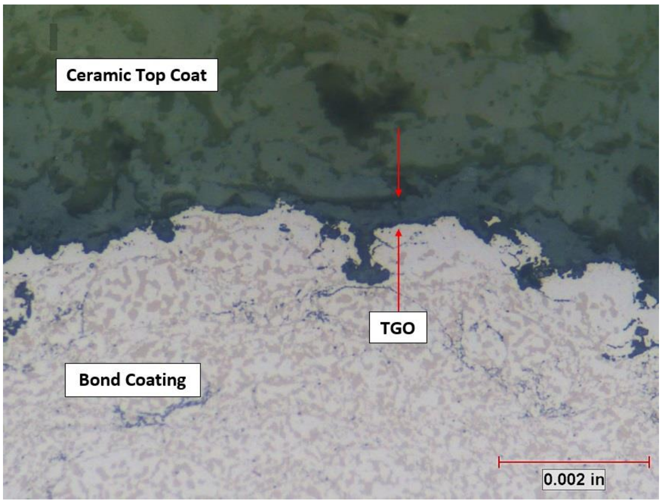

Figure 10 – TGO formation under the TBC

A life prediction model is then built to calculate the TGO growth based on the engines operating environment as well as its starts/stops. While the operator was calculating the unit's Equivalent Operating Hours (EOH) based on the OEM model,

$$\text{EOH} = \text{Operating hours} + 20 \text{ x Starts}$$

the TGO based calculation taking into account the engine's actually running conditions and requirements as well as the number of thermal cycles would render more accurate factored hours for the engine's hot section foils.

Engine Diagnoses

Combining aero-thermal and metallurgical analysis can also be used to diagnose engine operations, as can be seen in the case of BP Watson Cogeneration Company. (Canteenwalla et al. 2010) In 2004, the operator's MS7001EA units were up-rated from 1378°K firing temperature to 1397°K. The up-rate package included improved materials, bucket designs and cooling. 16,000 operating hours after the up-rate, the first stage turbine buckets of one unit were sent for metallurgical analysis. While the normal service interval for MS7001EA buckets are 24,000hours, the buckets from the operator already exhibited coating damage. (**Figure 11**)

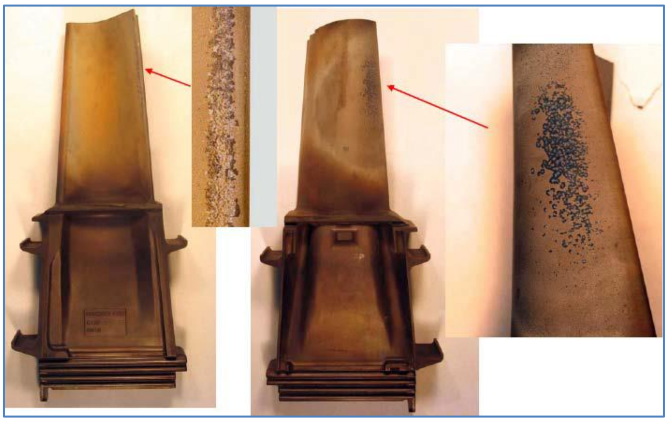

Figure 11 – Watson Cogen MS7001EA first stage turbine buckets after 16,000 service hours.

In addition to the coating damage, metallurgical analysis also revealed that the alloy microstructure had aged faster than anticipated. **Figure 12** illustrates the degrees of enlargement and agglomeration of gamma-prime precipitates in the foil microstructure at the leading edge, trailing edge and mid-height in comparison with the pristine microstructure in the root area. The aging rate of the microstructure indicated that the foil's metal temperature was 22-28°K greater than expected.

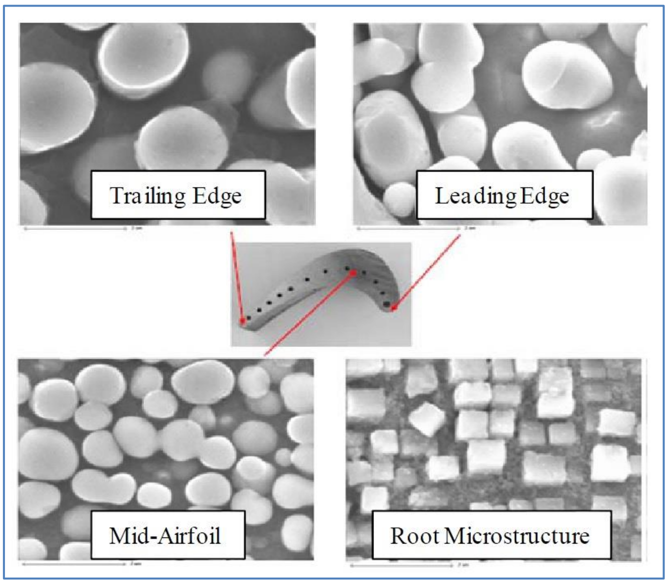

Figure 12 – Aging of microstructure in different parts of the foil vs pristine microstructure at root area, after 16,000 service hours.

The operator temporarily de-rated the engines back to the original 1378°K firing temperature for observation. However, the engines then produced 5-6% more power than before. After conducting performance calculation using an earlier version of GTAP, it was discovered that after de-rating the engine, the control curve did not return to the original firing curve before the up-rate. (**Figure 13**)

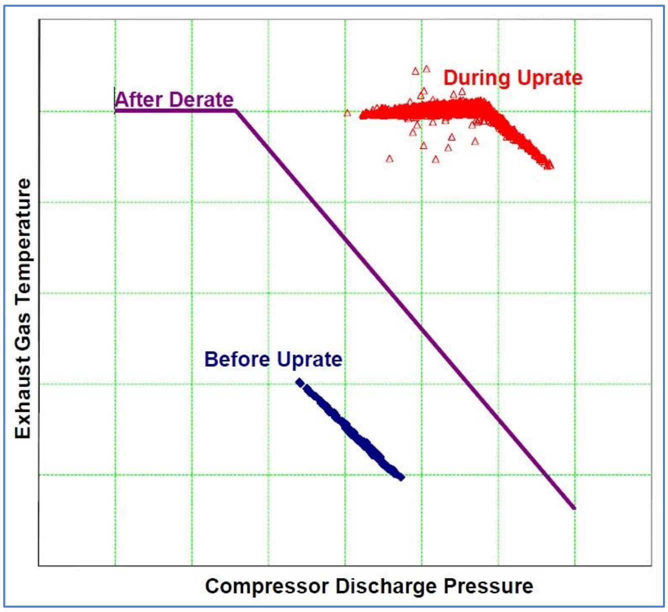

Figure 13 – Firing curve before up-rate, after up-rate and after de-rate.

This lead to the conclusion that the control curve constants were entered erroneously during the up-rate. Correcting the constants restored the engines to the original firing temperatures.

CONCLUSIONS

As an alternative to the conventional approach to gas turbine operation and maintenance, the GTHM system offers a true "on-condition maintenance" solution combining the results of mechanical, metallurgical and aero-thermal analyses of gas turbine components and mining large quantity of live operating data to compute actual engine performance and hot-section component life. This offers operators more accurate and independent means of diagnosing, maintaining and managing their turbine fleets and scheduling engine overhauls. Raw, processed and computed data will all be stored in a data historian collective and readily available for visualization and analyses. Significant cost savings could be realized by running the engines more efficiently, potentially extending service cycles and accurately diagnosing the engine operations to prevent failures.

NOMENCLATURE

CFD	Computation Fluid Dynamics
EOH	Equivalent Operating Hours
FEA	Finite Element Analysis
FSR	Fuel Stroke Reference
GTAP	Gas Turbine Analysis Program
GTHM	Gas Turbine Health Management
HMI	Human Machine Interface
HP	High Pressure
LP	Low Pressure
MCrALY	Super-alloy containing nickel and/or cobalt, chromium, aluminium, and yttrium
OEM	Original Equipment Manufacturer
PLC	Programmable Logic Controller
TBC	Thermal Barrier Coating
TGO	Thermally Grown Oxide

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APPENDIX A

GTAP performance calculation input parameters may vary among engine types. For 11NMC single shaft engine, the input parameters would include:

- Ambient temperature
- Ambient pressure
- Relative humidity
- Inlet guide vane angle
- Compressor inlet temperature
- Compressor inlet filter differential pressure
- Compressor inlet casing differential pressure
- Compressor inlet bell mouth differential pressure
- Compressor delivery temperature
- Compressor delivery pressure
- Turbine exhaust temperature
- Turbine exhaust loss differential pressure
- Generator power
- Rotation speed
- Fuel flow
- Starts/Stops

For RB211-24G twin spool engine, the input parameters would be:

- Ambient temperature
- Ambient pressure
- Relative humidity
- Compressor inlet temperature
- Compressor inlet flare differential pressure
- Compressor inlet differential pressure
- LP compressor delivery temperature
- LP compressor delivery pressure
- LP turbine exhaust pressure
- HP compressor delivery temperature
- HP compressor delivery pressure
- LP turbine exhaust temperature
- LP turbine exhaust pressure
- LP rotation speed
- HP rotation speed
- Fuel flow