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ASSESSMENT OF GAS TURBINE AND COMBINED CYCLE POWER PLANT PERFORMANCE DEGRADATION

Nina Hepperle, Dirk Therkorn, Ernst Schneider
Alstom Power
Baden, Switzerland

Stephan Staudacher
Institute of Aircraft Propulsion Systems
Stuttgart University, Germany

ABSTRACT

Recoverable and non-recoverable performance degradation has a significant impact on power plant revenues. A more in depth understanding and quantification of recoverable degradation enables operators to optimize plant operation. OEM degradation curves represent usually non-recoverable degradation, but actual power output and heat rate is affected by both, recoverable and non-recoverable degradation.

This paper presents an empirical method to correct longterm performance data of gas turbine and combined cycle power plants for recoverable degradation. Performance degradation can be assessed with standard plant instrumentation data, which has to be systematically stored, reduced, corrected and analyzed. Recoverable degradation includes mainly compressor and air inlet filter fouling, but also instrumentation degradation such as condensate in pressure sensing lines, condenser or bypass valve leakages. The presented correction method includes corrections of these effects for gas turbine and water steam cycle components. Applying the corrections on longterm operating data enables staff to assess the non-recoverable performance degradation any time. It can also be used to predict recovery potential of maintenance activities like compressor washings, instrumentation calibration or leakage repair.

The presented correction methods are validated with long-term performance data of several power plants. It is shown that the degradation rate is site-specific and influenced by boundary conditions, which have to be considered for degradation assessments.

NOMENCLATURE

Latin

c	Specific heat capacity	$[\frac{J}{kg\,K}]$
EOH	Equivalent Operating Hour	$[h]$
p	Pressure	$[Pa]$
R	Gas Constant	$[\frac{J}{kg\,K}]$
T	Temperature	$[K]$
$\dot{V}$	Volumetric Flow Rate	$[\frac{m^3}{s}]$
Z	Fouling Influence Coefficient	$[-]$

Greek

Δ	Difference	$[-]$
η	Efficiency	$[\%]$

Indices

1	Compressor inlet
2	Compressor exit
c	Compressor
n	Polytropic
p	Isobar

Abbreviations

CCPP	Combined Cycle Power Plant
GT	Gas Turbine
HEPA	High Efficiency Particulate Air Filter
ISO	International Standards Organization

LP	Low Pressure
OEM	Original Equipment Manufacturer
PSC	Plant Support Center
ST	Steam Turbine
VIGV	Variable Inlet Guide Vane

INTRODUCTION

During their operating life, gas turbine and combined cycle power plants are subjected to various environmental and operating conditions resulting in degradation effects such as fouling, erosion, corrosion, oxidation of their components and thus in a reduction of power output and efficiency of the power plant. The most important factor causing performance loss due to degradation is the ingestion of air-borne particles, since power plants operate in environments where the ingestion of solid particles such as sand, dust, water droplets, ice, fly ash, salt is inevitable [1].

There are several countermeasures available to reduce performance loss due to degradation and thus to increase the power plant revenue. These include air intake filters as well as compressor on-line and off-line washing. However, since performance degradation is dependent on site-specific boundary conditions, the right combination of countermeasures has to be chosen individually for each plant. To be able to do so an in-depth understanding of the different degradation effects is crucial. The present paper introduces correction methods to distinguish between fouling and non-recoverable deterioration with operational data.

DEGRADATION IN GAS TURBINE POWER PLANTS

Degradation Mechanism

There are several mechanism causing degradation of turbomachinery, which are extensively covered in the literature e.g. by Diakunchak [2] and Meher-Homji/Bromley [3]. Therefore only a short overview is given here:

Fouling is defined as the adherence of particles to airfoils and annulus surfaces. Fouling is the most common cause of performance loss. The adherence of particles, which is intensified by oil or water mists being present in the flow, results in a build-up of material that causes increased surface roughness, reduction of mass flow and to some degree changes the shape of the airfoil. Fouling can be controlled by air inlet filtration systems, and usually reversed to some degree by cleaning of the components, e.g. by compressor on-line and off-line washing, hand cleaning or abrasive grid-blasting [4].

Erosion is defined as the abrasive removal of material from the flow path by hard particles impinging on flow surfaces. The particles may be from an environment such as volcanic ash, sand, and chemical substances such as particles formed by fuel combustion, but also from water droplets coming from air inlet cooling or compressor washing and in the last stages of LP steam turbine [5].

Corrosion is the loss of material from flow path components caused by chemical reactions between the component and certain deposits, such as salts, mineral acids, or reactive gases [5].

Abrasion is caused when a rotating surface rubs on a stationary surface. This usually increases radial tip clearances or sealing gaps and results in higher leakage flows [5].

Other degradation mechanism are leakages in the GT hot gas path, and internal and external leakages, blockages, or deposits in the piping and condenser of the CCPP water steam cycle. Also instrumentation drift with time (degraded thermocouples, condensate in pressure sensing lines) can result in degraded performance data due to its impact on the control system.

Recoverable and Non-Recoverable Degradation

Degradation is generally classified into recoverable, non-recoverable and permanent degradation, depending on the effort it takes to recover it (see Fig. 1). The majority of performance loss due to degradation can be restored; however, the effort differs depending on the type of degradation. Degradation that can be recovered while the gas turbine remains closed (e.g. compressor on-line or off-line washing, hand cleaning, filter exchange) is called recoverable degradation. Non-recoverable degradation, however, can only be recovered during a major overhaul with opening of the GT or ST casing. Generally it can be said that fouling, instrumentation drift, internal valve and condenser leakages are mainly causing recoverable degradation, whereas erosion, corrosion, abrasion, other leakages, and steam pipe blockage or deposits are mainly responsible for non-recoverable degradation.

Usually also with a major overhaul not all performance degradation can be recovered. The part that cannot be recovered is called aging or permanent degradation. The reasons for permanent degradation are for example casing ovalisation, increased surface roughness of flow path components, distortion in platforms causing loss of aerodynamic performance and increased leakages. According to Alstom experience and open literature permanent degradation is usually small [2].

Measures to Reduce Fouling

According to Hoeft et al. [6] fouling is responsible for $70-85\%$ of all gas turbine performance loss. Therefore in order to introduce countermeasures to reduce degradation, the reduction of fouling has to be the main focus. The most common measures to reduce fouling are compressor washing and inlet filter exchange.

Compressor Washing A compressor can either be cleaned by compressor on-line washing, off-line washing, hand cleaning or abrasive cleaning.

Compressor on-line washing is usually done while the gas turbine is in base load operation with VIGVs fully open. The

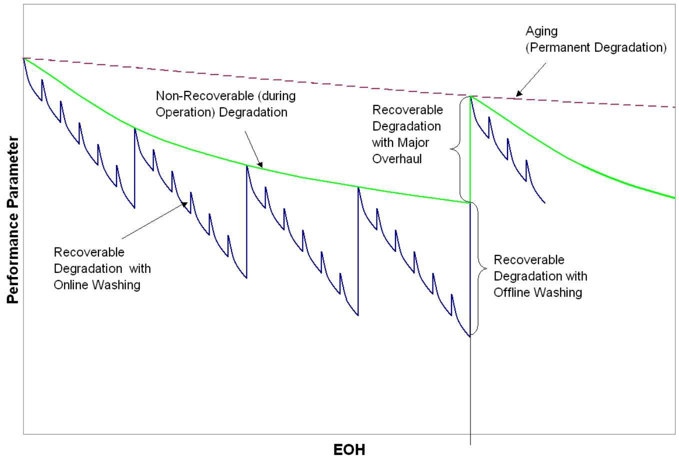

Figure 1. RECOVERABLE AND NON-RECOVERABLE DEGRADATION

cleaning effect of compressor on-line washing can only be observed in the front stages of the compressor, since the injected water evaporates due to the increasing temperature in the compressor. Compressor on-line washing can only diminish but not prevent the degree of fouling in the compressor [4].

Compressor off-line washing is done when the unit is shut down and cooled down. It consists of several steps including flushing, where usually a detergent is added, and several rinse-cycles. Compressor off-line washings can remove the effects of compressor fouling and thus put the engine into a state where only non-recoverable degradation remains [7].

Compressor hand cleaning implies cleaning of the VIGVs and of the first compressor row blades with brushes and a detergent. Hand cleaning is very effective for removing particles sticking to the blade surface and to restore the compressor mass flow lost due to fouling [4], [8].

Abrasive cleaning, e.g. the injection of rice or walnut-shells into the compressor, is hardly done anymore on a closed gas turbine due to the resulting erosion effects and the danger that the residual of the injected particles clog the passages of the secondary air system [4], [7].

Inlet Filter System The function of gas turbine inlet filters is to purify ambient air before it enters the compressor. Thus, it mainly reduces compressor fouling and erosion [2], [5]. The configuration of Alstom's intake housings are according to the client's preferences. Typically they are designed as a two- or three-stage static filter system, with a pre-filter as first stage, a fine filter as second stage and if present, a HEPA filter as third stage.

Power Plant Performance Optimization

Degradation of power and efficiency has direct impact on power plant revenues. In order to optimize power plant performance, operators can decrease recoverable degradation by optimizing maintenance activities with the measures mentioned above. It is not possible to define general optimization recommendations, because benefit and effort is strongly dependent on site-specific conditions.

Compressor off-line washing with hand cleaned first blades is an efficient measure to remove the majority of recoverable degradation, but for heavy duty gas turbines it requires a shut down of about two days due to the necessity to cooling down the GT. To compensate the loss of a two day shut down of a base load plant, the performance benefit needs to last half a year or more. This means the compressor off-line washings should be done only at scheduled shut downs, like inspections or according to the power demand, e.g. at weekends [4], [7].

Highly efficient intake filter systems are also recommended to lower degradation during the operation interval. The benefit of reduced degradation is usually higher than the disadvantage of higher inlet pressure loss.

In reference [9] a business case example for a CCPP compressor off-line washing is given. It is an easy calculation, and may be used for a rough estimation. Furthermore, a method to optimize operation and compressor cleaning time intervals of CCPP is described in reference [10].

USED DATA FOR ASSESSMENT OF GAS TURBINE DEGRADATION

The selection of data is crucial when analyzing performance degradation. For the analysis presented in this paper two different data types have been used: longterm monitoring data and performance test data.

Longterm Monitoring Data

Longterm monitoring data are most suitable for degradation analysis since they represent a continuous trend that enables not only to analyze the quantity of degradation but also the progression over time. This makes it possible to detect potential abnormalities occurred during the operating interval.

In the case of the Alstom GT fleet, the power plant data of customers with Plant Support Center (PSC) contract are transferred daily from site to the PSC, where they are analyzed in order to detect potential malfunctions in the power plant [11]. The transferred data points represent 5 minute time averages of the high resolution data (measured data having controller sampling time resolution).

To use these data for degradation analysis, measurement points that are comparable over time have to be taken, e.g. base load operation points. Every day a data selection routine detects the most stable and representative base load point where the machine is operated with maximum power output for a defined period of time. A heavy duty gas turbine has to run on high load for several hours to get fully heat soaked and all radial clearances are nominal. However, power plants are operated according to grid needs, which means that there might be days for which the engine has been operated on high load for only a few hours and therefore is not fully heat soaked, furthermore corrections (as explained below) of the data are required, which introduce uncertainties. Both aspects lead to scatter in the base load trends.

Performance Tests

In order to validate longterm monitoring data performance tests are used. Performance tests are usually conducted after an engine upgrade and for some service contracts also in regular time intervals (e.g. every 8000 EOH) in order to validate the power plant performance.

Performance tests are suitable to validate the results since they are conducted using special measurement instrumentation and the engine is in a clearly defined status during the test. This includes not only a fully heat-soaked engine but also an off-line cleaned compressor, which means that the measured power output and heat rate represent non-recoverable degradation.

CORRECTIONS

To be able to compare performance data with different boundary conditions (ambient and operation) and to distinguish and analyze recoverable and non-recoverable degradation, different corrections have to be applied to the field data. This includes standard corrections like ISO correction or instrumentation and water-steam cycle corrections, but also the developed correction for fouling.

Standard Corrections

ISO Correction In general corrections can be done with an appropriate plant synthesis model, which calculates the expected plant performance at site conditions. The deviation to ISO conditions is used to convert the actual measured data point. Historically the correction for power plant performance is done with simple correction curves, which are used for performance tests. For the degradation analysis further correction curves need to be applied, such as for aerodynamic speed, VIGV position, turbine inlet temperature, fuel type, inlet and exhaust pressure losses, inlet cooling, and steam injection to make the operation data comparable to each other.

Corrections for Malfunctions or Water-Steam Cycle Degradation Additionally to the above mentioned corrections, effects of known malfunctions and water-steam cycle degradation (in the case of single shaft units) on performance have to be corrected to eliminate their influence on the field data used for the degradation analysis. This includes amongst others corrections for increased pressure losses over the boiler or condenser, internal water-steam cycle leakages or wrong pressure measurements due to condensate in the pressure sensing lines. In order to correct steam turbine degradation the ANSI/ASME standard [12] has been used. Before applying the standard it has been validated with steam turbine field data.

Gas Turbine Compressor Fouling Corrections

As mentioned above compressor fouling is the main cause of recoverable performance degradation. Its effect on engine performance is twofold: on the one hand it reduces compressor efficiency, which negatively affects power output and heat rate. On the other hand compressor fouling reduces compressor mass flow, which results in decreased power output as well. These two effects can be revealed when analyzing power output gain against compressor efficiency gain due to compressor off-line washings as shown schematically in Fig. 2. The exchange rates between compressor efficiency and power, i.e. the effect of a compressor efficiency change on the power output, are known from performance calculations. Based on the exchange rates the expected power output gain due to compressor efficiency gain $P = f(\Delta\eta_C)$ can be determined. However, the measured power output gain is bigger than what is expected due to the compressor efficiency gain. The fraction of gain in power output that cannot be explained by gain in compressor efficiency can therefore be ascribed to increased compressor mass flow if all other effects on power are excluded. This is in accordance to the findings of Schneider at al. [4] where compressor on-line washings have been analyzed.

In order to be able to distinguish between recoverable and non-recoverable degradation and thus to optimize plant performance, corrections for the effects of fouling were developed and applied to field data.

Compressor Efficiency Correction In Fig. 3 the relative power and the polytropic compressor efficiency, both corrected for ISO, of an F-class gas turbine is plotted. The polytropic compressor efficiency is calculated based on the measured flow conditions at the compressor inlet and at the compressor exit

$$\eta_n = \frac{R}{c_p} \frac{ln\frac{p_2}{p_1}}{ln\frac{T_2}{T_1}}. \quad (1)$$

Also the dates of compressor off-line washings are marked in Fig. 3. After a thorough compressor off-line washing, the engine is assumed to be in clean condition.

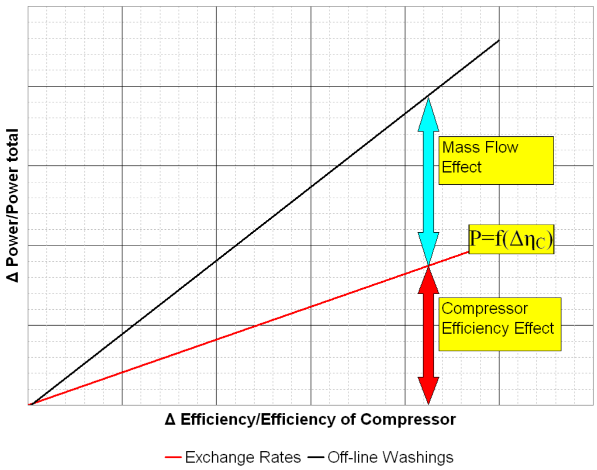

Figure 2. DERIVATION COMPRESSOR MASS FLOW EFFECT DUE TO A COMPRESSOR OFF-LINE WASHING

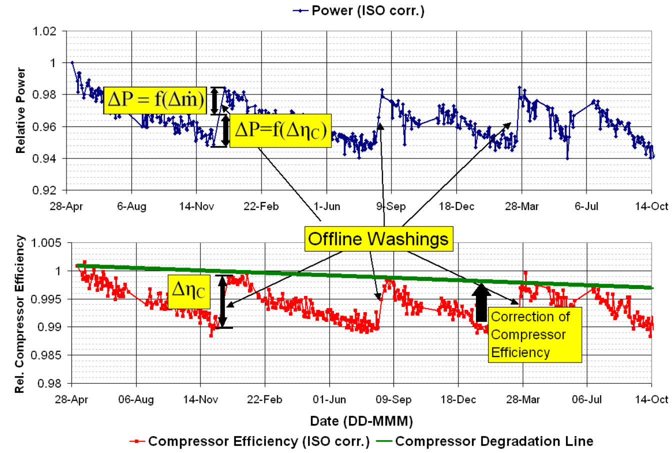

Figure 3. COMPRESSOR DEGRADATION LINE

An analysis of these field data after compressor off-line washings of Alstom's F-class gas turbines has revealed that non-recoverable compressor efficiency follows about a linear function in time called compressor degradation line. In the example shown in Fig. 3, the degradation line is marked in green.

The slope of the compressor degradation line however, varies for each power plant and is dependent on site-specific boundary conditions. In order to determine the slope for a certain plant, monitoring data of compressor off-line washings have to be analyzed. However, the compressor efficiency after a compressor off-line washing is also dependent on the washing effectiveness. This might be influenced for example by different numbers of washing cycles, use of detergent and whether the VIGVs and the blades of the first compressor row have been hand cleaned. Therefore, for the case where different compressor off-line washing procedures are applied on the same GT, the points after washings from which the compressor efficiency degradation line is derived have to be selected carefully. The compressor degradation line represents the efficiency the specific compressor would have, if it was always in a cleaned state.

The correction of engine power for compressor efficiency degradation due to fouling is done by calculating the difference in efficiency between the virtual compressor degradation line and the ISO corrected efficiency (see Fig. 3). Applying linear exchange rates accounting for the influence of compressor efficiency on power is with respect to noise of the trend acceptable. The power gain is added to every sample in the ISO corrected power trend.

Compressor Mass Flow Correction Besides leading to a reduction of compressor efficiency, fouling also leads to a reduction of compressor mass flow. Reduction in compressor mass flow reduces GT and in case of a CCPP also ST power. To consider this effect when correcting for fouling, the mass flow reduction has to be quantified. In the current study three methods are used to evaluate the mass flow reduction.

First approach is to use the pressure difference between the inlet flange and the bellmouth. However, in Alstom heavy duty gas turbines, this measurement is not suitable for mass flow changes less than 1%. Therefore, it cannot be used for minor changes.

Nevertheless, to correct longterm monitoring data for compressor fouling, the quantity of recovery potential of compressor mass flow after a compressor off-line washing has to be known. Therefore a second approach to evaluate the quantity of mass flow recovery due to a compressor off-line washing has been developed. According to Zaba [13] the relation between compressor volume flow degradation and efficiency degradation due to fouling can be expressed as

$$\frac{\Delta\dot{V}}{\dot{V}} = \overline{Z_C}\frac{\Delta\eta_C}{\eta_C}. \tag{2}$$

The factor $\overline{Z_C}$ is depending on the composition of the deposits and their distribution on the blade rows throughout the compressor. Zaba [13] has studied the influence of the distribution of fouling throughout the compressor on compressor efficiency and mass flow. The results showed very little dependence of compressor efficiency on the fouling location. However, compressor mass flow showed a higher reduction for front stage fouling as compared to fouling of the rear stages. Thus, there was a significant dependence of mass flow reduction on the location of fouling. These results were confirmed by fouling simulations done by Millsaps et al. [14]. As a result of these simulations, the distribution of the deposits throughout the compressor can be expressed as:

- $\overline{Z_C} > 1$: Deposits pronounced on the front compressor stages
- $\overline{Z_C} = 1$: Even distribution of deposits over the compressor stages
- $\overline{Z_C} < 1$: Deposits pronounced on the rear compressor stages

The quantity and distribution of fouling throughout the compressor depends on various factors, such as ambient conditions (e.g. humidity in the air), environmental conditions (e.g. amount and constitution of airborne particles), hardware (e.g. configuration of air inlet filter system) and compressor washing procedures (e.g. on-line washing, off-line washing). Thus, as long as these factors do not change, the compressor fouling process should be similar and therefore the value for $\overline{Z_C}$ should stay constant for each gas turbine [13].

However, these factors differ for each site and therefore also the factor $\overline{Z_C}$ is site-specific. In order to determine the $\overline{Z_C}$ for a specific plant, the power output gain and compressor efficiency gain due to compressor off-line washings are evaluated for each site as explained above and shown in Fig. 2. Based on the experience that the gain in power output that cannot be explained by compressor efficiency increase can be ascribed to increased compressor mass flow in case of a compressor off-line washing, the mass flow gain can be determined by applying linear exchange rates for the gained power output due to compressor mass flow.

The analysis of compressor off-line washings of different plants of Alstom's F-class fleet has shown that a linear correlation between compressor efficiency gain and compressor mass flow gain after compressor off-line washings can be established for each gas turbine. The result of the analysis in Fig. 4 shows that the factor $\overline{Z_C}$ is site-specific and consistent with time. The analysis of the gas turbines has yield to values for $\overline{Z_C}$ between 1 and 2.5. It is notable that the plants located in dirty environment and close to the sea have a higher value for $\overline{Z_C}$ than the plants located in less polluted areas. This is in line with the statements of Zaba [13].

With the site-specific factor $\overline{Z_C}$, the quantity of compressor mass flow restored during compressor off-line washings can be determined as a function of the delta between the compressor efficiency data and the compressor degradation line explained in the section before. By applying linear exchange rates the power output can be additionally corrected for influences of compressor inlet mass flow due to fouling as done above for the compressor efficiency.

As a third approach to quantify the mass flow change after a compressor off-line washing a performance tool is used. By recomputing longterm performance data, it is possible to determine the compressor efficiency and mass flow degradation due to fouling and their recovery due to a compressor off-line washing. For this purpose the cycle performance tool accepts measured compressor outlet pressure and temperature. Changes of compressor efficiency, mass flow and power output are then computed by the tool. The result of calculated power is in correspondence with

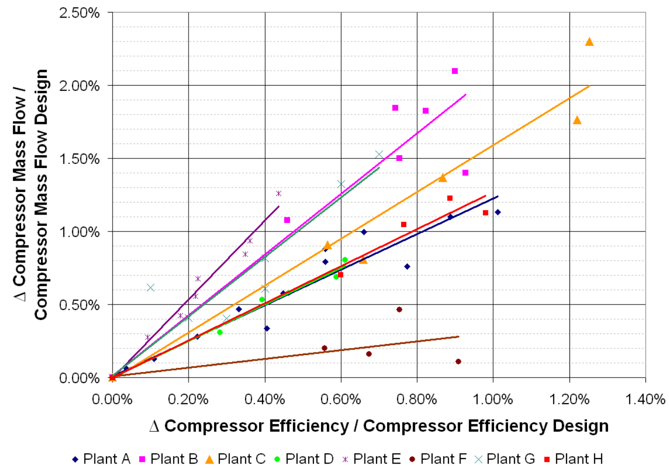

Figure 4. CORRELATION COMPRESSOR OFF-LINE WASHING EFFECT COMPRESSOR MASS FLOW VS. COMPRESSOR EFFICIENCY

the power output of the measured F-class gas turbine data. In Fig. 5 a site-specific calculation example of plant A in Fig. 4 is shown. The ratio of compressor mass flow gain to efficiency gain calculated with the performance tool is $\overline{Z_C} = 1.3$ and therefore well in accordance with the factor $\overline{Z_C} = 1.25$ determined with the second, aforementioned method. The minor deviation of measured and calculated power validates the correct assumption of the correlation between compressor flow and efficiency change. This method is probably the most accurate one to determine compressor mass flow gain based on monitoring data; however, the performance model has to be matched to site-specific plant configuration. Due to the good match, the second method explained above can be used as a straightforward approach to evaluate mass flow gain and thus correct performance data for recoverable degradation without requiring a performance tool.

If there is no sufficient amount of compressor off-line washings and no adequate performance model available to define a site-specific value for $\overline{Z_C}$ an average value for $\overline{Z_C}$ is used. By analyzing a representative amount of compressor off-line washings of plants independent on their location and plant configuration an initial average value for $\overline{Z_C}$ for Alstom's F-class fleet was determined (see Fig. 6). It was found that in average the amount of relative mass flow recovered due to a compressor off-line washing is about two times higher than the recovered compressor efficiency. Based on this finding $\overline{Z_C} = 2$ has been defined as average over the analyzed GTs. This is in line with most values found in open literature (see references [2], [13], [15], [16], [17], [18]) as listed in Tab. 1. All values of $\overline{Z_C}$ found for Alstom's F-class GTs are above $\overline{Z_C} = 1$, the same applies for all those values in Tab. 1 that have been derived from field data and not only from experiments. This implies compressor mass flow reduction to be the prime effect of

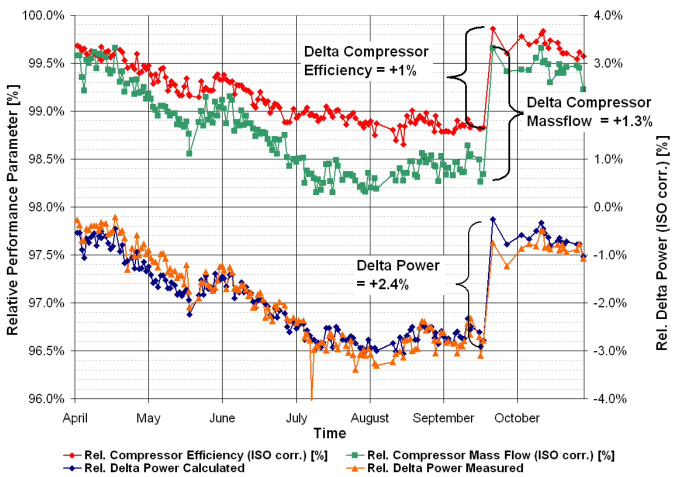

Figure 5. COMPRESSOR EFFICIENCY AND MASSFLOW CALCULATED WITH PERFORMANCE TOOL

fouling. This is consistent with Aker at al. [19] and Tarabrin et al. [20] who state that fouling mainly occurs in the front stages of the compressor and diminishes from stage to stage.

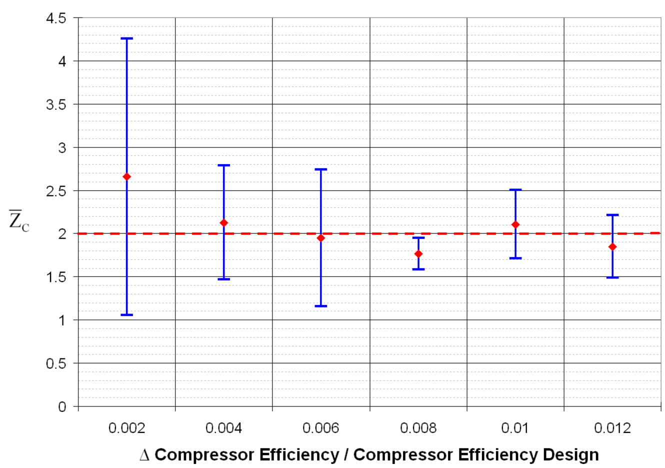

Figure 6. ANALYSIS OF FOULING FACTOR $\overline{Z_C}$ FOR F-CLASS GAS TURBINES

RESULTS

The presented method enables power plant manufacturers and operators to apply straightforward corrections for compressor fouling. By using these corrections it is possible to separate recoverable from non-recoverable performance degradation. The methodology provides a reliable quantification of recoverable degradation based on standard plant instrumentation and does not rely on performance tools, which need to be frequently adjusted to reflect actual degradation status. This ensures on the one hand the possibility to calculate non-recoverable degradation and thus being able for example in the case of a GT upgrade, where the guarantees given are based on the performance of the clean GT, to estimate the fraction in performance gain that can be attributed to compressor off-line washing and to the major overhaul recovery and actual upgrade. On the other hand a better knowledge about the site-specific amount and progression of recoverable degradation enables the operator to optimize performance output by scheduling maintenance actions.

Non-Recoverable Degradation of Power Plants in Service

For the purpose of this study, field data of 27 Alstom CCPPs has been analyzed and the previous mentioned corrections have been applied.

In Fig. 7 the resulting non-recoverable power is shown exemplary for one plant together with the compressor degradation line. The analysis of non-recoverable degradation has revealed that both recoverable and non-recoverable degradation is highly site-specific and influenced by boundary conditions. These boundary conditions do not only include ambient conditions like industrial environment, humidity or proximity to sea, but also operational (e.g. operating regime) and maintenance conditions (e.g. frequency of compressor on- and off-line washings), which result in the above mentioned degradation mechanism. Therefore degradation assessments have to be done individually for each plant taking into consideration these boundary conditions. The correlation between the boundary conditions, the degradation mechanism and the resulting degradation rate is not subject of this paper. The presented methodology can be used to quantify non-recoverable degradation of a GT or CCPP at any time.

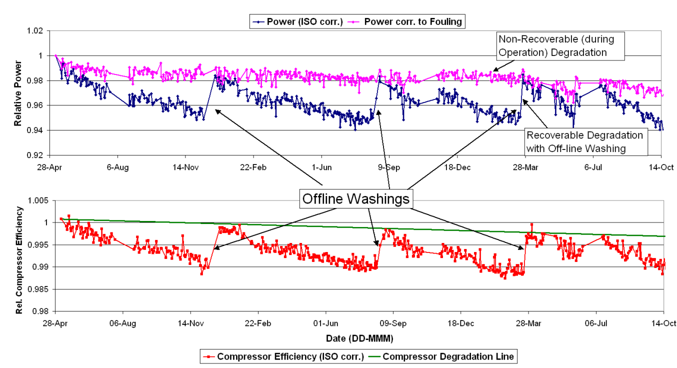

Figure 7. FOULING CORRECTED POWER

Table 1. FOULING FACTOR $\overline{Z_C}$

Source	$\overline{Z_C}$	Remarks
Diakunchak [2]	2.78	Field test data of a large industrial gas turbine
Zaba [13]	2.5	Operating experience of GT with high fouled compressor first stage
Macchi [15]	2.5	Experimental tests on both turboprop and large industrial machines
Frischmuth [16]	1	Typical factor for compressor fouling
Bammert/Woelk [17]	1	Experiments on compressors with equally fouled stages
Haq/Saravanamuttoo [18]	2.67	Field tests
Current Study	$1-2.5$	Alstom's F-class Fleet

Effect of Filter Efficiency on Fouling

As mentioned above analyzing recoverable degradation enables to improve plant maintenance and thus to reduce recoverable degradation. The methodology was applied to determine the effect of different inlet filter systems (different filter efficiencies, 2 or 3 inlet filter stages) on fouling as shown in Fig. 8. The amount of improvement of recoverable power degradation per year is plotted against the total filter efficiency for several analyzed plants, where the filter systems were changed during the operating period. The improvement of recoverable degradation due to improved inlet filter systems is evident.

The 2-stage static filter system (pre-filter class: G4, fine-filter class: F8) of unit B in Fig. 8 has been upgraded with a 3rd filter stage (HEPA-filter class: H10). As a result, the rate of power loss due to fouling decreased by about 3.5% per year despite the fact that the additional 3rd filter stage implies an increased inlet filter pressure loss that has a negative effect on power output.

The inlet filter systems of the units A, C, and D are equipped with two static filter rows (pre-filter and fine-filter) and are upgraded during their operating time with static filters with higher filter efficiency (compare Tab. 2). As can be seen in Fig. 8, in all three cases, the rate of power loss due to fouling decreased as a result of these filter efficiency upgrades.

The analysis shows that the optimization of the inlet filter system can significantly decrease performance loss due to fouling. However, a balance has to be found between increased revenue due to decreased power loss and potentially increased filter costs and filter pressure loss of high efficiency filters.

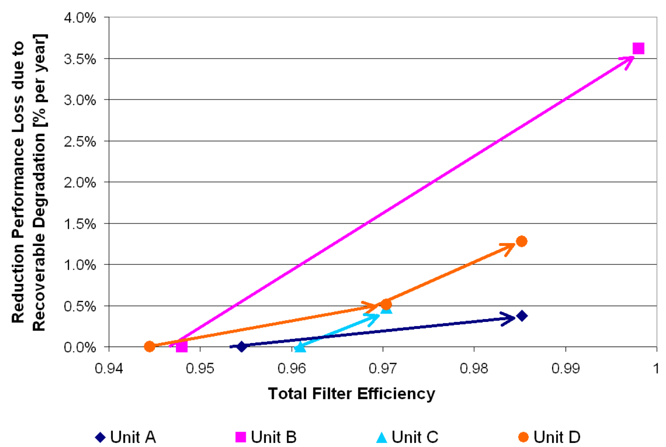

Figure 8. RECOVERABLE DEGRADATION DUE TO FILTER CLASS CHANGE $= f$(Filter Efficiency)

Table 2. FILTER CLASSES

Plant	Basic Configuration	First Upgrade	Second Upgrade
Plant A	G4 - F8	F6- F9	-
Plant B	G4 - F8	G4 - F8 - H10	-
Plant C	G4 - F8	F6 - F8	-
Plant D	F6 - F7	F6 - F8	F6 - F9

CONCLUSION

The presented methodology is used to quantify degradation from operational data, recorded with the standard instrumentation scope. Trending of corrected power and compressor efficiency provide information of the degradation rate and the amount of fouling, which can be removed with compressor off-line washing and inlet filter exchange. The compressor mass flow reduction due to fouling can be expressed with the factor $\overline{Z_C}$, which is the ratio between compressor inlet flow and efficiency, if no reliable inlet mass flow measurement is available. The analysis of compressor off-line washings of different Alstom F-class gas turbines has revealed that $\overline{Z_C}$ is not constant over the whole fleet. However, it could be shown, that $\overline{Z_C}$ is consistent with time for each gas turbine individually in case the boundary conditions do not change. This makes it possible to correct longterm trends for recoverable degradation once the site-specific value for $\overline{Z_C}$ is determined. The trend can also be used to predict degradation until the next scheduled shut down or to quantify the degradation rate based on site-specific boundary conditions.

The methodology was applied for several power plants at different locations and configurations and provided good information about the individual fouling rate and the non-recoverable degradation rate. It was shown that high filter efficiency or frequent compressor off-line washings reduces fouling significantly and is essential for continuous high power output.

The study has shown that both recoverable and non-recoverable degradation are dependent on site-specific boundary conditions. The identification and quantification of the main drivers for performance degradation is currently under investigation within Alstom and will be subject of future work.

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