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Compressor Performance Recovery Systems: a New Thermoeconomic Approach

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Abstract

Compressor fouling in a Gas Turbine (GT) is an important issue which has to be studied to define compressor performance and GT reliability. Three main aspects have to be taken into account: the type of pollutants that could enter into the compressor, with their possible effects such as blade erosion and/or corrosion; the power and efficiency losses caused by fouling;the economic loss due to increase in fuel consumption and reduction in power output.

Two main solutions can be considered for reducing the fouling effect and restoring compressor performance: compressor washing and the High Efficiency Particulate Air filter (HEPA). The choice of the most effective devices for each power plant is not trivial, because of the great number of parameters to be taken into account. The aim of this study is to provide a guide to identifying and managing the best washing or filter devices for a GT in a specific power plant site, using information from the literature and GT user data from European Turbine Network (ETN) members. Two procedures were designed in order to have a user friendly tool:

" Best Cleaning Devices" was developed to help GT users in the choice of the best devices for recovering compressor performance.

"Best Cleaning Time" is based on the "Best maintenance time" theory and it provides the user with an estimate about the best time to perform compressor off-line or on-line washing.

The procedures are explained in detail and tested on some real cases.

Nomenclature

B.C.D.	"Best Cleaning Device"
B.C.T.	"Best Cleaning Time"
C	Cost of maintenance [$]
c	Cost of exergy flow[$/J]
d	Days of maintenance [d]
h	Hours [h]
H.E.P.A.	High Efficiency Particulate Air filter
Hum	Humidity [%]
LHV	Lower heating value [kg/kJ]
$\dot{m}$	Mass flow rate
NIC	Non-dimensional Cost Index
p	Price of specific exergy flow [$/kWh]
Pow	Power [kW]
pres	Pressure [bar]
RV	Recommendation value
T	Temperature [°C]
$\dot{Z}_r^{\$}$	Capital cost [$/s]
Wl	Weight of literature data
Ws	Weight of real data
β	Slope of linear trend [1/s]
y	Exergy flow [kW]
λ	Reliability of literature data
η	Efficiency
π	Monetary cost of the exergy flow [$/s]
ρ	Free stream air density [kg/m3]
τ	Time [s]
cyc	Cycle
day	Day
ex	Exergetic
env	Environmental
f	Fuel
ideal	Ideal
in	Input
int	Interventions
M	Maintenance
night	Night
nd	Non-Dimensional
opt	Optimum
out	Output
PL	Production loss
Real	Real
ref	Reference

Introduction

The privatization of utilities, the increasing cost of fuel and competition in the energy market, have created a strong incentive for gas turbine operators to minimize compressor degradation. Any reduction in compressor performance has a direct and significant impact on the entire gas turbine / combined cycle performance, efficiency and reliability [1]. During normal operation, a compressor is mainly affected by fouling due to air pollution, which causes its performance to degrade over time[2-6]. Fouling is defined as degradation of flow capacity and efficiency caused by adherence of particular contaminants to the gas turbine engine airfoil and annulus surfaces [3].

Two main solutions to reduce compressor fouling are compressor washing and air filtration systems.

Compressor washing can be off-line, when the gas turbine is rotating at sub-idle speeds and no-load, or on-line, while the gas turbine is working at peak load and full airflow (typically). The former cleans the compressor blades better, but needs 2 - 12 hours of maintenance time and the consequent economic loss becomes significant. The latter allows continuous operation, but washing effectiveness is lower and the water droplets can erode the early stage compressor rotor blades.

An advanced air filtration system can stop most of pollutants particles, reducing the need for washing, but it reduces power output and the efficiency of the power system. Traditionally gas turbines employ filter barriers of EN799 class F8/F9, with a G2/G3 pre-filter to protect the fine dust filter from rain, fog, ice, snow, thus maximizing performance. Such a system with 2-stage filter is generally employed by Original Equipment Manufacturers (OEM);

High Efficiency Particulate Air filters (HEPA) are generally employed as a third additional stage, protected by the first G3/F6 stage filter and by the second stage F8/F9 filter. The third stage is typically classified as H10/H13 by EN 1822. Such a 3-stage high performance filtration system prevents the compressor from fouling and reduces the necessity for washing but increases the inlet pressure drop reducing the GT power output [7-9], or increasing the air flow area request by GT.

Overall, the choice of the best recovery system for each gas turbine in the specific power plant is not trivial: this study proposes a statistical approach to the problem, based on open literature data and database information on actual gas turbines kindly provided by European Turbine Network (ETN) members.

Two procedures were developed, "Best cleaning devices" and " Best Cleaning Time".

Best cleaning device procedure

The procedure called "Best cleaning devices" (B.C.D.), implemented in the similarly named software tool, aims at advising GT users on how to choose the best compressor recovery system for their power plants, using results published in International papers and experimental data provided by ETN members.

Once simple questions about environmental conditions at the site or GT performance are answered, the software provides a percentage value for each technology, which is the answer to the following general question:

"Is this technology the best cleaning device for the Gas Turbine in this power plant?".

The percentage value, called *recommendation value RV*, states the probability of a positive answer:

- if the RV is above 50%, the technology is recommended: the higher the RV, the more "recommended" the technology;
- if the RV is below 50%, the technology is not recommended: the lower the RV, the more "not recommended" the technology.
- If the RV is in a range close to 50%, then the technology can be employed, with a 50% probability that it is the best choice to make.

The RV percentage of each technology is independent of the others, because one technology does not exclude the others. In fact, in many real cases, two, or even all of the devices, are used together and it is possible that the best cleaning device consists of a combination of systems.

For each question the procedure outputs a recommendation value in the range 0 to 1 for each technology, depending on the answer selected. Changing the answer changes the recommendation value.

The of recommendation values are calculated using the real data provided by users of GTs and the theory and information provided by technical articles. The equation used to define the recommended value of a technology (for example: filter system) is given below.

$$RV_{ij} = \lambda_{ij} * Wl_{ij} + \left(1 - \lambda_{ij}\right) * Ws_{ij} \qquad (1)$$

Where:

RV_{ij} is the recommendation value for the i-th question with the j-th answer.

Wl_{ij} is the weight of literature theory or information for the i-th question with the j-th answer. It indicates how much the technology is recommended in the open literature in the conditions indicated in the question and answer selected. Its range is from 0 to 1.

Ws_{ij} is the statistical weight of real data (i.e. data from a real plant, or data from end-users) for the i-th question with the j-th answer. It gives the statistical probability of how many power plants use the technology in the conditions indicated by the question and answer selected. Its range is from 0 to 1.

λ_{ij} is the level of reliability assigned to data from the literature. Its range is from 0 to 0.5.

For example, let us assume the answer is "yes" to the question "Is the power plant close to the sea ?". Looking at the GT database from GT users, 80% of power plants near the sea have on-line cleaning, so Ws = 0.8.

Looking in the open literature, three authors strongly suggest using on-line cleaning in offshore applications or in seacoast plants, so Wl = 1 and $\lambda = 0.3$. The RV of on-line cleaning for the answer selected is therefore:

$$RV = 0.3 * 1 + (1 - 0.3) * 0.8 = 0.3 + 0.56 = 0.86$$

Summing up the RV for each question and averaging them into a percentage, the result indicates the probability of the technology to be the best choice for the site, i.e. to be recommended for the particular application. In the case above, there is an 86% probability that it is a good choice, hence 14% probability that it is a non-necessary choice.

The questions should ask general information about the power plant, such as environmental conditions, geographical position and GT performance, and more detailed technical information when available.

The definition of Wl values, whose range is from 0 to 1, depends only on results provided by published article(s). For example, if a paper shows that on-line cleaning is very useful for GTs operating in base load, supporting the result with a large amount of data from the field, the Wl value could be taken to be around 0.9 or 1. If the theory is not supported by much real data, Wl could be taken to be between 0.5 and 0.8. If the reported theory or field evidence does not recommend on-line cleaning technology, Wl will range between 0 and 0.3.

The values of Wl take into account also the number of papers: in fact, Wl values should be calculated as an average of the Wl values decided for each paper.

The definition of Ws values, whose range is from 0 to 1, depends only on the statistical data available. For example, if we consider power plants in industrial estates, if 60% use a high-efficiency filter system, Ws for the high-efficiency filter system for that answer (site = industrial estate) will be 0.6; if 10% use on-line cleaning, Ws for on-line cleaning for that answer will be 0.1. If statistical data are "not available", the Ws value is assumed to be 0.5, which represents total uncertainty between alternative choices.

The λ value changes depending on whether the theory or information described in the literature agrees with real data or not. As a general numerical rule, it has been assumed that when real data and literature data differ by less than 15 percentage points, they can be considered in good agreement. Hence, literature agrees with real data when the following condition is satisfied:

$$|\mathrm{Ws} - \mathrm{Wl}| < 0.15 \qquad (2)$$

If the literature perfectly agrees with real data, then $\lambda_{ij}=0$. If the literature disagrees with real data, then $0<\lambda_{ij}<0,5$, in particular:

- If references are only one paper or article, then $\lambda_{ij}=0.1$.
- If references are between two to four papers or articles, then $\lambda_{ij}=0.3$.
- If references are more than four, then $\lambda_{ij} = 0,5$ [1].

The database built during this work contains the values of Wl, Ws and λ for each question and answer proposed by B.C.D. To collect this data, a questionnaire was used where the same questions proposed by B.C.D. and generic queries about the washing or filter devices installed are asked. Using the information from the open literature to fill in the same questionnaire, it was possible to calculate the Wl for each question. These values were added in the database, which was built as a matrix: for each question, all possible answers were put on rows and the three compressor performance recovery devices available (HEPA, online washing and offline washing) were put on columns. Figure 1 shows an example. A similar matrix was also built to record the numbers of papers added to the database.

From the information reported by [1-9], it was possible to create a database of Wl and λ values.

When a new paper needs to be added, the new Wl value, to be inserted in the database, is calculated as a weighted average between the old values, already present in the database, and the value derived from the new paper. Obviously, the weighted average is based on the number of papers related to the Wl selected, in order to give the same credit to all articles collected.

		Weight licterature	H.P.F	On line	Off line	number of literatures	H.P.F	On line	Off line
1	Is the plant close to the sea?	Yes	0,30	0,80	0,70	Yes	1	3	1
		No		0,50	0,70	No	0	2	1
2	Is the plant in an industrial estate?	Yes	0,80	0,70	0,90	Yes	2	2	1
		No	0,40	0,80	0,90	No	2	1	1
3	Is the plant located in a place	Yes	0,40	0,30	0,90	Yes	2	2	2
		No	0,80	0,70	0,50	No	2	2	2
4	Gas turbine rated [MW] (Power)	1-10	1,00			1-10	1	0	0
		11-60	1,00	1,00	1,00	11-60	1	1	1
		61-100	1,00	1,00	1,00	61-100	1	1	1
		100-300	1,00	1,00	1,00	100-300	1	1	1

Figure 1: Example of Literature database for B.C.D. procedure

Regarding Ws values, the questionnaire was submitted to all ETN members, and from their answer it was possible to create a database of real data from 62 real power plants [10-12]. An example of a questionnaire is given in Table 1. The database was built in the same way as for the literature database, to make easier the future upgrade. The database is completely anonymous: The more extensive the database is, the more reliable results are.

[1] In this approach the number of International articles or papers has been taken into account to determine the λ value. An alternative approach would to be to define the λ value based on the number of different authors, instead of the number of papers.

		Plant 1
1	In which country or city is the power plant located?	North European country
2	Is the plant close to the sea?	No
3	Is the plant on an industrial estate?	No
4	Is the plant located in a place with high humidity?	Yes, average 80%
5	Gas turbine nominal power [MW]	55
6	Average actual operating hours per year	-
7	Is the compressor off-line washed?	Yes
8	How many times is the compressor washed (with off-line cleaning) during a year?	4 (every 3 months)
9	Is the compressor on-line washed?	No
10	How many times is the compressor washed (with on-line cleaning) during a month?	-
11	How many days per year does the environmental temperature allows on-line compressor washing?	-
12	How many filtration stages are installed (2 or 3)?	2
13	What is the class of each filtration stage (as defined by EN 799 and EN 1822)?	standard

Table 1: Information on Plant 1 for B.C.D.

Best cleaning time procedure

One of the most important issues of the compressor washing system is to understand when the compressor needs to be washed. With regard to on-line cleaning, some authors like Schneider et al. [1] suggest frequent on-line washing, even every day, to obtain good cleaning efficiency. With regard to off-line cleaning, some authors like Meher-Homji and Bromley [2] suggest washing the compressor when the GT is switched off or when the isentropic efficiency is lower than a fixed value.

Following the work of Napoli, Cafaro, Veer [13-16] and Gülen et all [17], the tool "Best Cleaning Time" was conceived as a straightforward program for understanding when it is thermo-economically advisable to wash the compressor.

Best Maintenance Time theory

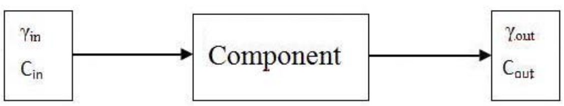

Figure 2: Thermoeconomic functional scheme of a thermodynamic system

In the thermoeconomic functional analysis, each component of a thermodynamic system (for example a heat exchanger, steam turbine, steam generator) is seen as a functional box which exchanges exergy flows with the other components.

Each component, as shown in Figure 2, has an exergy flow input y_{in} and an exergy flow output y_{out} expressed in power units (e.g. kW). A unitary production cost c is associated with each exergy flow, c_{in} and c_{out}. They represent the production cost of a unit exergy flow, expressed in $/kJ. The thermoeconomic cost flow π is the monetary cost of the associated exergy flow, expressed in $/s. The component balance equations are [18-29]:

$$y_{out} = y_{in} * \eta_{ex} \qquad (3)$$

$$y_{out} * c_{out} = \dot{Z}_r^{\$} + y_{in} * c_{in} \qquad (4)$$

$$\pi_{in} = y_{in} * c_{in} \qquad \pi_{out} = y_{out} * c_{out} \qquad (5)$$

$$\dot{Z}_r^{\$} = \frac{C_m}{\tau_{cyc}} \qquad (6)$$

Where:

$\dot{Z}_r^{\$}$ Capital cost [$/s]; includes amortization, interests, taxes. As far as just maintenance is concerned (and not the construction of a new plant), it refers to the annual overall maintenance cost.

C_M Maintenance cost [$].

τ_{cyc} Time between two maintenance intervals [s].

The maintenance cost C_M is defined as the sum of the actual intervention cost C_{int} and the cost of the lost production C_{PL} due to plant stoppage.

$$C_M = C_{PL} C_{int} \qquad (7)$$

$$C_{PL} = d * (y_{out,day} * h_{day} * p_{out,day} + y_{out,night} * h_{night} * p_{out,night} - \pi_{in} * (h_{day} + h_{night})) \qquad (8)$$

where:

d days of plant stoppage [-]

$y_{out,day}$ average exergy output during the day [kW]

h_{day} average operating hours per day [h]

$p_{out,day}$ daily price of exergy flow output [$/kWh]

$y_{out,night}$ average exergy output during the night [kW]

h_{night} average operating hours per night [h]

$p_{out,night}$ nightly price of exergy flow output [$/kWh]

π_{in} average monetary cost of exergy input flow

When the entire plant is considered, y_{out} typically corresponds to the electrical output. For cogeneration plants, steam exergy flow output is also included. y_{in} and c_{in} correspond to the fuel exergy flow and cost, respectively.

During their operating life, components tend to decrease their efficiency due to deterioration. If efficiency decreases, the unitary production cost c_{out} increases for the same y_{in} and c_{in} input (see eq. 4). Defining $c_{out,ideal}$ the cost when the component is clean and $c_{out,real}$ the cost when the component is working in real conditions, it is possible to define the non-dimensional cost index NIC as:

$$NIC = \frac{C_{out,real}}{C_{out,ideal}} \tag{9}$$

The NIC is able to show the component degradation rate. Collecting data on components during operation and plotting the NIC versus time, it is possible to observe a trend as shown in Figure 3 (data are taken from a real combined cycle plant, reference [30]).

This graph refers to the NIC of a HRSG in a cogeneration plant where the product γ_{out} is low pressure steam. In this case the scattered behaviour is due to measurement uncertainties, noise and model approximations: in fact, $c_{out,ideal}$ is estimated using an off-design model of the plant, and it is calculated at different ambient and load conditions over time. A linear approximation (shown in black) indicates that NIC tends to increase in value during the time, representing the degradation effect. This linear approximation could be expressed by:

$$NIC = 1 + \beta * \tau \tag{10}$$

where:

τ Time [s]

β angular coefficient of NIC linear regression [1/s].

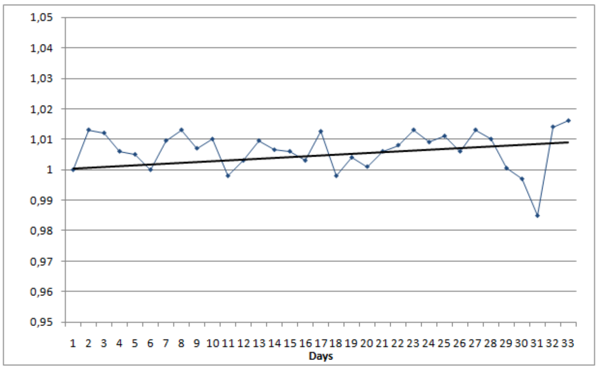

Figure 3: NIC trend versus time, with best fit linear trend

This kind of analysis is possible assuming steady conditions of the plant.

It is now possible to define the degradation cost C_{deg} as:

$$C_{deg} = \int_0^{\tau_{cyc}} \pi_{out,ideal} * [NIC(\tau) - 1]\, d\tau \tag{11}$$

Where:

τ_{cyc} total time measured [s].

$\pi_{out,ideal} = y_{out,ideal} * c_{out,ideal}$ monetary cost of the ideal exergy output flow [$/s].

It is then easy to derive:

$$C_{deg} = \int_0^{\tau_{cyc}} \pi_{out,ideal} * [\beta * \tau] * d\tau = \\ = \left[\overline{\pi_{out,ideal}} * \beta * \frac{\tau^2}{2}\right]_0^{\tau_{cyc}} \tag{12}$$

Where:

$\overline{\pi_{out,ideal}}$ average monetary cost of the y_{out}.

C_{deg} is the cost due to degradation. It depends on the degradation curve, the average cost of exergy flow output and operation time.

It is thus possible to define a new parameter, namely the Cycle cost, C_{cyc}, which is the sum of the degradation cost and of the maintenance cost.

$$C_{cyc} = C_M + C_{deg} = \\ = C_M + \overline{\pi_{out}} * \beta * \frac{\tau_{cyc}^2}{2} \tag{13}$$

The plant user wants to minimize the specific cycle cost, i.e. the cost C_{cyc} over time, finding the time $\tau_{cyc\ opt}$, that is the best time between two maintenance operations. Hence, we should minimize the function $\frac{C_{cyc}}{\tau_{cyc}}$.

$$\frac{C_{cyc}}{\tau_{cyc}} = \frac{C_M}{\tau_{cyc}} + \overline{\pi_{out}} * \beta * \frac{\tau_{cyc}}{2} \tag{14}$$

$$\frac{\partial\left(\frac{C_{cyc}}{\tau_{cyc}}\right)}{\partial \tau_{cyc}} = -\frac{C_M}{\tau_{cyc,opt}^2} + \overline{\pi_{out}} * \frac{\beta}{2} \tag{15}$$

Setting to zero equation (15), i.e. at the minimum value of equation (14), expression (16) then follows.

$$\tau_{cyc,opt} = \sqrt{\frac{2 * C_M}{\beta * \overline{\pi_{out}}}} \tag{16}$$

Such a calculation procedure is iterative on $\tau_{cyc\ opt}$, as it influences $\overline{\pi_{out}}$.

This theory is able to provide an indication of the best time to intervene on a component whose performance is degrading over time: however, it needs a collection of data to define the ideal condition, the degradation curve and the average cost of output exergy flow.

Application to GT Best Washing Time

The application of the Best Maintenance Time theory to the compressor degradation problem requires considering the gas turbine as a single thermoeconomic component, which has a single input, the fuel flow, and a single output, the electric power. To calculate the best time, logged data from the field is necessary for inferring the essential information required by the theory. The minimum data needed are fuel flow rate, produced power, fuel cost and maintenance cost. Nevertheless, it is also important to take into account environmental effects on GT efficiency, i.e, pressure, temperature and relative air humidity. The best way to do this is to correct one of the two parameters (fuel rate or power output) to ISO conditions. In the end, the parameters which have to be collected are (at least):

- Fuel flow rate, $\dot{m}_f$ [kg/s],
- Produced power, Pow [kW],
- Environmental pressure, $pres_{env}$ [bar],
- Environmental temperature, T_{env} [°C],
- Relative air humidity, Hum_{rel} [-].

A simple way to correct the real data to ISO (or reference) conditions is the method proposed by Cafaro and Veer [14]. Other correction methods are, however, possible (for example using the "classical" power correction curves that GT producers provide to their customers): the objective is to collect data with the lowest environmental influence.

The data useful for the ISO correction should be gathered during at least a year of operation, so as to allow for seasonal oscillations. Moreover, this dataset should be able to define the ideal GT condition in its geographical site. By "ideal condition" we mean "Clean" condition, i.e. just installed or just washed by off-line cleaning: unfortunately, this reduces the number of samples that can be effectively employed. The approach the authors propose is to build an $\dot{m}_f$ vs Pow curve in ideal conditions, starting from experimental data, given the constraints already explained. Plotting the ISO-corrected data of $\dot{m}_f$ and Pow in a $\dot{m}_f$ vs Pow diagram, it is possible to calculate the best fit curve of GT performance in the power plant in which it is installed. This experimental curve links the GT input and output and is able to define the reference fuel flow rate (GT exergy flow input) for each power production (GT exergy flow output), and vice versa. This curve is considered the GT performance reference, and can be used to calculate the $c_{out,ideal}$ and the NIC value.

Operation-wise, as fuel flow rate changes, the power produced is recorded (or vice versa) during operation in "Clean" condition. The plant can be assumed to be in Clean condition after washing and for 1/5 of the total period between two washings. For example, if we are studying off-line cleaning frequency, if off-line cleaning is done every 4 months, a GT can be considered working in ideal conditions for about 24 days after the compressor washing. This hypothesis is supported by the experimental data reported by Schneider, E. and al [1].

This experimental approach to defining the ideal ISO curve (baseline) is preferred to the use of correction curves provided by the manufacturer. It is clear that around a year of logged data is necessary in order to fully characterize GT performance under different environmental conditions. The reference curve obtained refers to a range of produced power (Pow). The larger the power range, the more comprehensive the reference curve. The power range has to be chosen: in this application the chosen power range is from 70% to 100%.

After the definition of the reference curve and ISO correction methods, new data has to be gathered from the plant in order to be able to calculate the actual degradation of the GT and the best maintenance time. The procedure is described below, and is based on the theory previously outlined:

1. Collection of new data (Pow_{real} , $m_{f\ real}$, $pres_{env}$, T_{env} , Hum_{air}).

2. Evaluation of non-dimensional real power and non-dimensional real fuel flow rate,
$$Pow_{real,nd} = \frac{Pow_{real}}{Pow_{nom}}$$
$$\dot{m}_{f,real,nd} = \frac{\dot{m}_{f,real}}{\dot{m}_{f,nom}}$$
In Figure 4 the real point is A.
3. Correction of Pow_{real} to ISO conditions, finding Pow_{ISO} with the correction method.
4. Evaluation of non-dimensional ISO power,
$$Pow_{ISO,nd} = \frac{Pow_{ISO}}{Pow_{nom}}$$
In Figure 4 the corrected point to ISO conditions is B.
5. Shifting of reference curve, forcing it to pass through point B.
Calculation of Non-dimensional average power output produced since the last off-line washing of the GT:
$$\overline{Pow} = \frac{Energy\ produced\ [kWh]}{Hours\ [h]}$$
$$\overline{Pow}_{nd} = \frac{\overline{Pow}}{Pow_{nom}}$$
6. From both the ideal reference curve and the shifted (or real) reference curve, calculation of fuel flow rates for the $\overline{Pow}$ coordinate. From ideal reference curve $\overline{\dot{m}_{f,ref,nd}}$ is found, from real reference curve $\overline{\dot{m}_{f,nd}}$ is found. The first is the fuel flow rate consumed by the GT in ideal conditions, the second is the fuel flow rate consumed by the GT in real conditions.
7. Calculation of $\overline{\dot{m}_{f,ref}}$ and $\overline{\dot{m}_f}$:

$$\overline{\dot{m}_f} = \overline{\dot{m}_{f,nd}} * \dot{m}_{f,nom}$$

$$\overline{\dot{m}_{f,ref}} = \overline{\dot{m}_{f,real,nd}} * \dot{m}_{f,nom}$$

8. Calculation of the output average costs, assuming a first attempt $\tau_{cyc\ opt}$:

$$\overline{c_{our,ref}} = \frac{\overline{\dot{m}_{f,ref}} * LHV * c_{in} + Z_r^{\$}}{\overline{Pow}}$$

$$\overline{c_{our}} = \frac{\overline{\dot{m}_f} * LHV * c_{in} + Z_r^{\$}}{\overline{Pow}}$$

$$\overline{\pi_{out}} = \overline{c_{out}} * \overline{Pow}$$

9. Calculation and plotting of the non-dimensional cost index NIC:

$$NIC = \frac{\overline{c_{out}}}{\overline{c_{out,ref}}}$$

10. Plotting of NIC and calculation of angular coefficient of the linear regression NIC (slope β).
11. Calculation of maintenance cost $C_{m.}$
12. Calculation of $\tau_{cyc\ opt}$.
13. Iteration on $\tau_{cyc\ opt}$ till convergence is achieved

This procedure is performed by B.C.T. using the information provided by ETN members. The database for B.C.T. was collected with a questionnaire. The data required were the five parameters discussed before, plus general information about the operation of the GT (rated power, fuel type, cost of maintenance, electricity price).

The procedures "Best Cleaning Devices" and "Best Cleaning Time" are performed by the software "Best Cleaning Devices 2.4" and "Best Cleaning Time 2.1". These software tools are written in MS Excel to provide an easy-to-access support for GT users and ETN members.

Case-study

Using an operational database of a 55 MW gas turbine [11], the following results were obtained.

Best cleaning devices

For confidentiality reasons, this plant is called "Plant 1". The information useful for B.C.D. is collected with a 13-point questionnaire. The information collected is summarized in Table 1. The GT is washed, with off-line cleaning only, every 3 months and it does not have a HEPA filter system installed. The results are reported in Table 2. The frequency column shows the recommended frequency of washing, on-line or off-line.

In terms of choice of the best technology, off-line washing is the most recommended, the high filtration system is not recommended and on-line washing has a RV close to 50%. The suggested frequency of washing is an off-line washing every 3 months with 44%, preferable to an off-line washing every 4 months with 24.5%. These results are clearly aligned with the actual configuration and operations schedule of the real gas turbine, thus providing to some extent a validation of the methodology and the database.

Best cleaning time

As a first step, the same data are used to calculate an on-line washing frequency for Plant1, in order to verify the validity of the results fr.

As a second step, data is used to calculate the best off-line washing frequency, in order to check the procedure and its results. The authors assumed as the right answer the off-line washing frequency employed in Plant 1 at present (i.e. every 3 months).

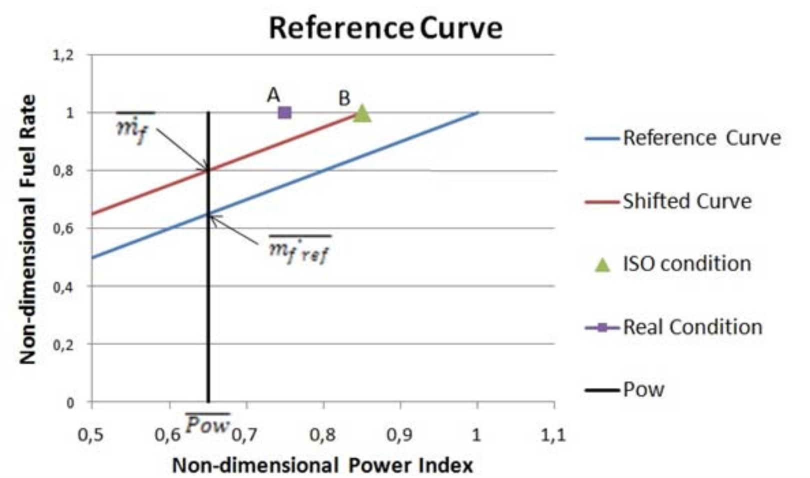

Figure 4: Example of correction of ideal GT performance curve and Power to ISO condition (at the same fuel flow rate)

The set of data is the same as before, with changes in the following parameters only: days of maintenance and cost of intervention. In both calculations the fuel is assumed to be methane, with a fixed cost of $4x10^{-6}$ \$/kJ, equivalent to 0.145 \$/Nm^3. The electricity energy price is assumed to be 0.07 \$/kWh during the day and 0.05\$/kWh during the night.

On-line Best Cleaning Time

Although on-line washing is not performed in the real application considered, the best cleaning time is still evaluated. The set of available data, not optimal for the study of off-line cleaning, fits the study of on-line washing frequency well.

To calculate the best cleaning time for on-line washing the following assumptions were made:

Days of maintenance: 0 (during an on-line cleaning the GT is not switched off);

Cost of maintenance: \$2000 (including cost of de-mineralized water and depreciation charge of the on-line washing device);

These assumptions disregard the power overproduction during washing and the additional future cost due to blade erosion.

To summarize, the additional economic data entered in B.C.T. are:

- Rated power 54 MW;
- Mass fuel flow rate 3.2 kg/s;
- Operating hours: 4000 h;
- Fuel: Methane (LHV 50,046.7 kJ/kg, 4x10-6 \$/kJ)
- Average power per day 56 MW
- Cost of energy during the day 0.07 \$/kWh;
- Cost of energy during the night 0.05 \$ /kWh;

Plant 1	B.C.D. result	Frequency
H.E.P.A	32%	
On-line	51%	2-3 days 60%
Off-line	87%	every 3 months 44% every 4 months 24.5%

Table 2: Plant 1 results from B.C.D.

Figure 5 shows the NIC trend. Even if the initial behavior of NIC trend shows a negative slope (between 0 to 0.8), the global trend of all data gathered shows a reduction in performance. Figures 6 shows the best cleaning time. The intersection of the blue and red curves shows the best time to wash the compressor and, in this case, it occurs after about 1 day of operation. This means the B.C.T. suggests an on-line washing every day. This is encouraging, being a realistic result.

Off-line Best Cleaning time

To calculate the off-line best cleaning time, the following assumptions were made:

- Days of maintenance: 3.
- Cost of intervention: \$10,000.

Days-of-maintenance is an item of information provided by the user.

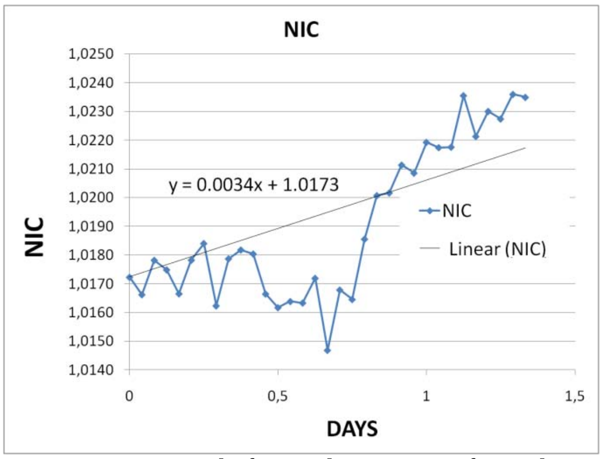

Figure 5: NIC trend of Best cleaning time for on-line cleaning, Plant 1

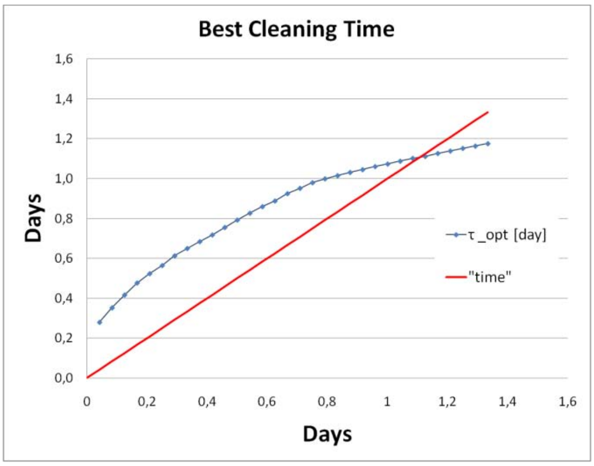

Figure 6 : On-line best cleaning time Plant 1

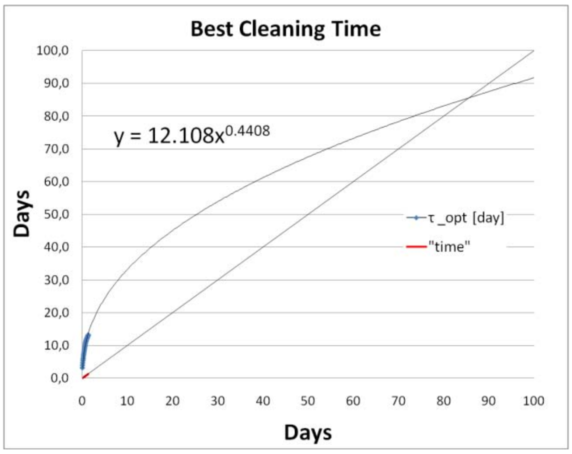

Figure 7: Best Cleaning Time estimation for off-line washing Plant 1

Generally, an off-line washing needs from 2 to 12 hours of operation. However, it may happen that during the planned outage the GT owner carries out a more detailed check of the compressor, which requires more time. In order to compare the results provided by the user and the procedure, as a first attempt, the information provided by the user was used. Afterwards, the same evaluation of Best Cleaning Time was made with a shorter value of days-of-maintenance, i.e. a smaller economic cost.

Since the blue line representing Best Cleaning Time does not meet the red time line, the curve of the blue line is approximated and extrapolated with a non-linear regression curve, for which the expression is:

$$\tau_{opt} = 12.108 * day^{0.4408} \qquad (23)$$

The intersection of the blue and red curves is at about the 84th day of operation, as shown in 7.

This result is in accordance with the real off-line washing frequency, since the information from the site was that the compressor is off-line washed every 3 months.

Changing the days-of-maintenance value from 3 to 0.5 (12 hours), it is possible to calculate the Best cleaning time when only off-line washing is done during the GT stops. The results are shown in figure 8, 9 and 10.

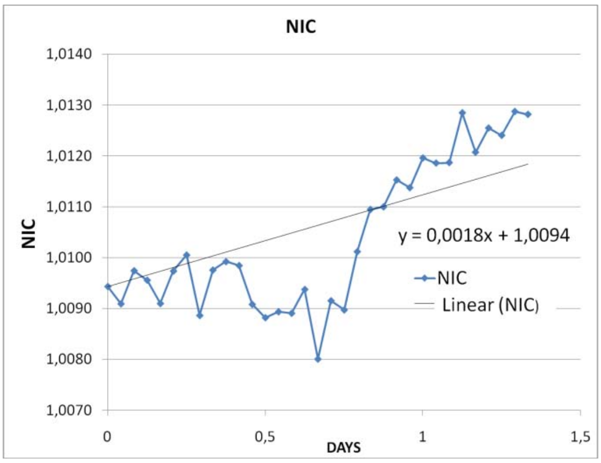

Figure 8 NIC trend for off-line washing of Plant 1

The non-linear regression curve of best cleaning time has the following expression:

$$\tau_{opt} = 5.393 * day^{0.4405} \qquad (24)$$

This regression curve meets the time line at the 20th day of operation. The large difference between this result and the real maintenance time is due to the reduction of the maintenance days, which reduces the impact of the lost power production.

The approximation of the non-linear regression curve of best cleaning time trend is in both cases good but not sufficient to calculate a reliable future trend and consequently is not a reliable final result. In this case, the main cause of uncertainty is the short range of time covered by the GT performance records available; it would be better to have data for a longer period of time, in order to tune the calculation better.

Conclusions

The aim of this work was to provide an useful procedure to help GT users understand the best compressor recovery system for a specified gas turbine in a specified environment, as well as the best frequency for performing compressor cleaning.

A database of real applications and information from the literature, anonymous and easy to update, was designed and populated.

The procedure "*Best cleaning devices*" provides the recommendation value RV for each technology, based on the answers to simple questions relating to operation and ambient conditions. The procedure provides statistical results based on real field data provided by ETN members, and collected from open literature results and papers.

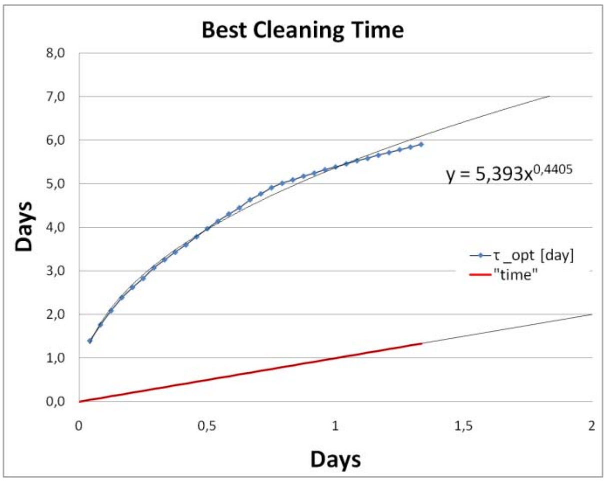

Figure 9: Best cleaning time Plant 1, off-line washing

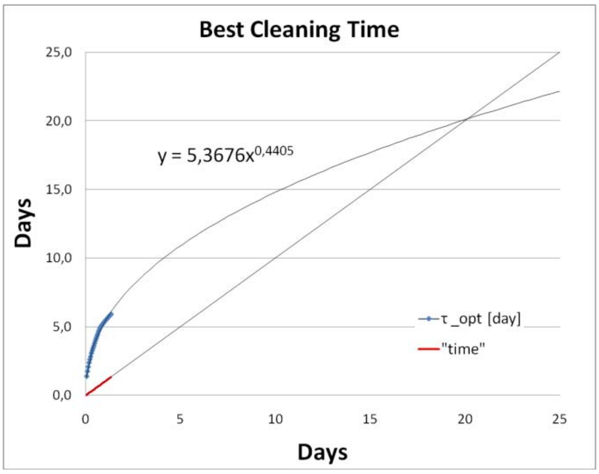

Figure 10: Best cleaning time estimation of Plant 1, off line cleaning with 0.5 day of maintenance.

In the case of an existing power plant already equipped with washing devices, the procedure "*Best cleaning time*" has been developed and written to optimize the frequency of compressor washings. This procedure aims at the thermo-economic optimization of the compressor washing schedule, using either off-line or on-line cleaning. The procedure needs recorded data from the field to define the degradation curve of the GT, as well as reference data to define the performance baseline.

The sample results for the so-called "Plant 1" demonstrate the functionality of the procedures B.C.D. (Best Cleaning Devices) and B.C.T. (Best Cleaning Time).

While the procedures have general validity, results can be continuously improved as additional information is made available in the open literature and by GT users, thus updating and augmenting the database.

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