**The Future of Gas Turbine Technology**
**8th International Gas Turbine Conference**
**12-13 October 2016, Brussels, Belgium**

**Paper ID Number (04-IGTC16)**

# F-TECHNOLOGY GAS TURBINE RETROFIT WITH EPA FILTERS (CASE STUDY)

V. Litinetski, Senior Gas Turbine Specialist
O. Weiss, Gas Turbine Section Manager.
A. Gutman, Mechanical Dept. Manager
Israel Electric Corporation (IEC).

P.O.B. 10, Haifa 31000, Israel
Ph. +972-481-83-306
E-mail: vic.lit4@gmail.com

## ABSTRACT

Operation of F-technology gas turbines purchased by IEC and equipped with one stage pulse-cleaning fine filters, revealed substantial performance degradation due to compressor fouling. In coastal environment, fast increase of the filter differential pressure was observed as well as sea salts entrainment.

To address the problem, an advanced filter technology was chosen. The new system consisted of three filtration stages with the final stage EPA (Efficient Particulate Air) filter. The filter provided excellent cleaning efficiency, prevented sea salt and soot ingress and kept low pressure loss.

The challenge was that this 3-stages filter would be arranged on the same place as the previous single stage filter. An unusual design of the chosen filter provided its implementation with no changes to the existing filter house.

The filter met most expectations and operated for about 16,000 hours before its replacement. On-line compressor washing was completely eliminated and necessity of off-line washing was substantially reduced.

The paper presents arrangements of the EPA filter. Detailed monitoring data on the filter pressure loss, gas turbine power output, heat rate and compressor efficiency are analyzed and compared with the previous filter performance. Recommendations on the filter operation and maintenance are discussed.

## INTRODUCTION

Modern gas turbines (F-technology and higher) are very sensitive to the inlet air contamination that increases requirements to inlet air cleanness. Israel Electric Corporation's (IEC) new F-technology gas turbines (250 MW-class) were equipped with OEM's one stage high efficiency pulse-cleaning filters (F9 by classification of EN 779:2012).

The filters entirely corresponded to the existing approach to GT air cleaning, which was considered as optimal: full filtration of erosion-risk particles (>5-10 µm), good filtration of particles ~1-3 µm (Fig. 1).

The rest of the micron-size particles, which penetrate the compressor and produce compressor fouling, should be washed out with off-line and on-line compressor washing systems (Meher-Homji and Bromley, 2004; Diakunchak, 1992).

Pulse-cleaning provided low pressure loss on inlet filters whereas performance degradation caused by fouling could be restored by periodical compressor washings. Filter life-time was quite acceptable – two-three years of GT operation (16-24K hours).

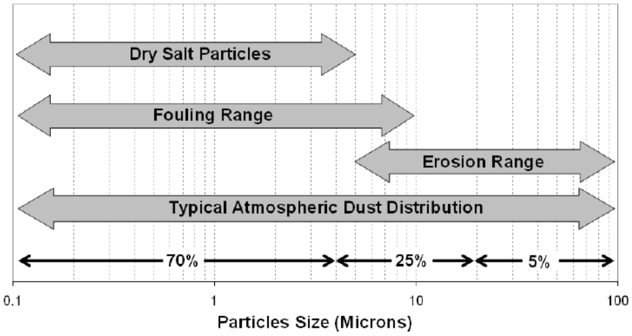

Figure 1.Typical Particles Size Distribution for Erosion and Fouling Range (Wilcox et al., 2010)

This approach was quite suitable for E-technology GTs and earlier technologies, when fast and considerable degradation of performance was encountered only in especially harsh environments (high contaminated refineries, off-shore platforms and some others).

Substantial and fast performance degradation due to compressor fouling had been observed on all new IEC's units. During the first three months of operation power output of gas turbines (GTs) dropped by 9-10 MW. Earlier long-time experience with E-technology GTs (12

Frame 9E units) equipped with similar air filters (and on the same GT sites) did not indicate such fast and extensive degradation of performances (Litinetski et al., 2006).

One gas turbine, installed on the Mediterranean Sea coast, encountered fast increase of the filter differential pressure. Use of pulse-cleaning was entirely ineffective and required a replacement of the filter elements long before their design life time. In addition, sediments of sea salt and soot were observed on compressor blades. This showed that the existing air filtration system entirely failed to provide the required air purity and filter life-time expectations.

The project of advanced filtration of compressor inlet air was triggered by a compressor failure which later occurred on this unit. A root cause analysis, performed by OEM, suggested the reason for the failure was corrosive pitting of the compressor stator vanes. The pitting occurred due to ingress of airborne sea salts in the compressor. According to the latest OEM specification, the existing air filtration system did not correspond to the unit environment (coastal, light industrial) and must be considerably upgraded.

Following OEM recommendations, IEC decided to upgrade the inlet air filter. The existing single-stage pulse cleaning filter has been upgraded to three-stage Efficient Particulate Air (EPA) static filter that has much higher filtration efficiency, especially on micron and sub-micron particle sizes. Pulse-cleaning feature and on-line compressor washings have been eliminated. A new three-stage filter has been installed at the same place as the previous single stage filter, with no reconstruction of the filter house.

Arrangement, advantages and disadvantages of the EPA filter, results of a three-year in field operation are discussed in this paper. Actual performance of the EPA filter and gas turbine are compared with the previous conventional filter.

The EPA filter has met all expectations. On the base of this good experience, two other gas turbines were upgraded with the EPA filters.

## ABBREVIATIONS

EN – European Standard.
EPA – Efficient Particulate Air filter (Classes E10 – E12, EN 1822:2009).
FF – Fine Filter (Classes F7 – F9, EN 779:2012).
GDX – filter system type existing on IEC's GT units.
GT – gas turbine.
HEPA – High Efficiency Particulate Air filter (Classes H13 – H14, EN 1822:2009).
IEC – Israel Electric Corporation.
ISO – International Standards Organization.
MPPS – Most Penetrating Particle Size (EN 1822:2009).
OEM – Original Equipment Manufacturer.
OFLW – Off-line compressor wash.
PS – Power Station.
RAB – Reverse Air Blowing (cleaning of pre-filter panels with reverse air flow).

## TERMS AND DEFINITIONS

Corrected Output – Output corrected to reference ambient and working regime conditions.

Pre-filter hoods – pre-filter in the form of socks pulled-on over the main filter cartridges.

Pre-filter panels – pre-filter in the form of plane panels installed in the weather hoods.

Main filter – the E-group filter composed of double layer F8/E11 cartridges.

Filter class (grade) – number designating a filter efficiency level within the group (F8, E11 etc.).

Filter group – letter designating a filter efficiency group, namely: G, M, F, E, H, U groups.

EPA-1 – the first EPA filter type with the main F8/E11 filter and pre-filter hoods (socks).

EPA-2 – the second EPA filter type with the main F8/E11 filter and pre-filter panels.

Filter, filter cartridge, cassette etc. – a filtering element itself, performing filtration of particles/droplets.

Filter, filtering system – the whole system including filter elements and other devices.

## EXISTING FILTER ARRANGEMENT

The original air filtering system is of a self-cleaning GDX type (GTS-101, 2000). The system consists of inlet weather hoods with moisture separators, horizontally arranged pairs of cone-cylinder filter cartridges (700 pairs), control box and a pulse air system (Fig. 2).

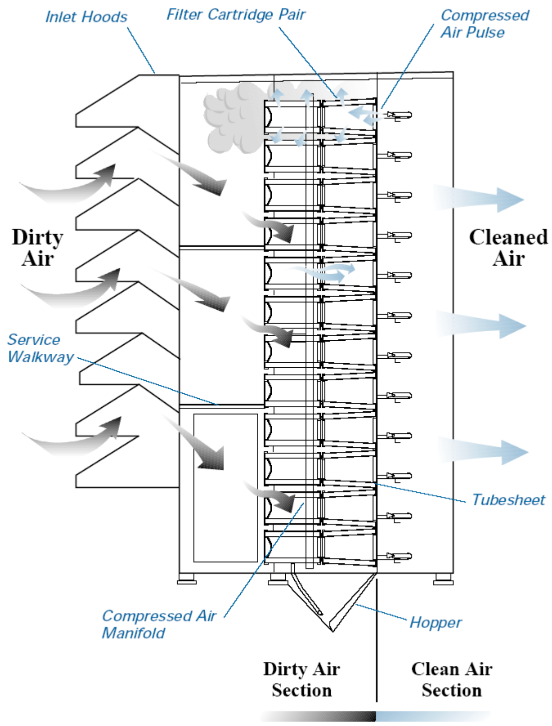

Figure 2. GDX filter system arrangement and operation schematic (GTS-101, 2000).

The filter operational basics are as follows: Air is drawn into the filter system through inlet hoods equipped with moisture separators that protect the filters from the effects of rain, snow and sun (Fig. 2). These inlet hoods contain deflectors that direct the incoming air downward.

The incoming air is cleaned in the single filtering stage by pairs of the filter cartridges installed horizontally against a tube sheet. Cleaned air then passes to the turbine. A walkway behind the inlet hoods provides easy service access to the filters and inlet treatment accessories, such as moisture separators, bird/trash screens etc.

Monitoring devices trigger a reverse blast (pulse) of air when the pressure drop across the filters reaches a certain point. The operator can set this point to fit the conditions of the environment.

The pulses clean the filters from accumulated dust and the pressure drop across the filters decreases. This pulsing continues until the pressure drop reaches a preset minimum. As a rule, the pressure drop could be maintained at a low level, between preset limits. As a result, this should provide low filter losses and extend filter lifetime of up to 2-3 years (16-24K operation hours).

During operation in actual environmental surroundings (coastal, urban and light industrial), the filter did not maintain the low pressure drop that required replacements much more frequently than expected. The unexpected performance of the filter was attributed mainly to extensive sea salts entrainment and high air relative humidity in coastal environment.

## COASTAL ENVIRONMENT SPECIFICS

In addition to hydrocarbons, soot, dust and other contaminants costal installations should be protected against corrosion of the gas path occurring due to ingestion of airborne sea salt (Wilcox et al., 2010; Mueller, 1997). In coastal or offshore environments, the amount of salt particles can be as high as 50% of the total environmental dust mass.

Salt in marine environment can exist in three forms: aerosol, spray and crystal. Coastal installations are most exposed to salt aerosols and crystals. The vast majority of the aerosol droplets are less than 10 micron in diameter and salt particles are 0.1 – 5 micron in size (Fig. 1).

The salt crystals are highly hydroscopic in nature. Salt absorbs water from the air and undergoes some transformations with rise of humidity.

At relative humidity below ~70% the salt is always dry and has a form of crystals. These solid salt particles must be caught by the filter. At about 80%, the critical relative humidity, the salt deliquesces i.e. becomes saline droplets, 2-3 times larger its original size. With decrease of humidity salt remains in the liquefied dynamic condition, shrinking in size, down to ~40% relative humidity and below this value salt is in the crystalline form. Additional information on the subject could be found in the above cited references.

Since relative humidity on sea cost can change from below 40% up to 100%, inlet filter design must handle salt in its dry, liquefied and dynamic phases. This purpose requires the simultaneous ability of the filter system to capture about 100% of sub-micron and micron size crystals, prevent penetration of liquefied salt and handle the significant change of the caught particles size with no permanent increase of the filter pressure drop.

These requirements could be met by usage of high efficiency filters with hydrophobic media. The term hydrophobicity means: "resistance of the filter medium to penetration by water." This resistance can be measured according to corresponding standards (for example EN20811:1992) and is expressed in pressure units (usually mm of water column).

Several other names are used for hydrophobic media, namely: water-repellent, water tight, waterproof etc. All these names must mean "resistance to water penetration" and represent the quantitative value. Qualitative values such as rain-resistant, moisture-resistant, hydrophobic (as possibility to use with moisture) are not suitable in the context under consideration.

## FACED PROBLEMS

1. Ineffective pulse-cleaning that resulted in the fast increase of the filter pressure drop and shortened life-time of the filter (Fig. 3).

A partial solution was implemented, the usage of cheaper F8-class cartridges. Pressure drop was decreased; fast increase of the pressure drop eliminated; the filter life-time increased slightly.

Frequency of compressor washings was increased just after replacements (Fig. 4), since F8-class filter had lower initial efficiency than F9-class filter.

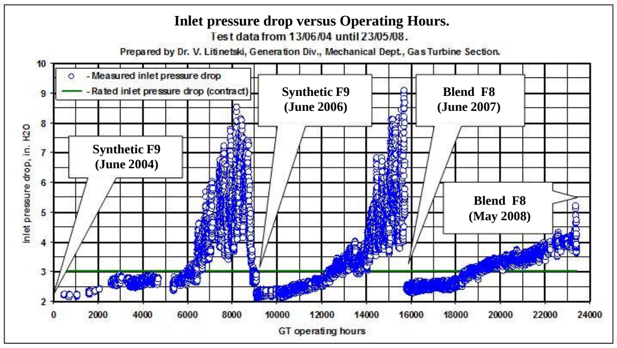

Figure 3. Filter pressure drop with previous F9-class & F8-class filters

2. Soot and sea salt ingression through the filter (Fig. 5). This could initiate corrosion of the compressor blades.

3. Compressor stator blades failure and cracks as a result of pitting corrosion.

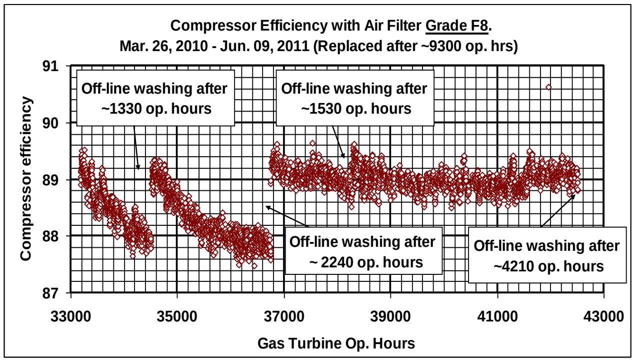

Figure 4. Compressor adiabatic efficiency with F8-class filter.

Figure 5. Fouled compressor rotor – black soot, white salt sediments on the first 6 compressor rows.

Figure 6. Broken compressor stage No. 1 stator blade: loss of the blade tip (~25% of the blade height).

## GOALS OF THE FILTER UPGRADE

1. Prevent or substantially decrease sea salt ingression into compressor.

2. Avoid or minimize a filter house reconstruction required for the upgrade.

3. Increase actual life-time of the filter for up to two years or more.

## POSSIBLE SOLUTIONS AND THE FINAL DECISION

1. Retrofit of the whole filter house to three-stage F9-class filter with combined pulse-cleaning/static filtration stages, with hydrophobic (water repellent) last stage (OEM's offer).

Pro's: optimal arrangement of filter stages, possibility to extend filter life-time.

Con's: very expensive and time consuming, partial solution of the problems (the micron and sub-micron size salt particles could still pass through the F9-class filter; according to experience accumulated by IEC, life-time of the pulse-cleaning filter stage could be short).

2. Upgrade filters to hydrophobic F9-class static filters (with no filter house retrofit, IEC's offer).

Pro's: cheap and simple; no changes to the filter house, decrease of sea salt ingress into compressor; possibility to extend filter life-time.

Con's: partial solution of the problems (the micron and sub-micron size salt particles could still pass through the F9-class filter).

3. Move to EPA static filter with minimal changes of the filter house arrangement (third party offer).

Pro's: acceptable costs; simplicity; no or minimal changes to the filter house, actual elimination of sea salt ingress into compressor; possibility to extend filter life-time.

Con's: limited experience with EPA filtration in GT field and absence of experience in IEC.

The first option was rejected mainly due to its high cost and the long time required for the extensive retrofit of the filter house. The second option was rejected because it could provide only partial solution of the problems.

The third option was finally chosen as providing an achievement of all goals of the upgrade at a reasonable cost (Litinetski at al., 2015).

## INITIAL STAGE OF THE RETROFIT (EPA-1 FILTER SYSTEM)

The offered filter system included a set of 700 cartridge pairs (the same number as in the original design), each pair being assembled from two cylindrical cartridges of large and small diameters. The new cartridge pairs were installed at the same place as the previous conical-cylindrical cartridge pairs. Thus, no any changes to the filter house were required.

Each cartridge represented a composite triple-layer filter (Fig. 7) providing E11-class filtration efficiency (EN 1822-1:2009). The cartridge consisted of the main filter and pre-filter. The main filter was composed of a fine filter (F8-class) and EPA filter (E11-class). Both fine and EPA filters had been made of pleated material with optimized pleat form that allowed substantial increasing of the actual filtration area and decreasing an operational pressure loss. The pre-filter was made of M5-class filter media as a hood (sock) being placed over the main filter

(Fig. 7, 8). Each layer featured high water repellent and oleo tight filter media.

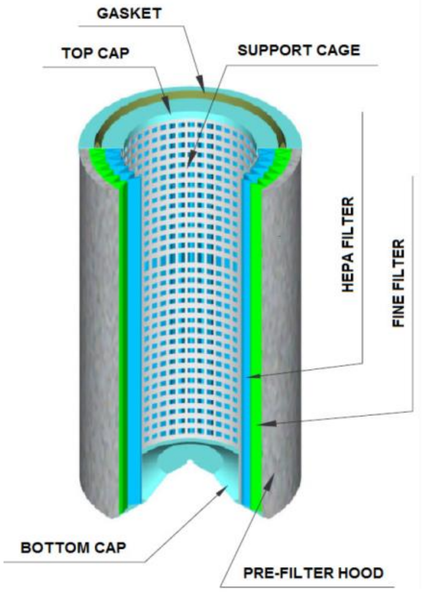

Figure 7. Scheme of the cartridge with hoods

The filter manufacturer anticipated the life-time of the main filter as at least one year (8000 hours). The maximum life-time of the pre-filter was estimated as half a year (and probably less). Therefore, during a year operation of the main filter, one or two replacements of the pre-filters should be planned. This was quite acceptable considering the very low cost of the pre-filter and expected simplicity of the replacements. The replacements were planned with the main filter in place and probably on operated GT unit. These plans were not achieved in actual operation.

Figure 8. Main filters with wrapped-on pre-filter hoods

## Operational results with EPA-1 system

The first EPA filter system, EPA-1, was installed in June 2011 and replaced in Dec. 2012. The main filter was in operation for about 18 months and had collected 9760 operational hours. During this time two replacements of the pre-filter hoods were performed, the first one (after 3680 operational hours) – due to high differential pressure of the hoods, and the second (after 2720 hours) – according to GT maintenance schedule. The third pre-filter operated 3400 hours and had been replaced with the whole EPA-1 filter.

During the whole project, the performance data was continuously acquired, validated and processed using special in-house performance monitoring software, developed by authors of this paper (Litinetski et al., 2006). The data was corrected to reference conditions using OEM’s recommended performance correction techniques and performance correction curves. The reference conditions included the following operational parameters, namely: compressor inlet temperature; ambient relative humidity; barometric pressure; turbine shaft speed; generator power factor (cosφ); fuel composition for natural gas fuel; fuel temperature; compressor inlet pressure drop; GT exhaust pressure drop. Performance degradation was evaluated by comparison of the actual corrected performance values of power output and heat rate with the predicted values calculated using the manufacturer's performance degradation curve. All performance results, presented in this paper have been obtained using above mentioned monitoring software,

Compressor, gas turbine and filter performance trends, presented below, demonstrate that the performances with the new filter are remarkably better as compared with the previous filters.

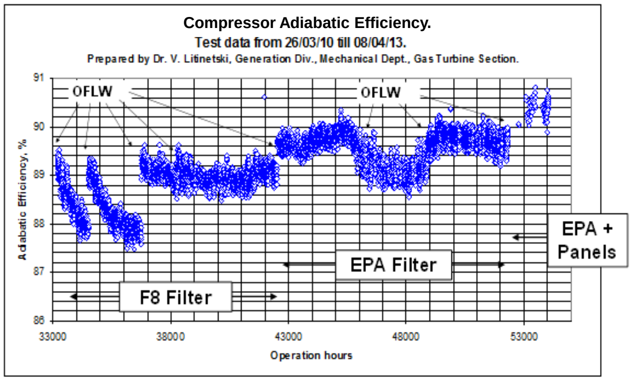

Figure 9. Trend of compressor adiabatic efficiency: previous F8-class filter is compared with the EPA filter. (“EPA+Panels” indicates EPA-2 filter, OFLW denotes off-line compressor wash).

Unlike operation with the previous filter, compressor efficiency does not show drops due to compressor fouling. The efficiency is not changed before and after off-line washings (Fig. 9). This indicates that compressor fouling is practically absent.

Decrease of the efficiency in the middle of the EPA filter operation (46-49 thousand hours operation interval in Fig. 9) is explained with colder ambient temperatures in the winter time. Regular scattering of the efficiency within ±0.5% interval is mainly a result of day-night changes of ambient temperatures.

Turbine Power Output was substantially better with EPA filter (Fig. 10) as well as Heat Rate. On average, Power Output had increased by ~4 MW and Heat Rate decreased by ~55 kJ/kWh. This provided a returned investment of the EPA filter within the first year of the filter operation (considering the actual operation with ~6500 hours annually).

During operation with the first pre-filter, the performances virtually did not degrade. But after replacements of the pre-filters, performance degradation became visible (Fig. 10). The reasons were found as minor air bypass through filter gaskets that was further fixed in EPA-2 filter, some air bypasses in GT unit valves and joints, oil leakage from the compressor bearing. Additionally, a dependence of the corrected performance on environment conditions was discovered, so that seasonal influence on performance could not be entirely excluded.

Trends of the filters pressure losses are presented in Fig. 11. The pressure loss of the previous F8-class filter increases steadily due to gradual clogging of the filtering medium. The EPA-1 filter demonstrated a short-time exponential increase of the pre-filter pressure drop. This behavior was indicated in advance by the filter manufacturer, but the anticipated increase of the pressure drop could not be avoided in field due to lack of experience in IEC.

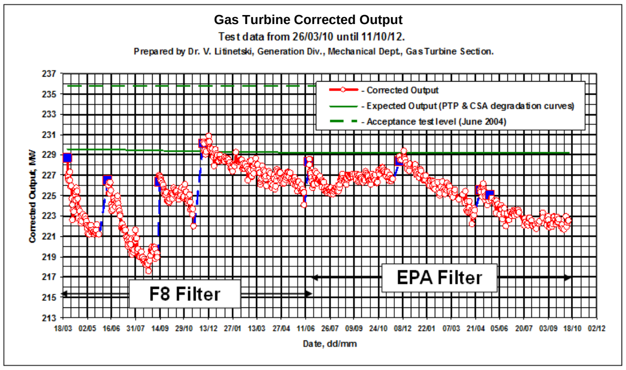

Figure 10. Trend of GT corrected output: comparison of the previous F8-class filter with the EPA filter. (Blue quads indicate off-line compressor wash).

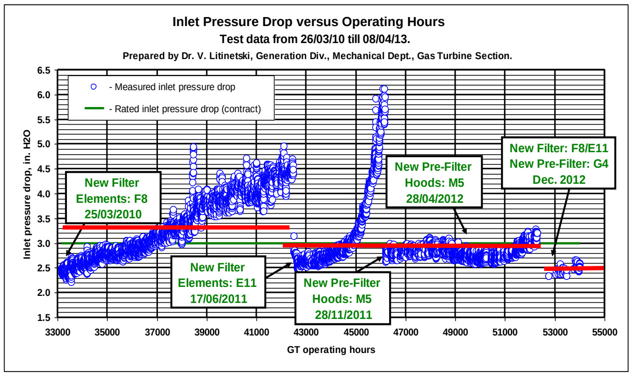

Figure 11. Trend of the compressor inlet pressure drop: comparison of the previous F8-class filter with the EPA filter. Red lines show average values over the whole operation interval of the related filter.

This phenomenon had two reasons (known in advance to the EPA project team). The first reason was the non-optimal (too low) filtration area of the pre-filter hoods due to their compact design suitable to the limited area of the existing filter house. The second reason was a local environment feature of high atmospheric dustiness periods that might occur several times a year during so-called Khamsins (hot desert winds similar to Sirocco). During Khamsin, dust concentration in the atmosphere could rise by several dozen times, producing fast clogging of the pre-filters. The only solution to the problem in such conditions is the urgent replacement of the pre-filter hoods that was not performed on time due to absence of experience.

Since such pressure drop rises are short, the average filter pressure loss of EPA-1 filter was lower than that of F8-class filter (Fig. 11) and especially lower than of the original F9-class filters Fig. 3).

EPA-1 operation revealed several drawbacks of the pre-filter hoods, which are described below.

- Replacements of the pre-filter hoods require disassembly and subsequent assembly of the main filters. Therefore, replacements of the pre-filter hoods are labor- and time-consuming, and additionally, it is difficult to verify quality of the replacements.
- Lifetime of the hoods is relatively short and requires 4-5 replacements during lifetime of the main filter (considering 16000 hours life time of the main filter).
- Fast increase of the pressure drop over pre-filter after sand storms that requires an urgent replacement of the hoods; otherwise a limitation of GT output is necessary.

The EPA-1 system was replaced in Dec. 2012 after 9760 operational hours of the main filter and two replacements of the pre-filter hoods. Both the main filter and pre-filter hoods were replaced according to a maintenance plan of GT unit. The replacement was not forced by the filter differential pressure limitations.

On the base of EPA-1 filter operation experience, the following conclusions were made:

- The first pre-filter operation during 3500 hours (Jun.-Nov. 2011) revealed the following main details:
  - virtually no Output and Heat Rate degradation;
  - virtually no compressor efficiency degradation;
  - no off-line/on-line compressor washings required.
- During the remaining 6300 hours the overall GT performance was worse than anticipated as a result of the several problems. Nevertheless EPA filter performed notably better than the previous F8-class filter.
- During the whole operation period of 9800 hours pressure drop of the main filter (F8/E11) remained almost unchanged (with two replacements of the pre-filters).
- The EPA filter has a lower average pressure loss than the previous conventional F8 filter; therefore the EPA filter provides no additional losses due to the higher pressure drop.

- The EPA filter demonstrated good performance and this filter type might be recommended to use at sea coast and industrial environment.
- In order to increase the life time of the pre-filter, the pre-filter hoods should be replaced with the pre-filter panels.

## SECOND STAGE OF THE RETROFIT (EPA-2 FILTER SYSTEM)

On the base of accumulated experience, the EPA system was upgraded to provide better performance and maintainability of both main filter and pre-filter, namely:

- Pre-filter hoods were replaced with water and oleo proof panels (G4-class) installed in the weather hoods as a replacement of the existed moisture separator;
- On each of 5 filter house floors the lowermost row of filters was equipped with cone-cylinder cartridges that comprised 20% of cartridges;
- Cylinder-cylinder cartridges were upgraded with guiders providing better assembly;
- Upgraded gasket design was implemented for better sealing of the main filter;
- Upgraded technology of the filter pleats manufacturing (provided by the manufacturer);
- Pre-filter panels enforced with stiffening ribs (on the last stage of the project);
- Differential pressure measurements has been implemented downstream of the pre-filter.

Views of the main filter cartridges and pre-filter panels are presented in the figures below.

Implementation of the pre-filter panels provided the following advantages:

- Improved maintenance because replacements of the panels are performed separately of the main filter;
- Extended life-time (due to increased filtering area) that allows two pre-filter replacements during the whole life time of the main filter.
- Elimination of the moisture separator that decreases pressure loss of the whole filter.

With the above mentioned improvements, anticipated life-time of pre-filter was estimated as 5000-6000 hours and of the main filter as 16000 hours.

At the same time, the filtration area of the panels remained to be non-optimal. Further increase of the area would allow increasing the panel's life time by ~40-45% that could extend the replacement intervals of the pre-filters up to ~8000 hours (once per year). Unfortunately, this required an additional reconstruction of the filter house weather hoods that could not be performed at this stage of the project.

Figure 12. EPA-2 Main filter during installation

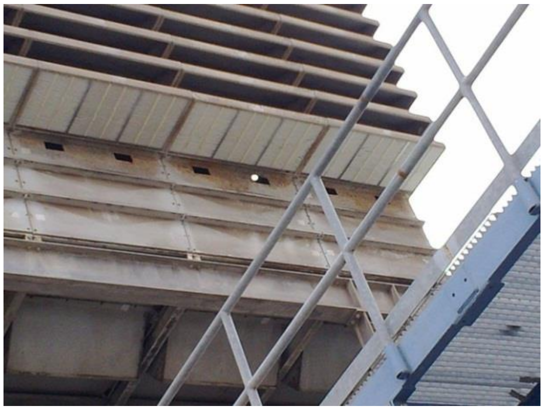

Figure 13. EPA-2 Pre-filter panels

### Operational results with EPA-2 system

Compressor, gas turbine and filter performance trends, presented below, demonstrate good performances with the EPA-2 filter.

Turbine Power Output was substantially better with EPA filter (Fig. 14) than with the conventional F8, F9-class filters. Performance degradation after off-line compressor washings was either low or absent at all. Some periods of irregular degradation were observed that could not be connected to compressor fouling. Some reasons were the same as those indicated in the previous paragraph.

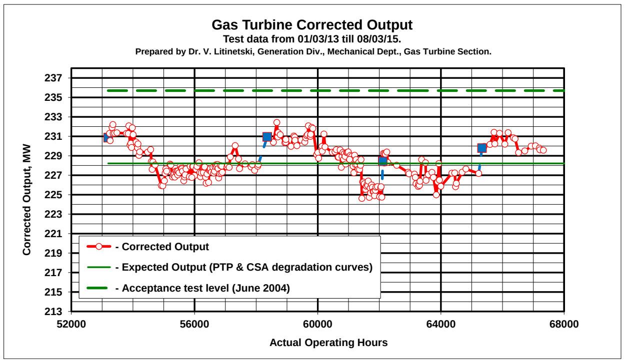

Figure 14. GT Corrected Power Output with EPA-2 filter. (Blue quads indicate off-line compressor washings).

Compressor efficiency did not show drops due to compressor fouling and did not change before and after off-line washings (Fig. 15). This indicates that compressor fouling is practically absent.

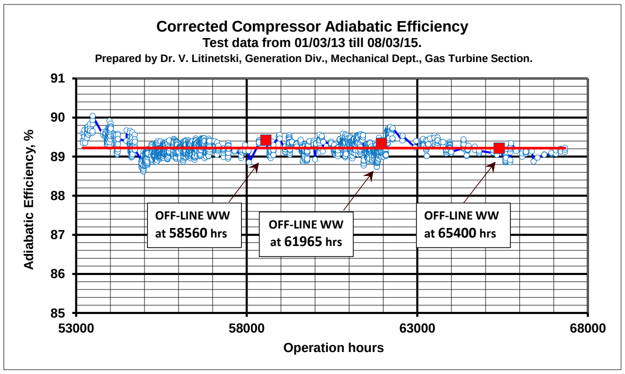

Figure 15. Compressor adiabatic efficiency. (Red quads indicate off-line compressor water wash).

The pressure drop trend of the Main filter shows, as expected, steady increase within anticipated limits (Fig. 16). The panel pre-filter, like EPA-1 pre-filter hoods, demonstrates the short-time exponential increases of the pressure drop.

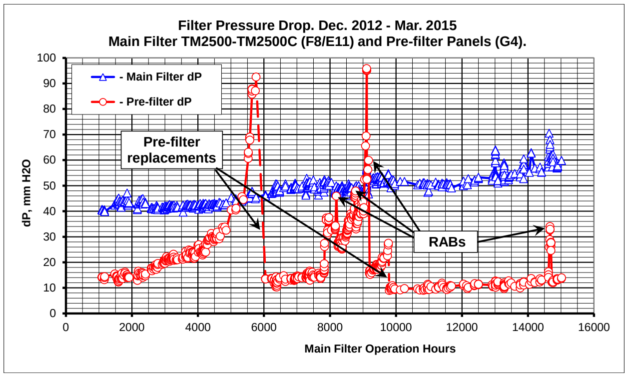

Figure16. Pre-filter and Main filter differential pressure (RAB – Reverse Air Blowing)

As it was explained earlier in this paper, this phenomenon had two reasons: the non-optimal (too low) filtration area of the pre-filter and the high atmospheric dustiness periods that might occur several times a year. The only solution of the problem was the urgent replacement of the pre-filter panels. In order to increase the pre-filter life-time, the power station personnel had implemented a cleaning technique with reverse blowing of the pre-filter panels with compressed air (RAB). After initial low effective attempts, an effective technique was developed that could provide increase of the pre-filter life-time by more than 1000 hours (Fig. 16). The last RAB (rightmost in Fig. 16) demonstrates the skilled performing of the RAB procedure.

Since such pressure drop peaks are short, the average filter pressure loss of EPA-2 filter was still lower than of regular F8 and F9-class filters (Fig. 4, 11).

On the base of EPA-2 filter operation experience, the following conclusions were made.

- The EPA-2 filter operated successfully during ~15220 operating hours, from Dec. 2012 till March 2015 (27 months). Since the main filter did not reach the recommended for replacement maximum pressure loss, life time of the main filter can be estimated as ~16000 hours.
- During the whole operation term of the main filter, two replacements of the pre-filter panels were performed, thus three pre-filter sets were in operation with the same main filter. Based on this experience, average life time of the pre-filter panels can be estimated as ~5500 hours.
- Compressor efficiency has shown no degradation during the whole filter operation term; some efficiency fluctuations could be correlated with seasonal changes of the ambient temperature.
- On average, the EPA-2 filter has a lower pressure loss as compared to the previous conventional F8, F9-class filters.
- Off-line washing intervals have been extended up to 5700 hours with no degradation of compressor efficiency. Even longer intervals are possible. Need of on-line compressor washings has been entirely eliminated.
- The overall GT performance was worse than anticipated as a result of the several problems unrelated to the filter. Nevertheless, with EPA filter the GT unit performed notably better than with the previous F8- class filter.
- The EPA-2 filter has demonstrated good performance and this filter type might be recommended to use at the site environment (sea coast and industrial).

## SUMMARY

1. The EPA-grade filtration features several difficulties, namely: this modern technique is relatively new in the GT industry; it has limited world-wide and manufacturers experience; some important filter tests are not standardized yet.
2. The implemented EPA filter represents the three-stage static air filter with panel-type pre-filter of G4 class, and cartridge-type main filter of F8/E11 class.
3. On average, the EPA filter had the lower pressure loss as compared to the regular F8, F9-class filters.
4. Based on the accumulated experience, life time of the main filter was evaluated as 16000 hours and the average life time of the pre-filter panels as 5500 hours.
5. The EPA filter operation provided high profits on the fuel economy. Additional profit is obtained by no on-line and much less frequent off-line washings, less compressor corrosion, longer life time.
6. The EPA filter demonstrated good performance and this filter type had been recommended for use in IEC's F-technology gas turbines.

## ACKNOWLEDGEMENTS

The authors would like to thank the personnel of the gas turbine site (IEC) for close participation and support in the filter upgrade project and Mrs. T. Malka (IEC) for thorough reading and correction of the paper text.

## REFERENCES

**Brandon Ost et al.** *Humidity & Moisture… the effects on air filters.* Posted on 14 May, 2013 on filtrationgroup.com

**I.S. Diakunchak.** *Performance Deterioration in Industrial Gas Turbines.* Journal of Engineering for Gas Turbines and Power. April 1992, Vol. 114. pp.161-168.

**European Standard EN 779:2012 (Supersedes EN 799:2002).** *Particulate air filters for general ventilation - Determination of the filtration performance.* European Committee for Standardization, 2012.

**European Standard EN 1822-1:2009 (Supersedes EN 1822-1:1998).** *High efficiency air filters (EPA, HEPA and ULPA) - Part 1: Classification, performance testing, marking.* European Committee for Standardization, Nov. 2009.

**GTS-101.** *GDX Self-Cleaning Filter System.* Leaflet of Donaldson Company, Inc., 2000.

**V. Litinetski et al.** *Compressor washing optimization: Field experience with Frame 9E and 9FA gas turbines.* Power-Gen Europe conference 2006, Cologne, Germany. Paper ID124.

**V. Litinetski at al.** *Upgrade of IEC Gas Turbine Air Filters to an Advanced EPA Filter Type.* IEC Internal Report. Haifa, Nov. 2015, 86 pp.

**C.B. Meher-Homji and A. Bromley.** *Gas Turbine Axial Compressor Fouling and Washing.* Proceedings of the 33d Turbomachinery Symposium 2004, pp. 163-192.

**Mueller Environmental Designs.** *Special Considerations for Gas Turbine Coastal, Marine and Offshore Installations.* 1997.

**M. Wilcox et al.** *Guideline for Gas Turbine Inlet Air Filtration Systems.* Release 1.0, Southwest Research Institute (USA), 2010, 107 pp.