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Impact of EPA Air Intake Filtration on Gas Turbines Operating in Middle East Offshore Applications and Fueled with Sour Gas.

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Abstract

Gas turbines, running both power generation and mechanical drive applications are essential to produce remote offshore assets in the oil & gas sector. Gas turbines offer the benefit of a high power density necessary for platforms. In the 10 to 30 MW range, the three different gas turbine technologies – aero derivative, light industrial and heavy duty have been operated in the Middle East for decades. Reliability and availability are of prime importance to ensure production efficiency and revenue yield.

The availability of high efficiency particulate arrestance (EPA) air filter technology means that offshore operations can be considered through a new paradigm. This paradigm consists in maintaining gas turbine performances with better compressor cleanliness, increasing availability by reducing the number of gas turbine water washing and pushing forward planned maintenance operations by improving long term part integrity. As an additional benefit, EPA filtration influences the gas turbine behaviour against hot corrosion mechanism resulting from the combustion of sour fuel gas, rich in hydrogen sulphide (H_2S).

The offshore complex of ABK (Abu Al Bukhoosh) is equipped with three gas turbine technologies issued by three different manufacturers. ABK runs three General Electric heavy duty PGT10 2-shaft (12 MW) and one Dresser Rand aero-derivative RB211 24G56 (26 MW) as turbo-compressors and three Siemens light industrial SGT 400 (13 MW) as turbo-generators. For decades, these gas turbines were equipped with high velocity low grade filters. In 2010, the operator of the different platforms that make up this production complex started an extensive retrofit of the air filter housings on these seven gas turbines. It was decided to install a low velocity EPA filtration system. The retrofit was completed in 2012. This offshore complex, after operating for three years offers a good overview of how EPA filters can influence the gas turbine operation and maintenance activity.

The principal purpose of this paper is to discuss the four topics that a large unique offshore asset, like ABK, can offer. The first is to provide a better understanding of gas turbine applications burning fuel gas, rich in H_2S. Secondly it is to share details of the offshore retrofit operation. The third is to identify the different characteristics of a high velocity low grade filtration and a low velocity EPA filtration for different sizes of turbine and for different technologies. Last but not least it is to share the outcomes of the EPA air filter technology on these three models of gas turbines through various aspects. A quantitative analysis of the availability and reliability for the three technologies is provided and discussed. Changes in water wash strategy will be addressed. The qualitative influence of EPA filtration on the hot gas path is reviewed in the light of part integrity and hot corrosion development. The impact on operation and maintenance activities is shared.

The coming challenges combining offshore and sour service applications are developed from an operator viewpoint.

Key Words: EPA filtration, offshore, hot corrosion, hydrogen sulphide, planned maintenance, availability, reliability, part integrity, aero-derivative, light industrial, heavy duty, carbon foot print, energy efficiency.

1. DESCRIPTION OF ABK OFFSHORE ASSET

Site
Abu Al Bukhoosh (ABK) is an offshore field located in the Arabian Gulf at the northern edge of the territorial waters of the Emirate of Abu Dhabi. The field is located 180 kilometres away from Abu Dhabi. It was discovered in 1969 with an exploration well. Subsequent delineation was conducted in 1973 and 1974 with an initial oil production taking place in 1974. This field, producing oil and gas, is an asset made up of various platforms, NKPP, GLP, KPP and PPSP.

Figure 1 – Platform complex of ABK -

Equipment
The gas turbines installed at ABK use three different technologies and come from three different original equipment manufacturers (OEMs). The platforms are equipped with one aero-derivative gas turbine RB211 24G56 from Dresser Rand (26 MW Iso) on KPP, three light industrial gas turbines SGT400 from Siemens (12,9 MW Iso) on NKPP and PPSP and three heavy duty gas turbines PGT10 2-shaft from General Electric (11,9 MW Iso) on GLP.

Applications
The RB211 24G56 gas turbine drives through a gear increaser, a compressor for gas export whereas the PGT 10's are coupled to two gas-lift compressors and one gas injection compressor. Each gas lift compressor train consists of a speed increaser gear box driving 2 compressor casings containing the LP/MP sections in one casing and one HP section in the other (Figure 2). The gas injection train consists of one gas turbine, one gear and one compressor casing (Figure 3). The compressor trains are not equipped with a back up. This means a train shut-down generates an immediate lack of production.

Figure 2 – PGT10 2-Shaft Gas Turbines Used as 2 x 50% Gas-lift and 1 x 100% Gas Injection Turbo-compressors -

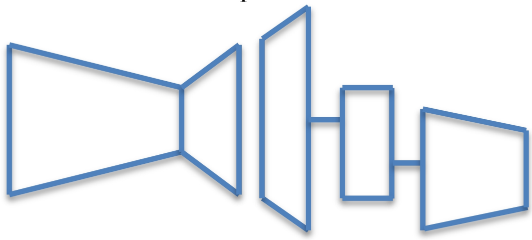

Figure 3 – RB211 24G56 Gas Turbine Used as 1 x 100% Export Turbo-compressor -

In parallel, three SGT 400 gas turbines are allocated to the production of electricity. These gas turbines run generators (Figure 4). The function ensuring the production of electricity is equipped with a back up shaft line ready to start up in case of a shut down. 2 out of 3 are necessary to meet the demand for electricity.

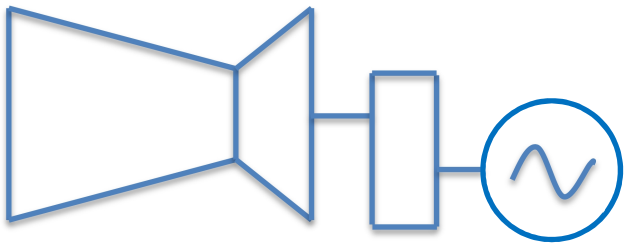

Figure 4 – SGT400 Gas Turbines Used as 3 x 50% Turbo-generators -

Fuel Gas
The NKPP fuel gas is a sour gas rich in hydrogen sulphide (H_2S) (Table 1). The 2% H_2S molar content is very high for gas turbines running offshore. As a matter of comparison, years of operating experience show that it is recommended to operate gas turbines with a level of hydrogen

sulphide below 10 ppm when the installation is offshore.

Component	Molar Composition (%)
Nitrogen	3,63
Carbon Dioxide	3,00
Hydrogen Sulphide	2,05
Methane	84,06
Ethane	4,29
Propane	1,45
iso – Butane	0,33
n – Butane	0,51
iso – Pentane	0,21
n – Pentane	0,18
Hexane	0,18
Heptane	0,11

Table 1 – Typical Fuel Gas Composition

Hot Corrosion
The ABK gas turbines are subject to hot corrosion attacks because its fuel gas contains H_2S and the location of the field is offshore where salts are available in large quantities in the marine atmosphere. The ABK gas turbines are sensitive to hot corrosion in the hot gas path. On ABK, this hot corrosion chemical reaction takes place between sulfur and the alkali (sodium, potassium, calcium, etc…) to create sulfuric acid as shown in the following equations.

$$H_2S + O_2 \Rightarrow SO_2 + H_2$$

$$2NaCl + SO_2 + O_2 \Rightarrow Na_2SO_4 + Cl_2$$

Operation Requirements
The objective is to run the different gas turbines 24/7. Each gas turbine stop related to water washing, inspection, maintenance or failure is detrimental to production. The best rates of availability and reliability are expected in order to maximize the use of the asset.
The gas-lift production arrangement is 2 x 50%, nevertheless the gas injection compressor train may sustain the gas-lift function to some extent. The gas injection production arrangement and the gas export production arrangement are both 1 x 100%. Commonly, the compressor train expected availability is 97.5% with gas turbines fuelled by mild fuel gas. Achieving this level of availability is particularly difficult.
The electricity production arrangement is 3 x 50%. The expected availability of the entire electricity function is 99.99% meaning availability per train of 66.7% on average. This requirement does not depend on the fuel gas acidity. This value is much easier to attain for teams in operation but necessitates additional investment.

Water Washing
The online water wash requires a substantial quantity of demineralised water on a daily basis. On ABK platforms, it is not possible to store this large quantity of demineralised water. This is why on line water washing is not the practice on this asset.
The remaining option to wash the axial compressor is to use an off-line water wash. This wash sequence consists of a soak period for the axial compressor with a detergent and then a rinse or clean sequence to remove the soaked dirt deposits from the machine. Although off line engine washes restore compressor performance, they generate costly servicing and even costlier downtime, along with a great quantity of dirty washing agent to dispose of. On a regular basis, the off-line water wash sequence duration can last up to twelve hours. The different steps are as follows:

- A gas turbine cool-down of 8 hours.
- A gas turbine water-wash preparation of 2 hours.
- A soak for the axial compressor with detergent of 1 hour.
- A rinse with clean water of 1 hour.

How long the soak and rinse steps last depends on the axial compressor level of fouling because the rinsing drains must be cleaned.

Boroscope Inspection
On an aero-derivative gas turbine, a 4-hour boroscope inspection is carried out after the water wash operation.

Compressor Efficiency
The axial compressor efficiency of the gas turbines is monitored by the ABK site operation team. Technical support from shore recommends washing when necessary.

Hot Section Wearing
This hot section wearing leads the engine exchanges and impacts the operations at site directly. This is mainly due to the capability of the engine to endure under the hot corrosion development.

Offshore Atmospheric Impurities
Generally with offshore fixed platform and FPSO environments in the Middle East, air intake

filtration systems must address the efficient removal of rain, fogs/mists, sea spray aerosols, hydrocarbons, salt particles, seasonal 'Harmattan' dusts and local sources of offshore asset generated pollution, in order to protect gas turbine compressor sections from erosion, corrosion and fouling.

The seasonal 'Harmattan' dusts is an industry-wide term used to describe the phenomena of land-produced dust like contamination, that become suspended in the air and are carried hundreds of miles out to sea, which, when ingested, interfere with aerospace, ocean going vessels and gas turbine engine performance.

However, it must be acknowledged for information and paper correctness, that the actual occurrence of 'Harmattan' is defined as warm, dry and dusty winds, that blow from the Sahara desert over the subcontinent of West Africa and out to sea, and are most prevalent between the months of November to March.

With regards to specific atmospheric impurities at ABK, several 'snap shot' air samples were taken at the platform, which, when averaged, provided airborne particle size and corresponding concentration data (particle count).

This average air sample data is shown below in figure 5, with the data range from 0.3 to 10.0 microns:

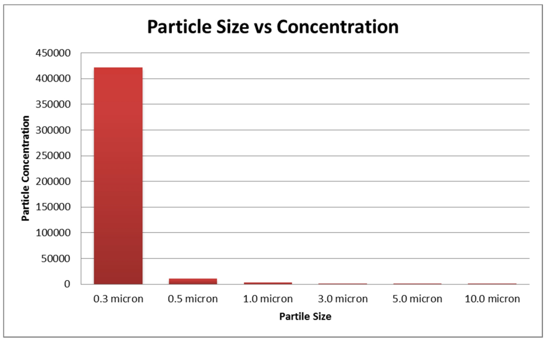

Figure 5 – ABK Average Air Sample Particle Size vs Concentration

From this average air sample data, it can be seen that 96.77% of the particles collected were 0.3µm, and it can be calculated that 99.828% of the airborne particles at ABK are in the 0.3µm to 1.0µm range as shown below in table 2.

Size (microns)	0.3	0.5	1.0	3.0	5.0	10.0
Percentage (%)	96.77	2.455	0.703	0.045	0.022	0.005

Table 2 – ABK Average Air Sample Particle Size (microns) versus Percentage (%)

2. ABK AIR INTAKE FILTRATION SYSTEMS BEFORE RETROFIT

Equipment

The air intake filtration systems installed on ABK prior to retrofit were multi stage high velocity, typically comprising upstream vane separators, pre-filter bags inserted into medium efficiency filter bags and a downstream vane separator, as shown in figure 6.

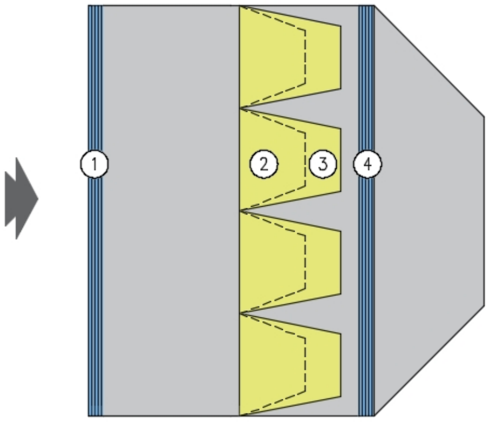

Figure 6 – Typical Multi Stage High Velocity Filtration System (1 - Upstream Vane Separator, 2 - Pre-filter Bags, 3 – High Efficiency Filter Bags, 4 - Downstream Vane Separator).

High Velocity Filtration System Operating Principles

The multi stage high velocity filtration principles of operation are:

- The upstream vane separator removes the majority of large airborne water droplets, such as sea sprays, fogs, mists and large aerosols.
- The pre-filter bags (G3 classification in accordance with EN779:2012) and medium efficiency bags (M5 classification in accordance with EN779:2012) remove airborne particulates and also coalesce small aerosols that have passed through the upstream vane

separator, whereby the small aerosols coalesce into larger droplets which can be captured by the downstream vane separator.

- The downstream vane separator captures the large coalesced droplets which pass through the pre-filter and medium efficiency filter bags, which are then removed from the air intake filtration system via a sealed manometric drain.

3. FILTRATION EFFICIENCY CLASSIFICATIONS ACCORDING TO EN779:2012 AND EN1822:2009.

In Europe air filtration products are tested in accordance with ISO standards EN779:2012 and EN1822:2009.

EN779:2012 distinguishes three filtration categories: coarse (C), medium (M) and fine (F). The classifications are based on the minimum efficiency (ME) of a filter. For testing and classification a single filter element is challenged with DEHS aerosol, an aerosol for measurement of filtration efficiency as a function of particle size, and a standardised test dust is used to compare filters for test dust capacity. Additionally for coarse filters, filtration efficiency with regards to loading dust arrestance is measured when filtration efficiency is not high enough to give a reliable result. This standard was tailored to HVAC filters, to provide a method of standardisation throughout the air filtration industry, and is applicable to air filters having efficiency lower than that required for testing in accordance with EN1822:2009.

EN1822:2009 likewise distinguishes three filtration categories: efficiency particulate air filters (EPA), high efficiency particulate air filters (HEPA) and ultralow penetration air filters (ULPA). For testing and classification, a single filter element is challenged with aerosols and at the MPPS (Most Penetrating Particle Size) both the local and overall efficiency are determined.

However, it should be noted, that testing to these ISO standards occurs in laboratory conditions, with relatively dry ambient air and new and clean filter elements, and thus does not take into consideration real world offshore conditions and the atmospheric impurities described above.

4. CONTRAST BETWEEN CURRENT DAY OEM FILTRATION CLASSIFICATION SPECIFICATIONS, THE ABK INSTALLED HIGH VELOCITY FILTRATION CLASSIFICATION AND EPA FILTRATION CLASSIFICATIONS

Today, gas turbine OEMs typically specify that air intake filtration systems are to meet the requirements of either F8 or F9 classification, in accordance with EN779:2012. Whereas in stark contrast, high velocity filtration systems of ABK meet the requirements of M5 classification, in accordance with EN779:2012

Therefore, in order to understand the differences in the air cleanliness quality and thus the contamination that enters the gas turbine compressor section, direct performance comparisons can be made at particle size filtration efficiencies.

For example, if we consider the ABK average air sample, where 96.77% of the particles were 0.3µm:

- A filtration product that is certified in accordance with EN779:2012 classification M5 will have a particle removal efficiency of approximately 30% at 0.3µm
- A filtration product that is certified in accordance with EN779:2012 classification F9 will have a particle removal efficiency of approximately 60% at 0.3µm.
- A filtration product that is certified in accordance with EN1822:2009 classification EPA E10 will have a particle removal efficiency approximately 97% at 0.3µm.
- A filtration product that is certified in accordance with EN1822:2009 classification EPA E12 will have a particle removal efficiency of approximately 99.993 at 0.3µm (AAF HydroCel EPA E12 efficiency).

Therefore, it is possible to calculate the quantity of 0.3µm particles that would pass through the different air filtration classifications into the clean air stream, from which a ratio may be derived on air cleanliness quality delivered to the gas turbine compressor:

From the average air sample data at the ABK platform, whereby there was an average of 421,829 particles collected at 0.3µm:

- 421,829 x (1 - 0.3) = 295,280 particles would penetrate a M5 classification filter element.
- 421,829 x (1 - 0.6) = 168,732 particles would penetrate a F9 classification filter element.
- 421,829 x (1 - 0.97) = 12,655 particles would penetrate an E10 classification filter element.
- 421,829 x (1 - 0.9993) = 295 particles would penetrate an E12 classification filter element.

Therefore, filtration to classification F9 is 2 times more efficient than M5. Filtration to classification EPA E10 is 23 times more efficient than filtration to classification M5, and EPA E12 is 1,000 times more efficient than filtration to classification M5.

5. RELATING FILTRATION CLASSIFICATION AND FILTRATION DIFFERENTIAL PRESSURE OVER TIME TO GAS TURBINE OUTPUT LOSSES

As a result of close cooperation and collaboration with end users, who employ 100s of small to medium and large gas turbines, of both aero and industrial derivatives, in offshore, coastal and inland applications, AAF has built a thorough understanding of engine losses and its direct correlations with air cleanliness quality and filter differential pressure (Δp) over time.

These correlations are common to both aero and industrial derivatives, the phenomena of which are common to offshore, coastal and inland applications, and are illustrated for filtration efficiency classifications F9, E10 and E12 as shown below in figures 7, 8 and 9:

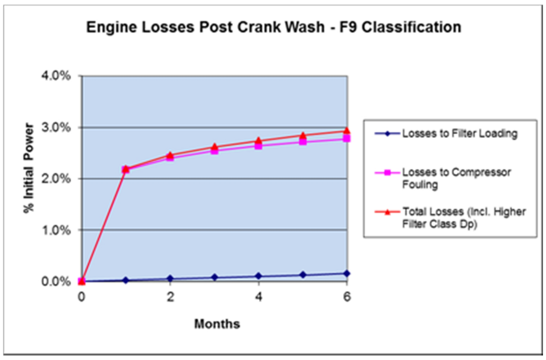

Figure 7 – Gas Turbine Losses (Filter Δp, Fouling and Total) Post Crank Wash F9 Classification -

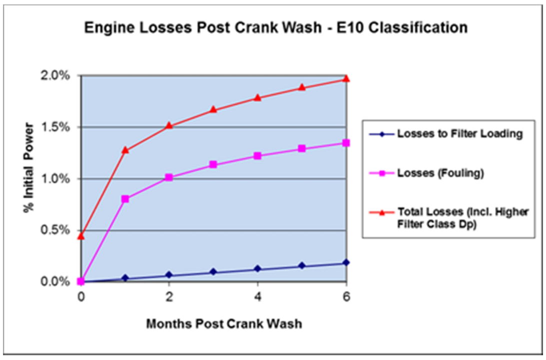

Figure 8 – Gas Turbine Losses (Filter Δp, Fouling and Total) Post Crank Wash E10 Classification -

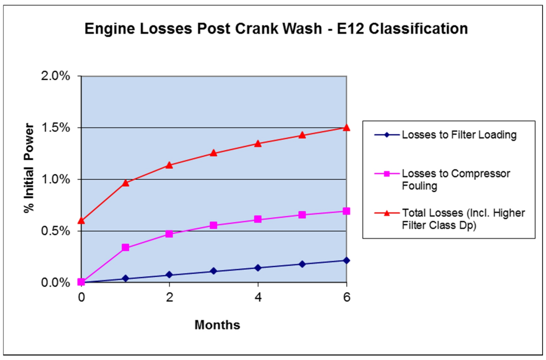

Figure 9 – Gas Turbine Losses (Filter Δp, Fouling and Total) Post Crank Wash E12 Classification -

Therefore, a comparison can be made of total gas turbine output losses post crank wash, resulting from both compressor fouling and filter differential pressure (Δp) over time, with regards to filtration efficiency class, as shown below in figure 10:

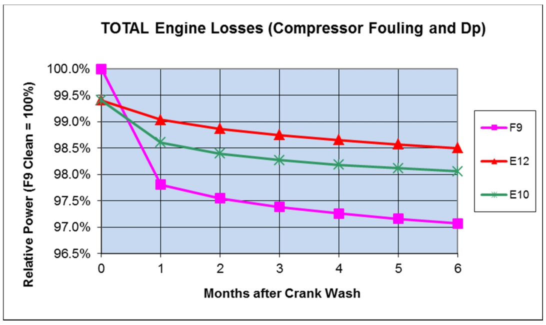

Figure 10 – Total Losses (Filter Δp, Fouling) Post Crank Wash F9, E10 and E12 Classification -

These losses post compressor crank wash attributed to compressor fouling and filter differential pressure (Δp) over time relative to filtration classification are summarised below, in table 3:

Filter Classification	Losses (Filter Δp)	Losses (Fouling)	*TOTAL Loss (6 Months)
F9	0.15%	2.78%	2.93%
E10	0.18%	1.34%	1.96%
E12	0.21%	0.69%	1.5%

*TOTAL losses include Δp penalty for higher filtration classification i.e. E10 or E12 in lieu of F9.

Table 3 – Total Gas Turbine Losses (Filter Δp, Fouling) Post Crank Wash F9, E10 and E12 Classification –

Therefore, it can be seen that increasing filtration efficiency classification significantly reduces engine losses due to fouling, and the resulting increased losses due to higher filter differential pressure, which historically has been viewed by end users and operators as highly undesirable, is in fact more than acceptable, when considering the overall improved engine performance.

6. ABK RETROFIT AIR INTAKE FILTRATION SYSTEMS AFTER RETROFIT.

Equipment

The high velocity air intake filtration systems installed on ABK were retrofitted with AAF multi stage, low velocity EPA system technology, which has been extensively proven offshore since its introduction in early 2003. The systems comprising upstream vane separators, temporary sacrificial extended surface DriPak GT60 filter bags, AmerKleen M80 pre-filter coalescing pads close coupled with HydroCel EPA E12 high efficiency filter panels, as shown in figure 11 :

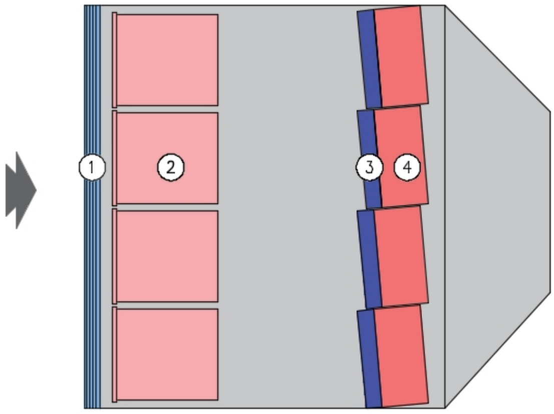

Figure 11 – Typical AAF Multi Stage Low Velocity EPA Filtration System (1 - Upstream Vane Separator, 2 - Temporary Sacrificial Extended Surface DriPak GT60 Filter Bags, 3 - AmerKleen M80 Pre-filter Coalescing Pads, 4 - HydroCel E12 EPA High Efficiency Filter Panels)

The AAF multi stage low velocity EPA filtration principals of operation are:

- The upstream vane separator removes the majority of large airborne water droplets, such as sea sprays, fogs, mists and large aerosols.
- The sacrificial extended surface Dripak GT60 filter bags (being a hybrid filtration stage addition for Middle East applications, temporarily installed during annual high dust concentration periods), remove sand and dust particulate that are carried from the Middle Eastern deserts out to sea by Harmattan like winds, and prevent the AmerKleen M80 pre-filter coalescer pads and AAF HydroCel EPA E12 high efficiency panel filters reaching an undesirable premature terminal resistance during these cyclical high dust load conditions.
- The AmerKleen M80 pre-filter pads remove airborne particulates and also coalesce small aerosols that have passed through the upstream vane separator, whereby the aerosols coalesce into larger droplets and due to gravity drain freely from the pad fibre structure.
- The HydroCel EPA E12 panel filters remove small and sub-micron airborne particulates and also capture any sub-micron aerosols that may

have passed through the upstream pre-filter coalescing pads.

- The HydroCel EPA E12 has many intricate innovative drainage design features, that in combination with highly hydrophobic and oleophobic media (in both clean and dirty media conditions) and full polyurethane potting of the media pack, ensures the aerosols cannot pass further into the clean air stream and drain freely from the filter elements.
- Additionally the AmerKleen M80 coalescing pre-filters and HydroCel EPA E12 panel filters are close coupled together and retained in an inclined filter matrix to effectively drain any captured aerosols and droplets into multi-level horizontal drain channels, thus furthermore ensuring effective removal of aerosols from the air intake system.

Note: as ISO EN779:2012 and EN1822:2009 test standards do not take into consideration real world offshore conditions, AAF take this shortfall in mind and perform additional testing of offshore filter elements and filtration systems, using a purposely developed offshore simulation rig, whereby the products under test are simultaneously challenged with hydrocarbon rich dusts, hydrocarbon aerosols and sea water aerosol sprays.

Materials of Construction

The retrofit multistage low velocity EPA filtration systems are constructed from industry recognised and widely specified materials, namely stainless steel 316L housings, filter bank matrices and vane separators.

Additionally, the filtration media materials comprise state of the art synthetics, progressive density glass fibres and EPA glass fibres, with varying degrees of advanced hydrophobic and oleophobic media treatments.

Filtration Efficiency Classes

The individual filtration efficiency classifications of the products employed for the ABK retrofit are shown below in table 4.

Filter Element	EN779 Class	EN1822 Class
DriPak GT60	F6	-
AmerKleen M80	G4	-
HydroCel E12	-	E12

Table 4 – ABK Retrofit Low Velocity Filtration Efficiency Classes -

The final filtration stage HydroCel EPA filter is tested to EN1822:2009, with a classification of E12 and a minimum efficiency of 99.806% at the MPPS of 0.134µm, as shown below in figure 12, thus the filtration efficiency classification being highly suited and matched to the atmospheric impurities at ABK.

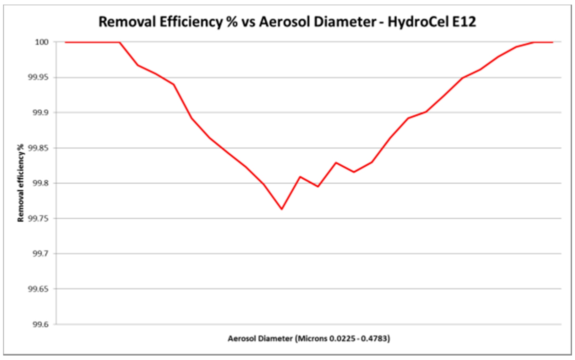

Figure 12 – HydroCel MPPS Performance Curve -

7. COMPARISON BETWEEN ORIGINAL FILTERS AND NEW FILTERS.

Comparison of Filtration Differential Pressures Original High Velocity Air Intake Filtration Versus AAF Low Velocity EPA E12 Air Intake Filtration

The individual differential pressures of both the original high velocity and retrofitted low velocity air intake filtration stages utilised at ABK, are shown below in table 5. The overall differential pressures are similar between the low velocity high efficiency EPA filter and the high velocity medium efficiency filter:

	High Velocity	Low Velocity
Vane Separator	70	23
*Temporary Sacrificial Filter	N/A	55
Pre-filter	100	96
High Efficiency Filter	310	N/A
EPA Filter	N/A	370
Vane Separator	70	N/A
TOTAL (Pa)	550	544

* Temporarily installed during Harmattan periods.

Table 5 – High Velocity and Low Velocity Filtration System Initial Differential Pressures Δp (Pa) -

Equipment Weight and Dimensional Envelope Comparison of Multistage High Velocity Air Intake Filtration Systems vs Retrofit Multistage Low Velocity Air Intake Filtration Systems.

The table 6 below illustrates the delta in equipment estimated weights for the multistage high velocity air intake filtration systems versus retrofit multistage low velocity air intake filtration systems.

Air Filtration	SGT400 (Kg)	RB211 (Kg)	PGT10 (Kg)
High Velocity	1800	10650	2030
Low Velocity	5940	14500	4450
Variation in Weight %	+330%	+136%	+219%

Table 6 – Equipment Estimated Weights -

The images below illustrate the differences in equipment envelope dimensions for the multistage high velocity air intake filtration systems vs retrofit multistage low velocity air intake filtration systems, including the associated intake duct systems, for the SGT400s (Figure 13), PGT10s (Figure 14), and RB211 (Figure 15):

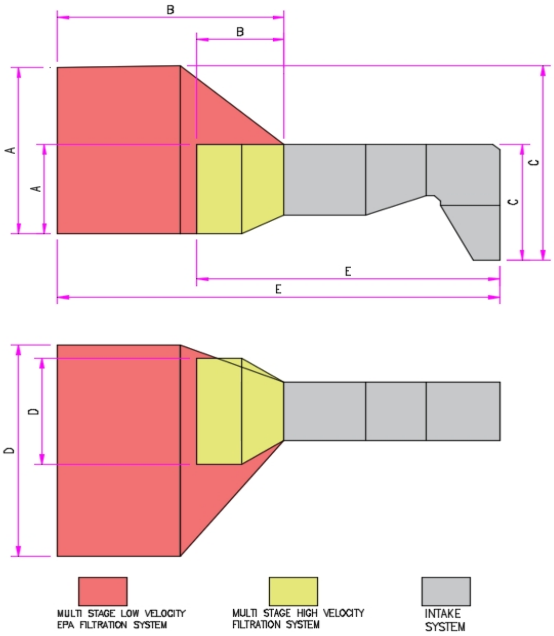

Figure 13 – SGT400s Filter Arrangement (Side View and Top View) -

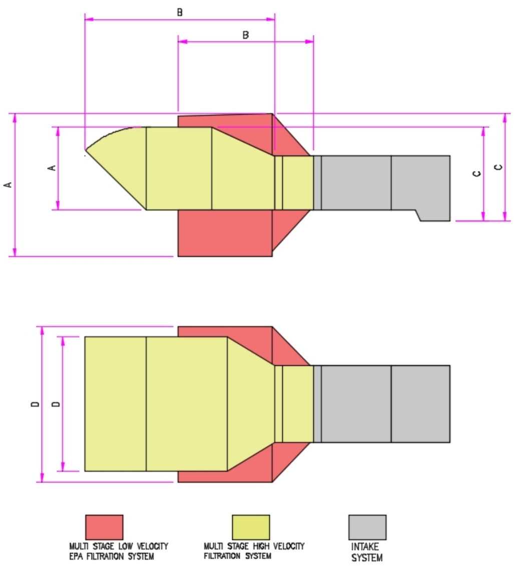

Figure 14 – PGT10s Filter Arrangement (Side View and Top View)-

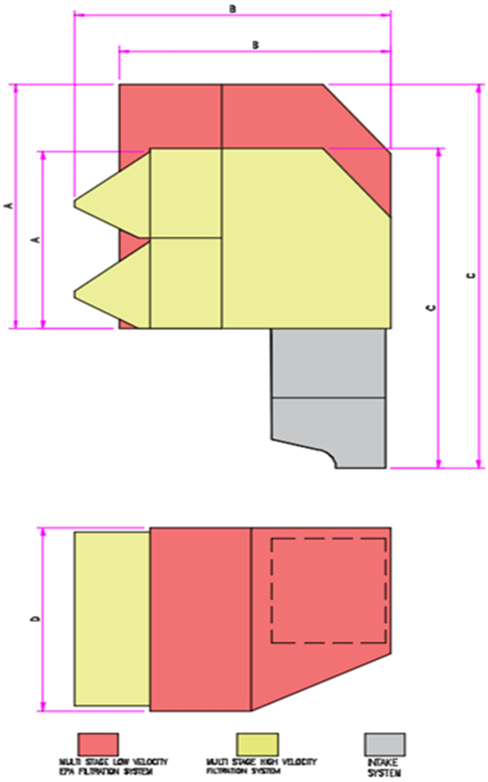

Figure 15 – RB211 Filter Arrangement (Side View and Top View)

A summary of equipment envelope dimensions is shown below in table 7-1 and table 7-2:

Engine	Air Filtration	A (mm)	B (mm)	C (mm)	D (mm)	E (mm)
SGT400	High Velocity	2,280	6,680	2,949	2,702	6680
	Low Velocity	4,240	9,750	4,959	5,380	9750
RB211	High Velocity	5,600	8,362	10,126	5,800	NA
	Low Velocity	7,739	7,162	12,165	5,800	NA
PGT10	High Velocity	2425	5476	2755	3938	NA
	Low Velocity	4190	3920	3138	4570	NA

Table 7-1 – Summary Equipment Envelope Dimensions –

Air Filtration	SGT400	RB211	PGT10
High Velocity Footprint (m^2)	18.0	48.5	21.6
Low Velocity Footprint (m^2)	52.5	41.5	17.9
Variation in Footprint %	292%	-14%	-17%

Table 7-2 – Summary Footprint –

8. CHALLENGES OF PERFORMING AIR INTAKE FILTRATION SYSTEMS RETROFIT OFFSHORE

Due to the various air intake filtration system equipment locations on the ABK platform and their associated access limitations, retrofitting of the air intake filtration systems warranted several challenges to be overcome by both TOTAL and AAF:

- RB211 24G56 on KPP and SGT400 on PPSP, the platform crane at full radius was short of the required centre-line lifting for the air intake filtration modules, requiring the design and manufacture of a bespoke overhanging platform and specialised lifting frame, which was used in conjunction with machine skates, to pull the equipment into the required position.
- SGT400s on NKPP were not accessible with the platform crane, but required the provision of a crane barge, to perform the heavy destruct and installation lifts.
- PGT10s on GLP due to space restrictions between adjacent units, required a modular retrofit concept and build sequence.
- Additionally the retrofits were performed in extreme heat of up to 50 degrees C, requiring the workforce to rest frequently on an hourly basis and follow a continuous hydration regime.

9. PERFORMANCE IMPROVEMENT AFTER AIR INTAKE RETROFIT

Pollution Arrested at ABK

In the case of ABK, filter elements from each stage were removed after 8,000 hours operation and examined using Scanning Electron Microscopy (SEM) and localised chemical information (EDX) analysis. The results of these tests showed that the filtration system had arrested inorganic materials of aluminium silicates, and calcium and sulphur rich particles that were most likely calcium sulphate.

Also present were other silicates (sand), sodium and sulphur rich particles (most likely sodium sulphate), salt (NaCl), iron oxide based corrosion residues, insect parts and what appeared to be turquoise coloured polymeric debris.

The size of the particulate residues arrested by the air intake filtration system varied considerably from large shards of wood, insects and feathers, to the major inorganic components. The inorganic debris was in general bound in agglomerates comprised of individual particles, with varying micron and sub-micron particle size, as shown below in figure 16.

Figure 16 – AAF HydroCel SEM Image-

Water Washing
The data analyses from 2004 up to 2016 are very interesting regarding water wash practices with EPA filtration. With low grade filtration, the average number of water washes per year was repeatedly ten per year for turbo-compressors (aero-derivative and heavy duty technologies), whereas it was five for turbo-generators (light industrial technology). After the installation of the EPA filtration in 2012, the number of water washes was drastically reduced to 1 per year on average for both applications and all technologies (refer to Figure 17). Theoretically, passing from 10 to 1, the suppression of the water washes allows 1.2% of availability to be recovered per gas turbine. If we consider a gas turbine that is available 90% of the time, this represents 12% of the necessary effort and becomes a huge improvement.

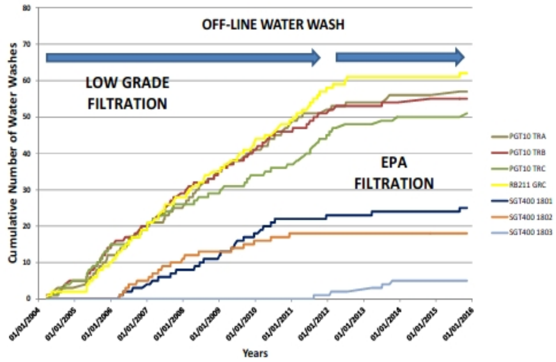

Figure 17 – Cumulative Number of Water Washes along Years –

Compressor efficiency
The effect of the E12 high grade filtration is quite impressive in maintaining compressor cleanliness. For the ABK turbo-generators and for operational reasons, we had the possibility to compare two rotors showing a similar number of running hours and equipped with two different filter grades (M5 and E12) shown figure 18 and figure 19. The SGT400 gas turbine exhibits a rotor that looks brand new with the E12 high filtration grade. The rotor equipped with the M5 low grade filtration displays salt deposits on both sides of the rotor blades.

Figure 18 - ABK SGT400 Compressor Fouling after 4000 Running Hours with the initial M5 Filtration Grade -

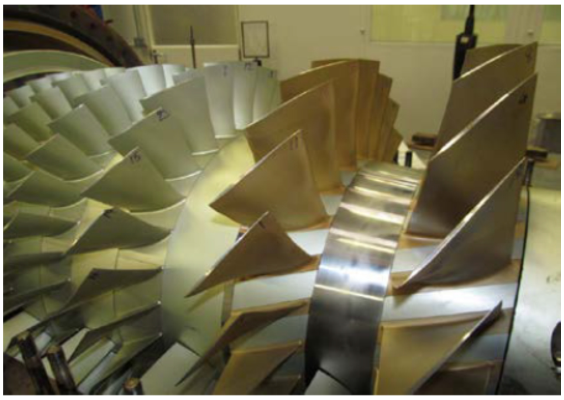

Figure 19 - ABK SGT400 Compressor Cleanliness after 5300 Running Hours with the Retrofitted E12 Filtration Grade -

In the example given, the E12 grade efficiency against salt ingress seems to be quite satisfactory.

Unlike the SGT400s, the RB211 engine is installed in a different part of the prevailing winds carrying the exhaust fumes from the PGT10 2-shaft and SGT400 gas turbines. The RB211 VIGV (Variable Inlet Guide Vane) shows varying degrees of contamination and oil staining over the concave and convex aerofoil surfaces with minor erosion, coating loss and corrosion. The IP (Intermediate Pressure) compressor blades exhibit airborne contamination and carbon built up even with the E12 high grade filtration (Figure 20). The size of the carbon fumes particle is less than 1 micron and for most of them it is around 0.1 micron. Despite the EPA E12 high grade filtration, quantities of soot, oil mist and carbon particles close to MPPS value (Most Penetrating Particle Size) are passing through the air filters potentially. The proper sealing of the filter is also questionable.

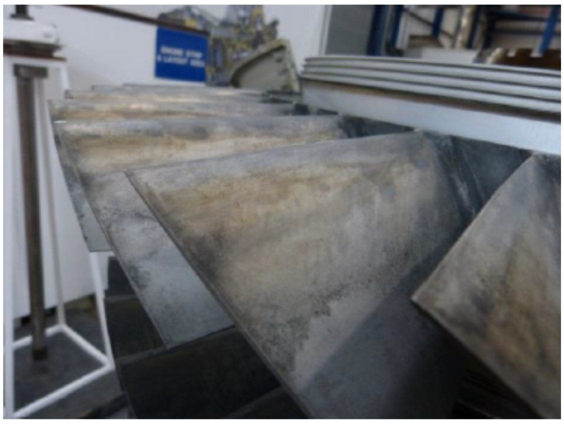

Figure 20 - IP Compressor Blades Displaying Carbon Deposit and Airborne Contamination after 7650 Running Hours. Rotor Equipped with E12 Filtration -

From a quantitative viewpoint, the impact of the EPA filtration on compressor efficiency is quite spectacular. With a low grade filtration system the compressor efficiency of a PGT10 2-shaft over 8000 running hours is 83% on average (Figure 21) whereas the performance of the axial compressor is constantly maintained at 85% with the EPA filtration system (Figure 22). Fuel gas consumption is therefore improved by 2.5% and contributes to an increase in production.

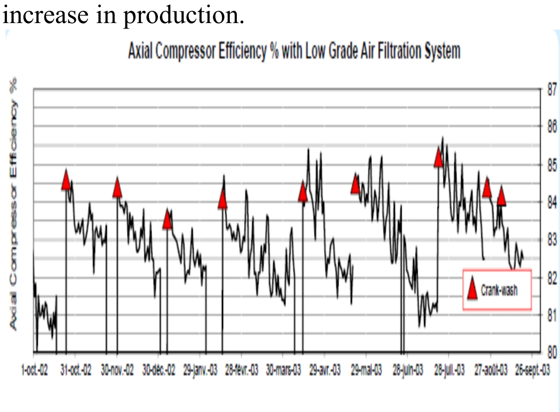

Figure 21 - PGT10 2-shaft Axial Compressor Efficiency over 8000 Running Hours and 9 Water Washes -

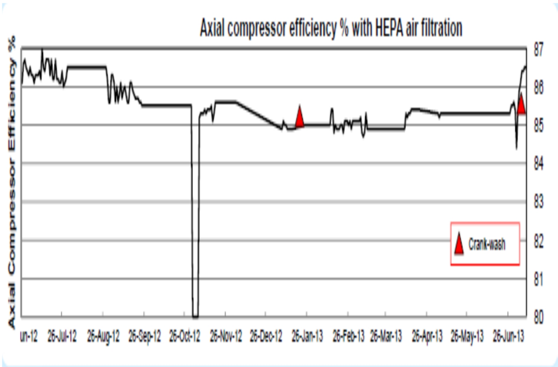

Figure 22 - PGT10 2-shaft Axial Compressor Efficiency over 8000 Running Hours and 2 Water Washes -

Engine Part Integrity - Hot section wearing

The new EPA filtration system makes it possible to delay the effect of hot corrosion. This is particularly noticeable on the heavy duty combustor liners of the PGT10 2-shaft. With the low grade filtration, the combustor liners were able to last 2,600 running hours on average. Figure 23 shows excessive damage on the combustion liners after 8,000 hours with a low grade filtration. With the E12 filtration grade, the liners are able to last 8,000 running hours on average in reasonable condition for an expected life, without being replaced, of 16,000 running hours.

Figure 23 – ABK PGT10 2-Shaft Combustion Liner Subject to Hot Corrosion after 8,000 Running Hours with Low Grade Air Filtration –

For aero-derivative gas turbines, a hot gas path exchange with mild fuel gas is normally anticipated at 25,000 hours. A sour fuel gas application is very demanding because a hot gas path is a matter of hot corrosion (Figure 24). The engine integrity is clearly impacted by running EPA filters. Before EPA implementation the gas generator life span varied from 1,000 to 4,000 hours and the generator generally had to be replaced after a major breakdown creating an unplanned event and a production shortfall.

Figure 24 - ABK RB 211 Front Combustion Liner not Re-Usable after 6,800 Running Hours and Low Grade F7 Filtration –

Since 2013, the gas generator replacement for the RB211 engines initially engaged after 3,800 running hours has been pushed forward to 7,650 running hours (Figure 25).

Figure 25 - ABK RB 211 Front Combustion Liner Re-Usable after 7650 Running Hours and E12 High Grade Filtration -

The table below (Table 8) shows the replacement of the gas generators in recent years.

Exchange Date	June 2013	February 2014	November 2014	October 2015
Running Hours	3,800	4,500	6,300	7,300
Increase	0%	+18%	+66%	+92%

Table 8 – RB211 Gas Generator Exchange -

This delay in the gas generator exchange is obtained principally by reducing the impact of the hot corrosion mechanism. EPA filtration helps to retain both the dry particulates of alkali and some of the wet alkali.

Availability, Reliability
From an availability and reliability standpoint, the use of EPA filtration seems to be beneficial on all three technologies. It reduces the availability variances and improves the general availability average as shown in figure 26. The variance spread is particularly high for heavy duty and light industrial.

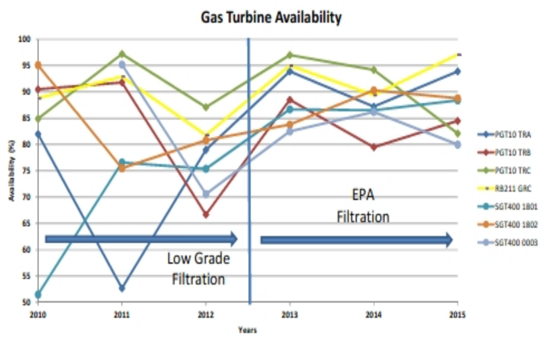

Figure 26 – Gas Turbine Availability

EPA filtration exhibits the same effects on reliability showing variance containment and the improvement of the average reliability value as shown in figure 27.

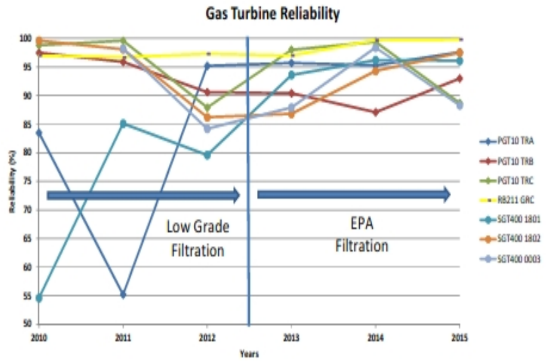

Figure 27 – Gas Turbine Reliability -

Planned and Unplanned Downtime
The EPA filtration provides a reduction in unplanned downtime for the three gas turbine technologies (Figure 28). Variance is contained in a lower value at around 500 minutes on average in 2015. This represents 8 hours of unplanned downtime in a year.

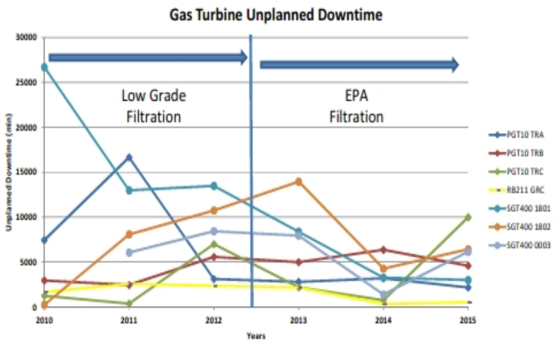

Figure 28 – Gas Turbine Unplanned Downtime -

The effect of EPA filtration on gas turbine planned downtime is not significant (Figure 29).

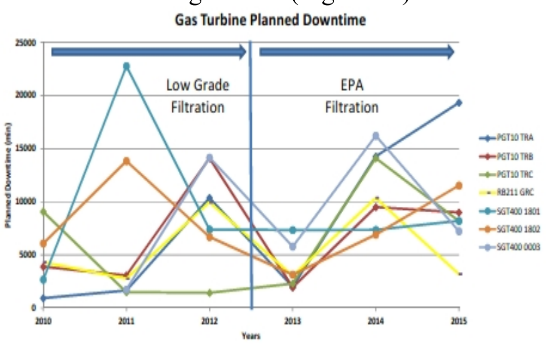

Figure 29 – Gas Turbine Planned Downtime -

MTBF, MTTF
Considering the hot corrosion phenomena in ABK gas turbines, EPA filtration generates a beneficial trend for the three gas turbine technologies. MTBF

values exhibit a continuous improvement. The most spectacular consequence is relative to the aero-derivative gas turbine. The aero-derivative MTBF value is multiplied increased by 6 and moves from 200 hours to 1,300 hours (Figure 30).

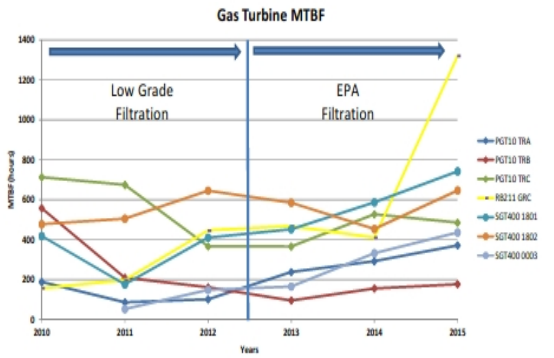

Figure 30 – Gas Turbine MTBF -

The incidence of EPA filtration on MTTR is difficult to identify (Figure 31).

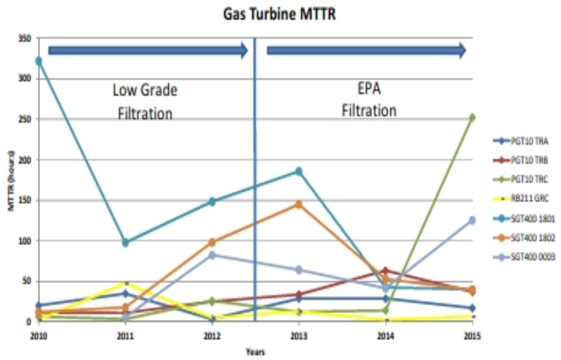

Figure 31 – Gas Turbine MTTR -

Filter Exchange
With the new configuration, the pre-filter GT 60 and M80 coalescer are removed and changed every 6 months. For the Hydrocel E12, new filter elements replace the old ones every 12 months.

Production
The new EPA filter arrangement provides a reduction in production shortfall over time. This reduction mainly comes from the reduction in gas turbine axial compressor washing. The production shortfall improvement is highly dependent on the machinery duty as shown in figure 32.

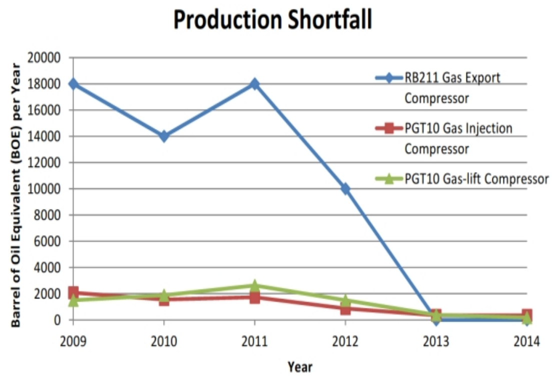

Figure 32 – Production Shortfall for Turbo-compressors –

10. DISCUSSIONS

Hot Corrosion still Continues
Despite the installation of high efficiency EPA E12 air filtration, hot corrosion continues to progress inside the gas turbine in marine environments. Gas turbines are not able to reach their expected life span. Alkali, such as salt, are still passing through the air filters even when they are EPA and hydrophobic. Industry standards and codes do not consider the efficiency of the filter regarding salt and dissolved salt in water in humid environments. The alkali filtration remains a matter of interest knowing hot corrosion eradication is still a strong driver for future Opex and Capex cuts.

Soot and Oil Ingestion
According to this 3-year ABK experience, gas turbine cleanliness is highly sensitive to the installation location. Locations which are more exposed to oil fumes and soot have an impact on axial compressor efficiency. The pointing question is how oleophobic filters are and what the optimum size would be for the MPPS (Most Penetrating Particle Size) value.

Filter Exchange
Complementary experience is necessary in order to have a good understanding of filter ageing.
Additional data are needed to optimize the air filter exchanges on ABK.

11. CONCLUSION

The EPA E12 air filtration retrofit is a huge task to carry out offshore but this grade of filtration brings a real improvement in oil and gas operations.

Quantitatively, for seven gas turbines, EPA filtration maintains the cleanliness of the axial compressor and reduces the water washing operations (7 per year instead of 31) with multiple associated consequences. Firstly, this is a tremendous reduction in demineralised water usage generating energy savings and grey water disposal reduction. Secondly, keeping a high compressor efficiency, it generates a reduction in the carbon foot print of 2.5% per machine. Both of these reductions are good contributors to improving the overall ABK energy efficiency. In addition, EPA filtration delays the effect of the hot corrosion, contains the variance of availability and reliability and, depending on the gas turbine application, improves the production.

Qualitatively, such a high grade of filtration helps to maintain a longer integrity of gas turbine internal parts generating Opex savings in the long term.

12. REFERENCES

EN 779:2012 Particulate Air Filters for General Ventilation – Determination of the Filtration Performance.

EN 1822-1:2009 High Efficiency Air Filters (EPA, HEPA and UPLA) – Part1: Classification, Performance, Testing and Marking.