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Outstanding Operational Behavior of Taylor-Made Nonwovens Filters for Intake Air Filtration of Gas Turbines

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ABSTRACT

During the last years nonwovens have set new standards of excellence, particularly high-quality, application-specific nonwovens made of synthetic-organic fibers. Filters basing on these fibers show an excellent filtration performance and operational behavior. One key application for these filters is the filtration of intake air for turbomachines.

Particulate impurities in the intake air represent an important factor affecting the operational characteristics of turbomachinery. Given a dust content in the ambient air at a particular site, the effectiveness of the intake air filters will significantly determine the time frame for efficiency decline and performance decline. The particles, entering together with the air, will cause, depending on their size, material abrasion or dust caking on the surface of blades and vanes.

This paper describes the primary function of the filters and the physical requirements for air intake systems. In addition, the paper will compare different filtration concepts concerning their economy. Doing this, significant economic differences between different products and concepts can be shown.

PARTICLES IN AMBIENT AIR

Depending on location and season, ambient air is more or less loaded by particles. In general there are two different types of particles:

- natural particles, mostly from erosion of the earth crust (Ø > 1µm)
- artificial particles, from industry, furnace processes and traffic (Ø < 1µm)

Dust loaded air can be characterized by the particle size distribution and the mass concentration of the dust. Meteorological effects like fog, rain or snow as well as special conditions at the location can influence the particle size distribution. E.g. in coastal areas, the air is loaded with crystalline salt particles (crystals < 2µm) and with salt solved in water droplets (droplets ≈ 10µm). The dust concentration is measured by the mass of the dust per volume unit of air (e.g. mg/m^3) and shows a significant variation depending on location and time (see tab. 1). Extreme conditions as in desert areas may cause the need of special pre-separators in front of the filters.

Particles in the intake air have a big influence on the operational behavior of gas turbines and turbo compressors. The performance of the filters determines the temporal development of efficiency, power loss and maintenance cycle of the turbomachine.

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Tab. 1: Typical values for dust concentration and particle size.

region	dust concentration	particle size
housing areas	0,01 – 0,05 mg/m³	0,01 – 5 µm
rural areas	0,01 – 0,2 mg/m³	0,01 – 10 µm
light industry areas	0,05 – 0,3 mg/m³	0,01 – 5 µm
heavy industry areas	0,1 – 1 mg/m³	0,01 – 30 µm
coastal/off-shore areas	0,01 – 0,5 mg/m³	0,01 – 10 µm
desert	0,01 – 500 mg/m³	0,1 – 100 µm
arctic areas	0,01 – 0,5 mg/m³	0,01 – 5 µm
tropical areas	0,01 – 0,5 mg/m³	0,01 – 10 µm

DAMAGES CAUSED BY PARTICLES IN INTAKE AIR

Normally the intake air is treated, e.g. by filtering and humidifying, before it enters a turbomachine. Doing this, the cleaning of the air by suitable filter systems is an important process. Poor filtration does not only result in power loss after a short operation time but also in different damages on the turbomachine (see tab. 2).

Tab. 2: Typical damages on turbomachines.

damage	particle size	gas turbine	turbo compressor
erosion	> 5 – 10µm	x	x
fouling (resulting in unbalanced state and reduced air mass flow)	≈ 0,1 – 5µm	x	x
fouling of intercoolers and downstream components	≈ 0,1 – 5µm		x
wet corrosion	≈ 0,1 – 5µm	x	x
high temperature corrosion	≈ 0,1 – 5µm	x	x
clogging of cooling air slits	> 0,1µm	x	

To prevent damages on turbomachines great demands have to be placed on intake air filtration systems. Viledon depth-loading filters as Compact pocket filters, TFP depth-loading cartridges and MaxiPleat cassette filters have proven their exceptional behavior in many installations. These Viledon filters represent the state of the art in depth-loading filter design. In heavily polluted areas, also pulsable Viledon surface filtration cartridges can be used.

DEMANDS ON AIR FILTRATION SYSTEMS

The major task for air filtration systems used in turbomachinery is to prevent damages on turbine blades and guiding vanes; allowing an economic and save operation under different conditions. From a physical point of view, the filtration system has to fulfill contradictory demands. The filters have to clean reliably the intake air from particles while having a low pressure drop level for a long operation time. Using extreme high efficient air filters the power loss of the turbomachine caused by fouling of the compressor will decrease. But simultaneously the pressure drop of these filters leads to a reduced power output. In addition the filter life time normally reduces with increasing efficiency. The life time of filters is an important factor, especially if the filters can only be changed once a year - during the yearly maintenance of the turbomachine. An earlier change of the filters causes high costs, because (due to safety reasons) the filters can only be changed if the machine is shut down.

The selection of a suitable pre-filter/fine-filter combination leads to an individual solution. It should offer to the operator of the turbomachine an optimized filtration system, regarding economic and technical aspects. The optimization bases on:

- the selection of raw material, filter media and type of the filter element,
- the selection of a suitable pre-filter/fine-filter combination, according to the ambient conditions at the location and the clean air quality needed by the turbomachine,
- a long life time and a reliable performance,
- corrosion free filters for the whole life time, despite of different weather conditions,
- the existence of safety reserves for extraordinary conditions (e.g. if the pressure drop exceeds the design data for a short time or if instationary states of the turbomachine occur),
- constant quality of all products.

DEPTH-LOADING FILTERS

Filters used in turbomachinery can be divided in depth-loading filters (also called storage filters) and surface-loading filters (also called cleanable or pulsable filters). A depth-loading filter cleans the air by depositing airborne particles in the depth of the filter media. This can be improved by two ways. One is the use of a voluminous media allowing an easy dust penetration into the filter and creating a large dust storage capacity. The other way is a large effective filtration surface by using very thin fibers.

If surface-loading filters are used, the particles are deposited on the surface of the filter. Therefore it is possible to clean these filters. Mostly these filter elements are cartridges cleaned by pulses of pressurized air.

This paper exclusively discusses depth-loading filters. Their advantage is a high filtration efficiency at relatively low pressure drop level. The reason is the dust deposition inside the filter medium. There is no dense dust cake on the surface which could cause significant pressure drop. In addition depth-loading filters can be installed very easy in the filter house, without any pulse-jet system or dust collecting unit, causing additional pressure drop.

Based on their gravimetrically determined arrestance for synthetic dust (e.g. ASHRAE dust), or on their photometrically determined fractional collection efficiency for 0,4 μm droplets of a test aerosol (DEHS), depth-loading filters are categorized in different filter classes. In Europe this classification is done according to norm EN779.

Tab. 3 shows an overview about different types of depth-loading filters and their filter classes. Higher filter classes can best be reached by pocket filters, cassette filters and depth-loading cartridges. Normally these filters types are used as fine filters for gas turbines. Filter classes exceeding F9 can be reached by HEPA or ULPA cassette filter, which are also available in the Viledon product portfolio. In addition pulsable Viledon surface-loading cartridges are available in filter classes F8 and F9.

POCKET FILTERS

Viledon Compact pocket filters (fig. 1) with filter classes G3 – F9 (according to EN779) have proven their safe and economic operational behavior in many applications.

Fig. 1: Compact pocket filter T60 (filter class F6).

Their features offer many advantages to the operators of gas turbines:

1. The filter media of synthetic-organic fibers are progressive or triple-layered in structure (see fig. 2) and provide high dust holding capacity in conjunction with slow rise in pressure drop and thus long lifetimes.
2. Inherently rigid design of the filter pockets ensures uniform dust storage. The pockets will neither sag nor collapse, precluding any possibility of dust penetration at shutdowns or load changes. Even with dust loads and damp conditions the inherent rigidity and the filtration efficiency are fully maintained.
3. The pockets are welded to prevent leaks and securely foamed into a polyurethane front frame; dust penetration is thus reliably precluded even at high pressure drops.

Tab. 3: Depth-loading filters, their types and filter classes.

Filter types			Pocket filters						
					Cassette filters				
		Roll band filters							
		Filter mats				Depth-loading cartridges			
According EN779	G1	G2	G3	G4	F5	F6	F7	F8	F9
	Average arrestance A_a				Average dust spot efficiency E_a				
	65% ≤ A_a	65% ≤ A_a < 80%	80% ≤ A_a < 90%	90% ≤ A_a	40% ≤ E_a < 60%	60% ≤ E_a < 80%	80% ≤ E_a < 90%	90% ≤ E_a < 95%	95% ≤ E_a

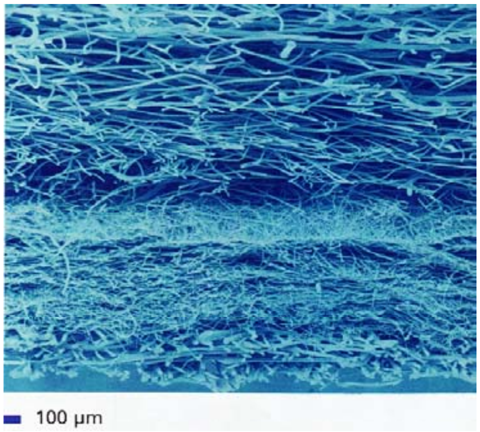

Fig. 2: triple-layered depth-loading filter media.

4. The welded-in spacers ensure optimum shaping of the filter pockets during operation, preventing any loss of active filtering area due to pocket surface contact.
5. The polyurethane front frame is corrosion-proof and reinforced by a foamed-in profile for maximum mechanical strength.
6. The filter elements are moisture-resistant up to 100% relative humidity, thermal stable up to 70°C, stand up well to most chemicals, and can be completely incinerated.
7. Low maintenance and service costs.
8. High resistance to pressure surges (burst pressure > 3000 Pa).

CASSETTE FILTERS

Viledon MaxiPleat cassette filters (see fig. 3) with filter classes F6 – F9 (according to EN779) are used as depth-loading fine filters in the second filter stage of gas turbines.

Fig. 3: Viledon MaxiPleat Filter MX85 (filter class F7).

A patented thermal embossing process for the filter media allows optimized pleat geometry for homogeneous air flow, guaranteeing long life time and high dust holding capacity at low pressure drop level. During this process the heated filter media is pleated and conical impressions are embossed. The result is an extreme stiff pleat pack with a deepness of the pleats of 250mm.

It is not necessary to use additional spacers, which can easily damage the filter media and are often a source of leaks. The filter media is a high-strength glass fiber media. The aerodynamic optimized pleats cause homogenous dust deposition and with it maximization of the effective filter area.

The pleat pack is leak-proof mounted in a frame, especially designed for gas turbine applications. A protection grid on both sides prevents damages on the filter media during mounting and operation of the filter element. Tests done by the American institute AFTL (Air Filter Testing Laboratories) showed a burst pressure of > 8000 Pa. This was a unique result for burst pressure tests at AFTL. Due to their metal-free design the filters can be completely incinerated.

DEPTH-LOADING CARTRIDGE FILTERS

Viledon depth-loading filter cartridges (see fig. 4 and 5) are patented storage filters. They are used in air intake systems for on- and off-shore gas turbines and turbo compressors. Their use is particularly successful at low dust concentrations or if the dust is very fine and/or sticky. Surface-loading cartridges often fail in these applications if the dust can not be removed from the surface by the pulse- jet cleaning. The result is a significantly reduced life time of the surface-loading cartridges. Periodically cleaning of depth-loading cartridges is not intended.

Fig. 4: Viledon depth-loading cartridge TFP60 (filter class F6).

Fig. 5: Viledon depth-loading cartridge TFP90/95 (filter class F7/F8).

Viledon depth-loading cartridges use filter media with progressive or triple-layered structure and provide high filtration efficiency and high dust holding capacity at low pressure drop level. Even at high volume flow, collapse of pleats can not be observed. The synthetic-organic filter media is moisture-proof up to 100% relative humidity and withstands rain or fog.

Experience gained in operation shows that, even under wet and cold weather conditions, neither significant increase in pressure drop nor blocking by icing occur (see fig. 6).

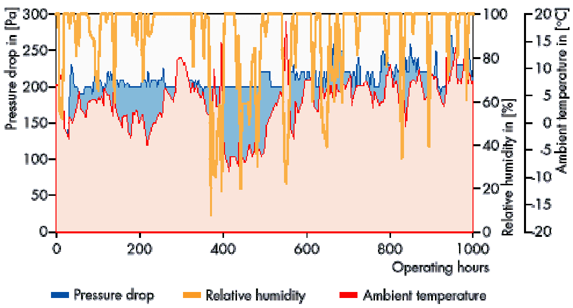

Fig. 6: Experience gained in an off-shore operation of Viledon depth-loading cartridges.

ECONOMY OF AIR INTAKE FILTRATION SYSTEMS

Economy of intake air filtration systems for turbo machines is much more influenced by operation costs than by the purchase price. Special attention has to be paid to the influence of the filtration system on power output of the machine. Considering this, Viledon filtration solutions offer significant advantage on costs, due to their low pressure drop level and long life time.

But the advantage of low pressure drop should not be impeded by poor filtration efficiency. Particles in the intake air lead to fouling of compressor blades and sometimes to damages on the rotor. To reduce the power loss caused by fouling, it is necessary to clean the machines periodically by on-line washing. For on-line washing demineralized water and expensive cleaning chemicals are used. During the washing the machine is operated under partial load resulting in reduced power output.

The frequency of on-line washing is significantly influenced by the particle concentration of the intake air and consequently by the filtration efficiency of the filter system. A well designed filtration system minimizes this particle concentration. But crucial for the economy is the incline of pressure drop of the filters as function of operation time. The pressure drop of one- or two-stage filtration systems causes a decrease in compressor efficiency and thus a reduction of power output.

The loss of power output of axial compressors can be estimated as 0,1% per 50 Pa pressure drop of the intake air system.

At constant volume flow and concentration, the increase of pressure drop Δp as function of time t follows a polynomial of second order

$$\Delta p = A\, t^2 + B\, t + C, \tag{1}$$

with A, B, and C as filtration specific constants. To calculate the loss of energy output E_L, the pressure drop according Eq. (1) has to be multiplied by coefficient of loss (K_p = 0,1 %/50 Pa) and by machine power P, than integrated over time, as shown in Eq. (2):

$$E_L = \int \Delta p(t) \cdot K_p \cdot P\, dt. \tag{2}$$

The integral can be approximated by a sum shown in Eq. (3):

$$E_L = \sum \Delta p(t_i) \cdot K_p \cdot P\, \Delta t. \tag{3}$$

The cost for the lost of energy output can be calculated by multiplying the loss of energy with the specific energy costs.

Following the economy of two different filtration systems is discussed. In both cases the Viledon solution is compared with competitive products, which ran under same conditions. Even if both applications differ in energy costs as well as service cost, for reason of better comparability, the base costs were assumed to be the same. The influence of on-line washings is neglected because the operators did not report significant differences between the different solutions.

EXAMPLE 1: POWER PLANT IN MALAYSIA

This power plant operates three identical gas turbines. Also the air intake systems are identical: two stage filtration with pocket filters and evaporating cooler. Tab. 4 for shows the key figures of this power plant.

Tab. 4: Key figures of power plant in Malaysia.

country	Malaysia
number of gas turbines	3
power out put	165 MW per machine
intake air volume flow	1.540.000 m^3/h per machine
filtration system per machine	two stage filtration; each stage with 320 pocket filters, pocket filter size 1/1
comparative test	
machine 1: pre-filter Viledon Compact pocket filter T60 (filter class F6 according EN779); fine-filter Viledon Compact pocket filter T90 (filter class F8 according EN779); thermal bond, synthetic filter medium with progressive structure resp. triple-layered; no fiber shedding; reinforced polyurethane frame	
machine 2: competitive pocket filters (filter classes F5 and F7 according EN779); glass fiber filter medium (danger of fiber shedding); metal frame (danger of corrosion); frame not completely incineratable	

The power plant operator was looking for alternative filters because he was not satisfied with the life time of the filters he was using. Fig. 7 shows the pressure drop of both installations as function of operation time. Even if the Viledon Compact pocket filters T60 and T90 have higher filter classes (F6 and F8) than competitive glass fiber pocket filters (F5 and F7), Viledon pocket filters show a significant lower pressure drop and a much longer life time.

Economy Calculations

Operation costs for both filtration systems are different and influence the economy of the gas turbine significantly. For the economy calculations following costs were included:

- costs for the filters
- costs for the change of the filters
- costs for the disposal of the filters
- costs for the power loss, due to increasing pressure drop

Not included are:

- costs for on-line washing, inclusive the costs for the power loss during washing
- costs for shutdown time during filter change

The costs for the two variants were calculated until the filters of each variant has to be changed. Based on these results the yearly costs were calculated and compared. The pure filter costs consist of purchase costs, change costs and deposition costs. The costs for the change are assumed to be 5,- €/pc. and for the deposition to be 0,5 €/kg.

Despite the fact that Viledon pocket filters are more expensive than glass fiber pocket filters (it's assumed that a glass fiber pocket filter is 30% cheaper than a Viledon Compact pocket filter), there is a big advantage of the Viledon solution of 14.400,- €/year due to it's longer life time.

But the total costs of ownership of the filter system does not only consist of the pure filter costs. Also the costs for reduced power output due to pressure drop of the filter system have to be considered:

Tab. 5: Calculation of additional profit due to use of Viledon Compact pocket filters T60 and T90 (Exp. 1).

output power of the machine	165 MW
operating time	8000 hours/year
average reduction in pressure drop if Viledon Compact pocket filters T60 and T90 are used	340 Pa
increase of output power if pressure drop is reduced by 50 Pa	0,1%
energy price	0,04 €/kWh
increased power output if Viledon Compact pocket filters T60 and T90 are used	1,122 MW/year
additional profit if Viledon Compact pocket filters T60 and T90 are used	359.000 €/year

Considering pure filter costs and additional profit due to reduced pressure drop, the use of Viledon Compact pocket filters T60 and T90 results in an advantage of approximately 373.400,-€/year.

After the test, the power plant operator decided to use only Viledon Compact Pocket filters T60 and T90 for all his machines.

EXAMPLE 2: POWER PLANT IN UNITED KINGDOM

Tab. 6 for shows the key figures of a power plant in the United Kingdom.

Tab. 6: Key figures of power plant in United Kingdom.

country	United Kingdom
number of gas turbines	2
power out put	220 MW per machine
intake air volume flow	1.760.000 m^3/h per machine
filtration system per machine	single stage filtration; total number of cartridges 1408 pieces; each time a cylindrical (Ø = 327 mm) with a conical (Ø = 327-445 mm) cartridge coupled; high of each cartridge 660mm
comparative test machine 1: Viledon depth-loading cartridges TFP60; TFP60S66S2 (cylindrical) and TFP60K66S0 (conical); synthetic filter medium with progressive structure; filter class F6 according EN779 machine 2: competitive cartridges; paper as filter medium; filter class F6 according EN779	

Operator's motivation for the comparative test did have been significant power loss during winter time. High humidity during winter months led to moisture absorption of the paper's cellulose fibers, causing swelling of the filter medium and hence increased pressure drop. The competitive test was start in 1997. The first set of competitive cartridges has already to be replaced after less then one year, due to strong corrosion of the integrated supporting cages. The second set reached a life time of two years. The life time of one set of Viledon depth-loading cartridges was 3 years. Fig. 8 shows the pressure drop of both installations as function of operation time.

Economy Calculations

Operation costs for both filtration systems are different and influence the economy of the gas turbine significantly. For the economy calculations following costs were included:

- costs for the filters
- costs for the change of the filters
- costs for the disposal of the filters
- costs for the power loss, due to increasing pressure drop

Not included are:

- costs for on-line washing, inclusive the costs for the power loss during washing
- costs for shutdown time during filter change

The costs for the two variants were calculated until the filters of each variant has to be changed. Based on these results the yearly costs were calculated and compared. The pure filter costs consist of purchase costs, change costs and deposition costs. The costs for the change are assumed to be 5,- €/pc. and for the deposition to be 0,5 €/kg.

Despite the fact that Viledon cartridges are more expensive than paper cartridges (it's assumed that a paper cartridge is 30% cheaper than a Viledon TFP60), there is a big advantage of the Viledon solution of 7000,- €/year due to it's longer life time.

But the total costs of ownership of the filter system does not only consist of the pure filter costs. Also the costs for reduced power output due to pressure drop of the filter system have to be considered:

Tab. 7: Calculation of additional profit due to use of Viledon TFP60 depth-loading cartridges (Exp. 2).

output power of the machine	220 MW
operating time	8000 hours/year
average reduction in pressure drop if Viledon TFP60 is used	100 Pa
increase of output power if pressure drop is reduced by 50 Pa	0,1%
energy price	0,04 €/kWh
increased power output if Viledon TFP60 is used	0,44 MW/year
additional profit if Viledon TFP60 is used	140.800 €/year

Considering pure filter costs and additional profit due to reduced pressure drop, the use of Viledon depth-loading cartridges TFP60 results in an advantage of approximately 149.000,-€/year.

After the test, the power plant operator decided to use only Viledon depth-loading cartridges TFP60 for all machines. After 3 years life time it is intended to change the filters in summer 2003.

CONCLUDING REMARKS

The paper described the primary function of the filters and the physical requirements for air intake systems. Nonwovens filters like pocket filters, cassette filters and depth-loading cartridges were presented. On the basis of two examples, the economy of these solutions was compared with competitive products. Hereby the purchase costs for the filters as well as the operating costs were considered. The examples demonstrated the excellent performance of taylor-made nonwovens filters regarding filtration performance and economy.

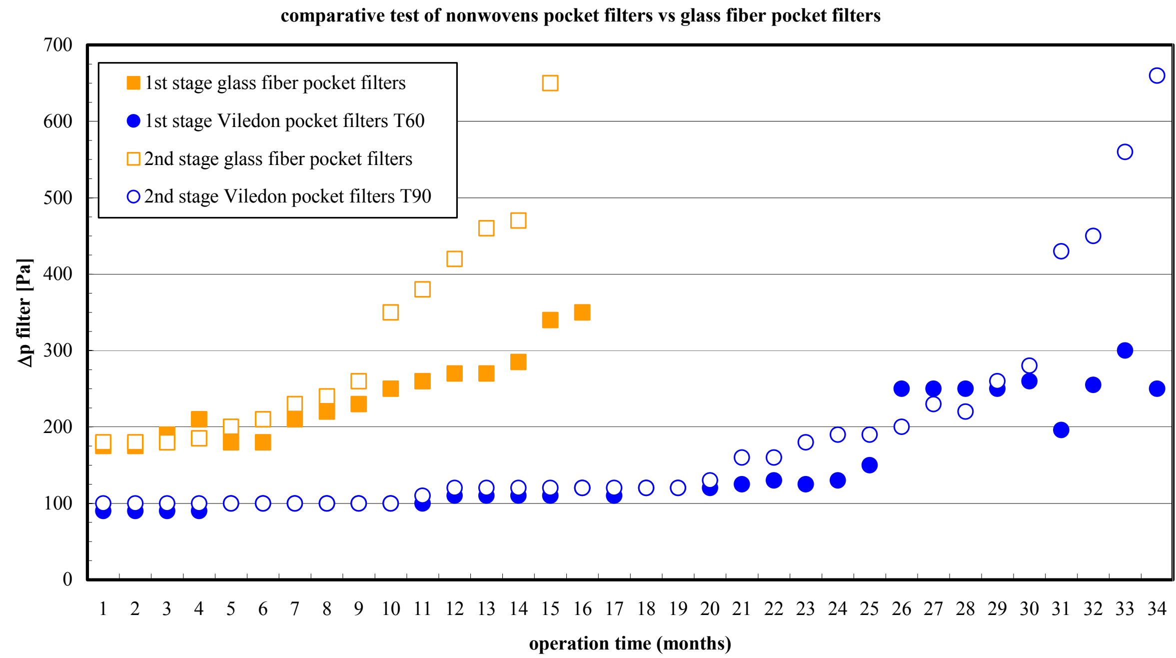

Fig. 7: Power plant in Malaysia, pressure drop for both installations as function of operating time.

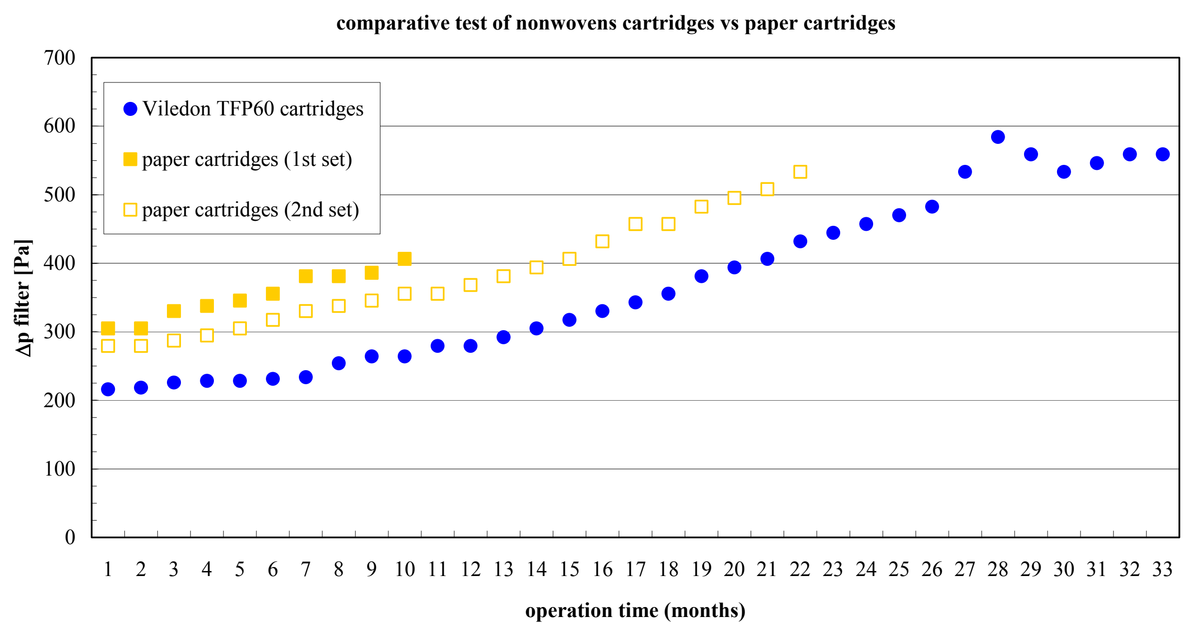

Fig. 8: Power plant in United Kingdom, pressure drop for both installations as function of operating time.