

### Novel filtration and separation products and a deep understanding of material science and fluid contamination are required to reduce the Opex of carbon capture processes

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In addition to electrification, hydrogen, and other clean energy technologies, large-scale carbon capture, utilisation, and storage (CCUS) is critical to achieving netzero 2050 goals. These goals were set forward by the International Energy Agency (IEA) in 2021 as a challenging path to restrict global temperature rise to 1.5°C. One of the key aspects of the plan is to limit emissions from point-source industrial emitters that produce elevated levels of CO<sub>2</sub>, which are often hard to abate. These industries include cement, lime, steel, and aluminum production, bioenergy, refineries, chemicals, natural gas and coal power plants, pulp and paper, and waste-to-energy.<sup>1</sup>

Looking at the carbon capture value chain, there are a range of technologies at widely varying technical readiness levels (TRL). The most mature carbon capture technology, which is currently used in most industrial carbon capture installations, is chemical absorption, where a solvent selectively binds with the CO<sub>2</sub> in one column called the absorber and regenerates in a secondary regenerator column where the CO<sub>2</sub> is released. Solvent-based absorption technology is well known and has been used extensively in gas treating plants, such as in amine sweetening processes. Other carbon capture technologies at lower TRLs include physical absorption, adsorbents, oxyfuel combustion, cryogenics, calcium or chemical looping, and membranes.

Once CO<sub>2</sub> is captured, it is typically dehydrated, compressed into a dense or supercritical phase for easier

transport, then transported via pipeline or ship. It can be utilised in material production, enhanced oil recovery, or other processes or stored in depleted reservoirs or saline formations.

Which technologies are favourable highly depends on process economics, often cited in units of \$/ton CO<sub>2</sub>. Because CO<sub>2</sub> does not have an intrinsic value, installations are driven by credits and regulations. This drives the industry to seek the lowest expense-proven solution and actively pursue technologies that offer cost reduction and increased equipment lifetime.

### Solving the contaminant challenge

In the critical-to-decarbonise industrial sectors, CO<sub>2</sub> is typically captured after a combustion process. Therefore, flue gas feed streams entering CO<sub>2</sub> capture processes can contain an elevated level of combustion byproduct contaminants. These feed contaminants can increase process operating expenses by (1) increasing the need for water replacement in wash systems and direct contact coolers, (2) increasing the frequency of solvent, membrane, or adsorbent replacement, (3) for solvent-based processes, causing amine emissions in the flue gas outlet from the absorber, and (4) fouling critical process equipment such as heat exchangers, reboilers, compressors, and absorber internals, thereby reducing process efficiency, increasing energy requirements, and requiring more frequent maintenance.

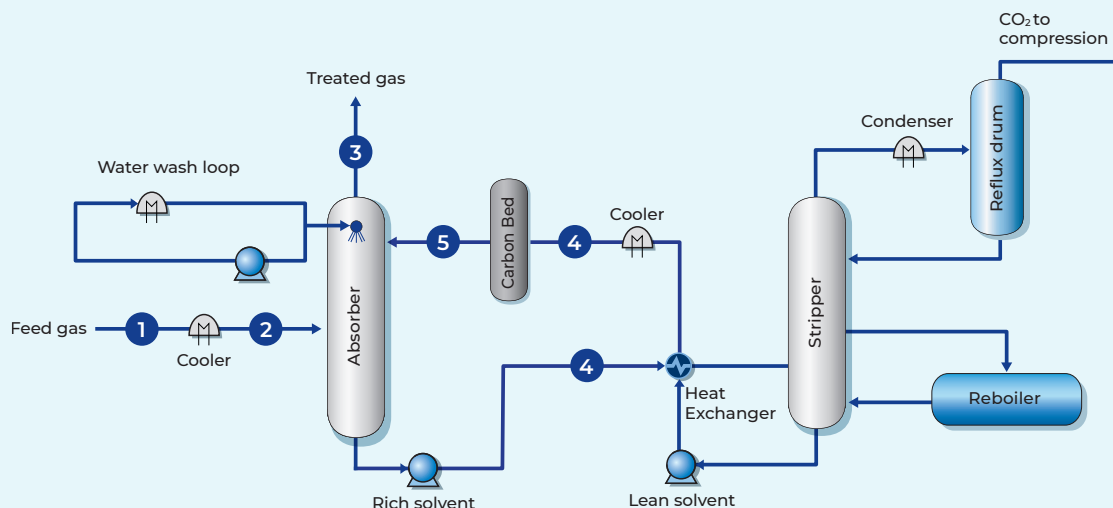


Figure 1: Pretreatment and solvent-based capture filtration and separation needs

## Filtration and separation recommendations for select process locations in Figure 1

#	Need	Driver	Separation solution
1	Bulk particulate removal from dry gas feeds	Protect equipment, prevent solvent loss	Low ΔP flue gas filter
2	Remove contaminants on inlet gas	Protect equipment, prevent solvent loss	Low ΔP aerosol removal
3	Prevent amine carry-over on absorber outlet	Meet environmental specs, prevent solvent loss	
4	Remove solid contaminants from solvent loop	Prevent fouling of critical equipment	Absolute-rated particulate filter
5	Prevent activated carbon fine carry-over in solvent loop	Prevent fouling of critical equipment	Absolute-rated particulate filter

Table 1

Additionally, contaminants can be generated during the carbon capture process. For instance, corrosion byproducts, solvent degradation compounds, and heat-stable salts can build up over time in solvent loops. Similarly, in downstream process steps, lube oil and solid contaminants can be introduced into the concentrated CO<sub>2</sub> stream. These contaminants also increase operating expenses by contaminating successive stages of equipment, leading to off-specification pipeline contents, and can plug reservoirs.

For each of these problems related to contaminants, reliable filtration and separation steps are critical to maintaining low operating expenses. Filtration and separation products for solvent clean-up are well known due to decades of experience with gas treatment. However, other applications, such as feed treatment before CO<sub>2</sub> capture processes, solvent emission prevention, and downstream, including dense-phase CO<sub>2</sub> purification are less known, emerging applications in this sector. Pall applications in solvent clean-up, feed treatment, and solvent emission prevention are shown in Figure 1, with detail in Table 1. Applications downstream and in dense-phase CO<sub>2</sub> purification are shown in Figure 2, with details in Table 2.

### Solvent purification

With a solvent-based CO<sub>2</sub> capture process, the process efficiency and operating expenses of the entire unit hinge on the cleanliness of the solvent and equipment.

On a positive note, recommended filtration and separation steps are well-studied due to the longevity of these processes in gas processing plants.

Solid feed contaminants such as fine fly ash particulates (<1 μm diameter) that can bypass feed pretreatment steps due to their small size can build up and foul the lean/rich heat exchanger, the reboiler, the absorber internals and require more frequent solvent change-out over time. Contaminants can also alter the surface tension of the solvent, causing an increased tendency to foam and requiring the use of anti-foam. Finally, fine particulates can form aerosol nuclei, which contribute to solvent emissions, resulting in solvent losses out of the absorber vent, as found from tests at the post-combustion carbon capture plant at Niederaussem.<sup>2</sup> Corrosion products from stainless steel and similar equipment can also precipitate in the rich side of the solvent loop into solid particulates such as iron compounds, causing similar issues.

To remove these solids, particulate filtration of the solvent is recommended at a minimum of 10% slipstream. The target level for solids after filtration is 1-5 ppmw. Five or 10 μm-rated absolute particle filters are recommended, based on the diameter of the solid particulates.

It is important to understand the differences between how particulate filters are rated. Nominal ratings are arbitrarily assigned by the filter manufacturer, and there is no regulation for the value of the nominal ratings to indicate the performance of removing certain particle sizes.

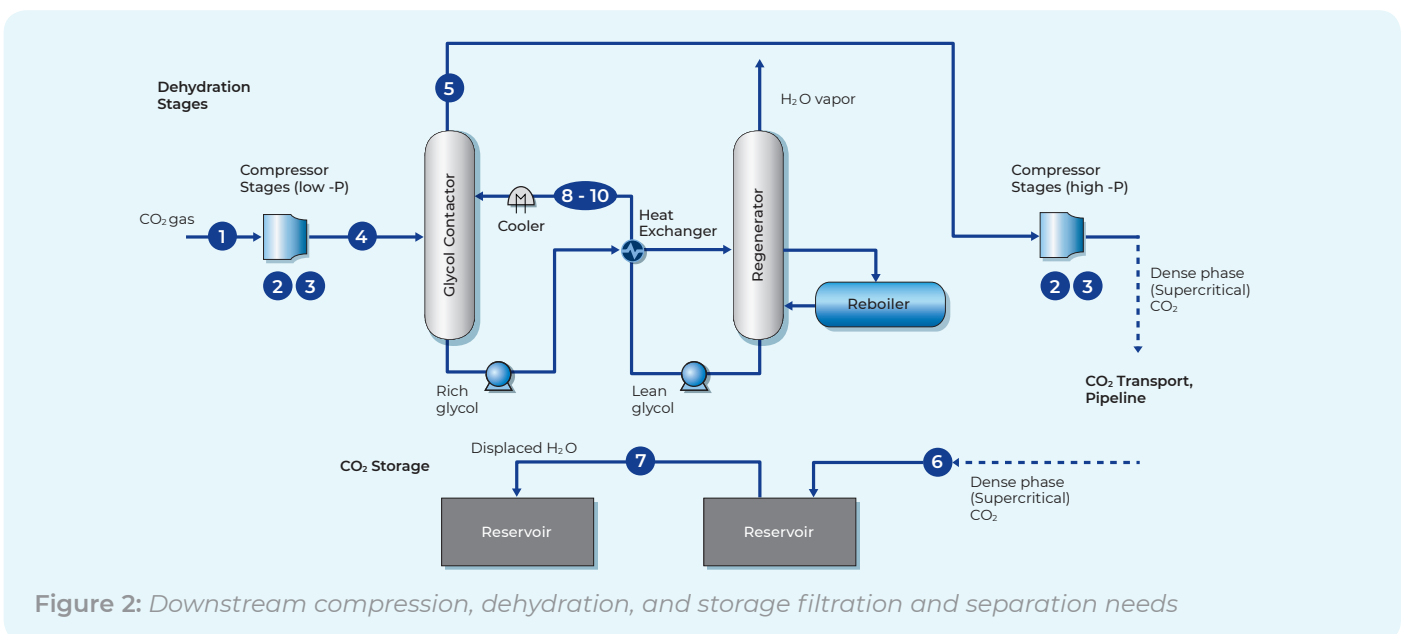


Figure 2: Downstream compression, dehydration, and storage filtration and separation needs

## Filtration and separation recommendations for select process locations in Figure 2

#	Need	Driver	Separation solution
1	Remove solids and liquids on inlet	Compressor protection	Liquid-gas coalescer
2	Remove solid contaminants from lube oil component wear	Keep lube oil clean, reduce compressor	Particulate filter or vacuum purifier
3	Compressor vent	Prevent compressor cavitation (depends on compressor)	Vent filter, also called a 'breather'
4	Prevent lube oil carry-over to TEG dehydration loop	Keep TEG/dehydration loop process efficiency high	Liquid-gas coalescer
5	Remove solvent carry-over	Protect downstream compressor	Liquid-gas coalescer
6	Remove contaminants from supercritical CO <sub>2</sub>	Prevent reservoir fouling	Absolute-rated particulate filter
7	Remove contaminants from displaced water	Prevent reservoir fouling	Absolute-rated particulate filter
8-10	See applications 4-5 in solvent carbon capture, Figure 1.		

Table 2

In contrast, absolute particle filter ratings must meet rigorous ISO or ASTM standards. The absolute rating of a particle filter directly corresponds to the largest diameter of particle that the filter will allow through – all larger particulates will be captured. An example of the difference between solvent cleanliness after using no filter, a nominally rated filter, and an absolute-rated filter is shown in **Figure 3**.

Rich side filtration is commonly recommended to remove precipitated corrosion like iron sulphide and to protect the lean/rich heat exchanger. Significant improvements in the removal of solvent contaminants have been demonstrated using Pall absolute-rated filters, with extensive data proving the removal of precipitated corrosion products and process equipment protection from the gas treating industry <sup>3</sup>.

Lean filters can also be added to the process scheme to prevent fine particulates from entering the absorber. Lean filtration is particularly recommended for polishing and removing adsorbent fines if there is a carbon bed on the lean solvent side.

Carbon beds are often installed to remove solvent degradation products and have been found to remove some metal ions. Degradation products such as organic acids, formed by the solvent degrading through oxidative and thermal mechanisms, can be corrosive, cause foaming, solvent losses, and reduced absorber capacity. Metals are common from internal metallurgy and can catalyse amine degradation. Not all activated carbon targets the same contaminants, so the product must be selected carefully to ensure that it does not prematurely plug.

Other concerns in the solvent loop include heat-stable salts, which are produced when amines react with acidic components such as O<sub>2</sub>, CO, and SO<sub>2</sub>. Concerns with heat-stable salts are that they render the amine inactive and can make the solution corrosive if allowed to reach a level above 3%. Ion exchange techniques are commonly recommended for treating heat-stable salts.

Finally, there is increasing concern about nitramines and nitrosamines in the carbon capture industry due to their nature as a potential carcinogen. These compounds are produced from NO<sub>x</sub> in the flue gas reacting with amines. Water wash prevents nitramines and nitrosamines

from venting out of the absorber, but they must still be removed from the water wash before disposal to avoid environmental contamination. Processes to remove nitrosamines and nitramines, such as selective catalytic reduction (SCR) for NO<sub>x</sub> removal and use of activated carbon, are ongoing areas of study to ensure that these compounds remain below desired levels <sup>4</sup>.

### Flue gas pretreatment

The top three contaminants commonly present in post-combustion flue gas are NO<sub>x</sub>, SO<sub>x</sub>, and particulates such as fly ash. All three of these contaminants should be removed prior to CO<sub>2</sub> capture, regardless of the capture technology used. NO<sub>x</sub> levels are reduced in the pretreatment step before the absorber with a selective catalytic reduction process (SCR); SO<sub>x</sub> levels are also reduced during pretreatment with a wet or dry scrubbing process.

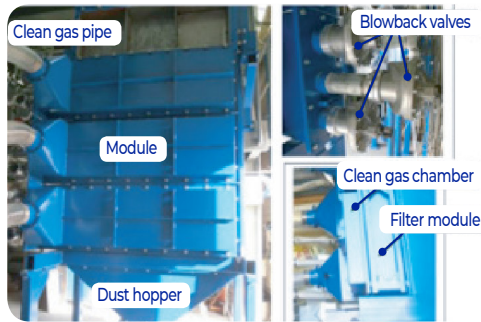
Particle filtration is commonly employed in pretreatment steps with cyclones, electrostatic precipitators, and bag filters. Cyclones use rotation to separate solids but have difficulty removing small particulates. Electrostatic precipitators (ESPs) remove fine particulates by applying an electric charge but can be expensive and associated with an increased safety risk. Furthermore, wet ESPs have been found to break up large contaminants, increasing the total number of contaminants in some cases. Finally, bag filters can be temperature-limited due to the use of polymeric material. They can have a shorter lifetime and lower lifetime particulate removal efficiency when compared to absolute-rated filters or inorganic filter media.



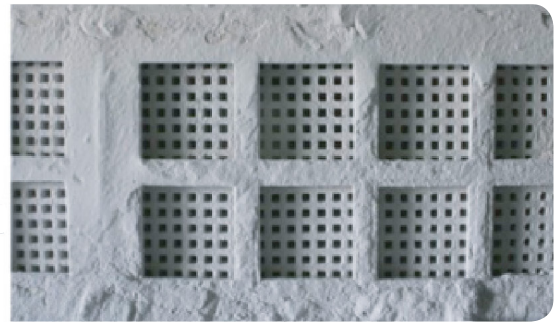
Figure 3: Amine cleanliness after no filtration, nominal filtration, and absolute filtration



**Figure 4:** Fine fly ash present in flue gas feed to a carbon capture process



**Figure 5:** Low pressure drop filtration testing. **Left:** test stand setup. **Right:** filter inlet following tests. Fine particulate contaminants are visible on the face plate



One key requirement of filtration pretreatment is that it operates at a low pressure drop due both to the excessive costs of compressing large gas flows and near-atmospheric process conditions of flue gas feed to CO<sub>2</sub> capture processes. Low pressure drop filtration systems are often large, making their integration into existing plants a potential challenge in terms of space constraints. They also do not always capture fine (<1 μm) particulates present in industrial flue gases, such as those shown in **Figure 4**.

Pall has recently developed a new low pressure drop particulate filter to address this application. The system and overall operation are based on decades of experience with Blowback filter technology, where particle contaminants build up on the feed side of a filter. After a period, caked contaminants are ejected off the filter for collection or disposal at automated intervals via a short gas pulse in the reverse direction. Filters regenerate at separate times, such that most of the filters in the system provide continuous operation and filtration. Through regeneration, filters maintain a long on-stream service life, and the pressure drop after solids are blown off reaches an equilibrium point. Blowback filters were conventionally cylindrically shaped and made from organic materials such as metals or ceramics to withstand harsh process conditions and offer fine filtration ratings with good reliability. However, to achieve an extremely low pressure drop with an order of magnitude in the 10s of millibar, as requested by the CCUS industry, conventional blowback technology would need to be oversized and thus would not have been an economical solution and would have been challenging to fit into brownfield industrial plants.

This new product development leverages recent advances in additive manufacturing (AM) to produce a remarkably high surface area filter element with minimal manual manufacturing, enabling bulk production of filters at a given time. The high surface area ensures a small footprint to handle a given flow rate and pressure drop (down to <20% the size compared to the conventional product and similar alternatives), which directly translates to reduced infrastructure needs and production costs.

The new filter design was optimised through iterations of advanced computational fluid dynamics (CFD) modelling, coupled with rapid 3D printing prototypes that were tested at a lab scale with representative test dust and varied

blowback cycle time to regenerate the filter. Larger bench-scale tests depicted in Figure 5 with multiple elements were performed internally at Pall and offer impressive results. The pressure drop across the filters for the duration of the tests is kept between 20-30 mbar, with an estimated pressure drop below 60 mbar for full-scale installations, which include piping and infrastructure. Solid loading in the gas feed varied above 1 g/Nm<sup>3</sup>, with exceptionally low downstream solid loading after filtration – well below 1 mg/Nm<sup>3</sup>. Removal efficiency is above 99%, even for sub-micron particulates down to a 0.5 μm diameter and below. The next steps are to continue to prove performance at increasing scales.

## Emission prevention

Aerosol emission management has been another major focus of carbon capture technology providers. In solvent-based carbon capture technology, SO<sub>x</sub> and fine (<1 μm) flue gas feed particulates are responsible for most of the solvent losses out of the vent, which have been found to reach more than 1,000 mg/Nm<sup>3</sup>. In contrast, desired levels are typically as low as possible to minimise solvent losses and environmental impacts, well below 10 mg/Nm<sup>3</sup>.

A water wash mounted on the top of the absorber unit limits gas-phase solvent emissions, but particulates and SO<sub>x</sub>, which form H<sub>2</sub>SO<sub>4</sub> aerosols, serve as sub-micron diameter droplet nuclei. Droplet nuclei can then grow to larger micron-sized droplets as they travel through the water wash section.

In this application, like flue gas pretreatment requirements, there is an extremely low pressure drop (<20 mbar, as an example) available due to pressure conditions near atmospheric. Again, Pall is developing a product to uniquely meet the low-pressure requirements, while removing fine aerosols with an exceedingly high-efficiency (>99% aerosol removal) separator, producing well below 1 ppmw downstream and also providing a minimal footprint. The unique ability of this separator to meet high-efficiency removal requirements and a low desired pressure drop is a result of the material science used in its fabrication and in-house technical expertise. The product design allows liquid to drain off quickly and easily, similar to the industry-proven high-efficiency liquid-gas coalescers shown in **Figure 6**.



## Downstream purification and dense phase CO<sub>2</sub>

After CO<sub>2</sub> has been captured, it is dehydrated and compressed to a high pressure for transport and storage. After dehydration and compression, CO<sub>2</sub> reaches a high-pressure 'supercritical' or 'dense phase' state, with a high density nearing that of a liquid and a viscosity nearing that of a gas. Converting CO<sub>2</sub> to a dense phase enables the use of smaller pipelines and increases the amount of CO<sub>2</sub> that can be stored in reservoirs.

In downstream applications, lube oil can become contaminated through compressor wear, requiring filtration. It can also be carried over after the compressors, which can cause the CO<sub>2</sub> to become off-specification. Similarly, dehydration processes such as mol sieves, desiccant dryers, adsorbent beds, or glycol loops can require filtration and liquid/gas coalescence to prevent fouling of adsorbent beds, absorption loops, and to prevent carry-over of fines or glycol contaminants.

After compression and dehydration stages, undesired contaminants such as water, lube oil, oxygen, and H<sub>2</sub>S can be present in the CO<sub>2</sub>, which pose a threat to the integrity of the pipelines. Hydrogen sulphide and oxygen are corrosive, damaging the pipelines and, in the worst case, causing cracks. Trace water can react with CO<sub>2</sub>, forming corrosive byproducts, and can also form hydrates, which produce pipeline blockages.

As pipelines deteriorate, solid corrosion products and pipe scale formed through these reactions can be carried downstream, plugging critical equipment needed for carbon capture storage, such as control valves, metering stations, and high-pressure injection pumps. This increases maintenance costs and can require equipment replacement or unscheduled downtime. Solid contaminants can also plug permeable storage reservoir pore structures, requiring increased energy for CO<sub>2</sub> injection and even limiting the amount of available and accessible reservoir storage capacity.

In selecting filters and separators for dense phase CO<sub>2</sub> applications, substantial care must be taken on which materials are used, how filter sizing is performed, and what the filtration rating is. To fully protect reservoirs, the filter rating must be selected based on the reservoir permeability and approximate pore diameter. Regarding material choice, safe operation favours corrosion-resistant metallic materials or CO<sub>2</sub>-stable plastics. Plastics must be carefully selected, as some materials may swell under contact with supercritical CO<sub>2</sub>. Additionally, some polymers can mechanically fail by explosive decompression if there is a rapid pressure drop during upset conditions or routine maintenance after CO<sub>2</sub> has adsorbed and diffused into the polymer due to high-pressure operation.

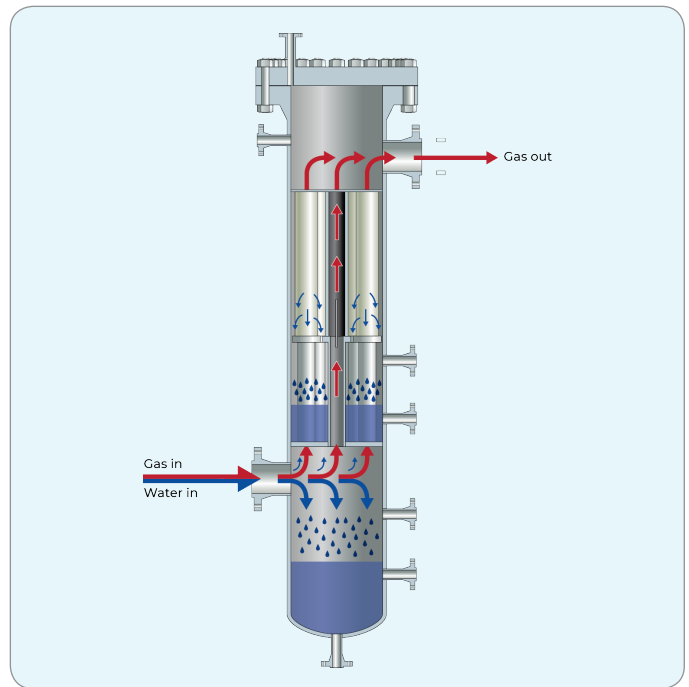


Figure 6: Pall high-efficiency liquid-gas separator

## Conclusions

Filtration and separation applications in solvent-based absorptive carbon capture are well-known from decades of gas processing technology with amine solvents. However, there are emerging requirements specific to carbon capture, such as low available pressure drops in pretreatment and high pressures in downstream CO<sub>2</sub> transport and storage.

These requirements mean that new filters and separators tailored to the applications outlined in this article, as well as expert knowledge in material and product selection, are needed. By choosing the right purification product with the right material compatible with the application, both capital and operating expenses can be minimised by protecting critical equipment, meeting environmental specifications on contaminant levels, and keeping process efficiency high.

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