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The Art of Filtration – SF_6 Gas July 13, 2020

SCOPE:

To provide information on how SF_6 gas filtration works and what are the processes required to ensure safety, quality, and consistency when filtering SF_6 gas of contaminants.

The major contaminants are, moisture, decomposition products, other vapors, and oil. These major contaminants must be removed from SF_6 gas exposed to those contaminants to ensure its condition meets the specifications for re-use in SF_6 Gas Insulated Equipment (GIE).

The paper will also provide further guidance on the resources required to perform proper SF_6 gas filtration for reuse, including a recommendation of tools needed, how these tools must be maintained to ensure the objective of the scope is met. Further the paper will provide guidance on the proper use of the tools and the training any maintenance team must have to guarantee the health and safety of the team, the tools and equipment and just as important the environment.

DEFINITIONS:

- Filter: A porous device for removing impurities or solid particles from a liquid or gas passed through it
- Filtration: Is the process used to separate substances based on their different physical and chemical qualities.
- Gas/Vapor: One of the three fundamental states of matter, is a state of matter that has no fixed shape and no fixed volume with distinctly different properties from the liquid and solid states
- Liquid: A material that has a definite volume, but it does not have a definite shape and takes the shape of the container. In physics, one of the three principal states of matter, intermediate between gas and crystalline solid.
- Solid: The state in which matter maintains a fixed volume and shape
- Particle: A minute portion of matter
- Recovery: The removal of SF_6 gas using a SF_6 gas recovery system from a GIE or container into another container.
- Gas Insulated Equipment: Electrical power equipment insulated with SF_6 gas for the purpose of a) electrical insulation or b) electrical arch quenching

ABBREVIATIONS:

- b.c: before Christ
- GIE: Gas Insulated Equipment (i.e. SF_6 gas circuit breaker)
- SF_6: Sulfur Hexafluoride
- CO_2: Carbon Dioxide
- N_2: Nitrogen
- SO_2: Sulfur dioxide
- AL_2O_3: Aluminum Oxide
- H_2O: Water/Moisture
- µm: micrometer/micron
- EPA: Environmental Protection Agency
- OSHA: Occupational Safety and Health Administration
- 3-R's: Recovery, Recycle, Reuse
- PPMv: Parts Per Million by Volume
- PPMm: Parts Per Million by Mass
- °C: Celsius
- %: Percent/Percentage

HISTORY:

The history of filtration and how it came about can be traced back to the origins of water purification. The origins of water filtration date as far back as 500b.c. where Greek scientist known as Hippocrates invented a cloth type filter which captured particles from water as it was strained through a cloth after the water was boiled. The process allowed for a cleaner and better smelling water source.
In the 1800's London experienced epidemics of cholera and typhoid as water from the Thames was contaminated with raw sewage. It is believed around that time, a man by the name of John Doulton and his son Henry created a ceramic filter to capture bacteria from drinking water in London. It was so effective and popular they were commissioned by Queen Victoria in 1835 to develop a filtration system for the Royal household.
This eventually led Henry Doulton to work with a French Chemist by the name of Louis Pasteur whose studies concentrated in Microbiology. Henry's research and development team created micro porous ceramic (diatomaceous earth) cartridges which could remove bacteria with 99% efficiency. The Doulton famed filter design was adopted and used by the military and his company was given the permission to use the royal crest in his logo and eventually led to the design of more effective filtration such as carbon type filters.

General:

Filtration occurs when a material such as a liquid or a vapor passes through a media designed or made of a material that ***ad-sorbs***, *or* ***ab-sorbs*** thus separating a substance (or number of substances) from the liquid or vapor that is passed through the filter. Depending on the type of filter material it may be designed to separate either molecules, particles, or a foreign substance from the filtered material as it passes through the filter.

To explain further, **adsorption** occurs when the pollutants bond to the outside of the filter matter such is the case with carbon type filters. **Absorption** occurs when the pollutants are taken into the filter matter and become part of the filter element (i.e. such as a sponge which absorbs a liquid).

There are a many types of filtration and/or filtration processes. Some may be mechanical, chemical, or biological. As an example, the following describes some of the types of filtration processes (and many more types exist).

- **Mechanical filtration**, uses sponges, filter socks, and filter floss pads that physically strain out debris from a liquid, much like a coffee filter. (i.e. the Hippocrates design is a sock design)
- **Biological filtration** uses beneficial bacteria that can consume the toxic ammonia and nitrogen compounds that result from your waste in water (i.e. fish in an aquarium for example create waste and bacteria type filter captures the waste allowing the water to be safe for the fish life).
- **Chemical filtration** uses activated carbon or special resins that can remove medications, tannins, and other impurities from a liquid and in some cases a vapor.

These types of filtration processes are dependent of the respective industry or applications which as a result are required for several reasons. These reasons can be (but not limited to):

- **Protect Equipment**. In industrial manufacturing application, filtration can aid the process by protecting production machinery. When particles are not properly filtered out, they can cause damage to the equipment, which can ultimately lead to entire system failures. For example, an engine which is part of a machine that runs with fuel and oil can be damaged if either are not filtered to avoid particles to enter combustion chambers or valve seats.
- **Purification**. Filtration is extremely important to keep things like water, chemicals, and pharmaceuticals clean, pure, and free of contaminants. Filtration allows for safe drinking water, because it plays an important part in separating sediment, sand, gravel, carbon, and other suspended particles.
- **Safety**. Filtration can help prevent cross-contamination, health hazards, workplace safety issues and environmental issues. It even helps companies comply with the safety and quality standards set by agencies like the EPA & OSHA.

- **Product Isolation**. Perforated tubes are designed with holes to separate particles from each other. Like straining pasta, many manufacturing and industrial processes need to isolate their own solids, gases, oils, water, and other fluids to keep their systems functioning right.
- **Efficiency**. Filtration helps many industrial operations flow smoothly and more efficiently. Take oil rigs, for example. When bringing oil up out of the ground, sand and debris get mixed in with the oil. Placing perforated tubes at the source can help get rid of some of those particles on the way up, saving time and effort on the surface.

SF_6 Gas filter types

There are generally three filter types which apply to SF_6 gas filtration for SF_6 gas recycling (otherwise known as the **3-R's**. The 3-R's are **R**ecover, **R**ecycle and **R**euse). It is important to note that all SF_6 gas must be analyzed prior and post handling.

- **Activated Charcoal** has a high surface area, high bulk density and particle size distribution, **activated carbon** is used for the removal of organic compounds such as oil from SF_6 gas.
- **Aluminum Oxide** (AL_2O_3) is an inert compound of aluminum and oxygen and has been utilized in removing fluoride from water since 1936. When used with SF_6 gas, it separates moisture and by-product from the vapor by acting as an absorbent attracting those compounds.
- **Molecular Sieve Desiccant** uses the process of dehydration by means of physical separation, rather than thermodynamic separation (heat). Molecular sieve desiccant removes and traps water molecules within them to achieve separation from SF_6
- **Particle filters** are designed to trap solid particles that may include solid decomposition material from SF_6 gas by-products and other solids which may cause damage to recovery system and accessories, and GIE. Particle filters are generally designed to maintain a 100% capture rate of particles that are ≥1.0µm

SF_6 Gas Filtration

In the process of SF_6 gas filtration, the goal is to meet a specific criteria based on a standard and application. In this application, SF_6 gas filtration is to remove contaminants such as oil, moisture, and by-products. This is what is specifically considered recycling as part of the 3-R's process. It is important to understand filtration is a process in which we are removing contaminants from the gas by adsorption or absorption. Filters will NOT remove contaminants such as AIR (O2, N2), CF4, and other non-reactive gases. SO_2 SOF_2 can be found in vapor form. However, because of their reactivity, these contaminants may be adsorbed by active alumina filters.

To separate oil from SF_6 gas, for example, activated carbon filters are required. To remove by-product and moisture, Aluminum Oxide and Molecular Sieve Desiccant filters are required. And, of course, to remove any solids, a particle filter is required. The filter must be set up to have the Aluminum Oxide (AL_2O_3) on the input and Molecular Sieve on the output of the filter cartridge. Dependent on the specific concentration of the contaminants, this filter set-up allows for the proper adsorption of humidity and by-products immediately on the input with minimal contact time to reduce filter saturation.

To explain further, the design and set-up of a filter system must maximize adsorption and absorption as well as particle filtration. As part of the design and capabilities the combination of the filter types must meet the requirements to allow optimum surface area contact with the filter element and gas flow. The filtration process must capture the contaminants without contributing further to the contamination as well as have the capabilities to support the quantity of contaminants to be captured so the filter system does not become saturated to a point that any contamination captured would not be released back into the gas at the output of the filter element. Hence why it is recommended that if additional filters are required, they are placed in parallel and not in series.

For example, if the SF_6 gas to be recycled and filtered and is suspected to have oil, and the moisture and the SO_2 content (presence of by-product) is above the acceptable standards for use, a filter skid capable to filter oil, moisture and SO_2 must be used to ensure all the elements of adsorption, absorption and capturing of solid particles is achieved.

To further expand on the example above, if a sample from 2,140lbs. of SF_6 gas was analyzed and resulted in the following condition: **Oil Content:** 12ppm (mass), **Moisture**: 1,095ppmV, and **SO_2 Content**: 25ppmV, a filtration system set up with new filter cores to perform the filtration of the contamination is required.

A typical filtration skid setup and gas process:

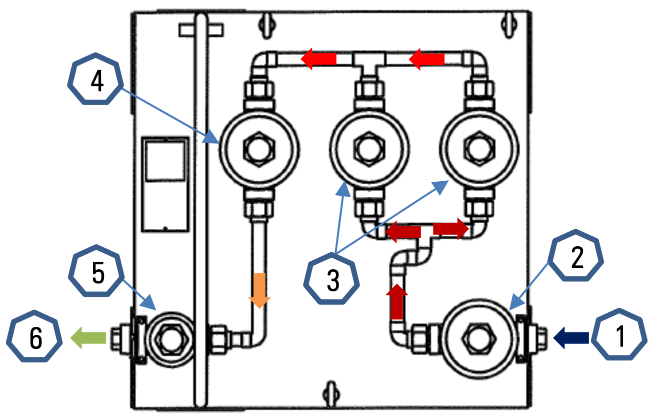

FIG: 1a - Top View typical larger size SF_6 gas filtration system using 4 filter elements for adsorption and absorption and one particle filter.

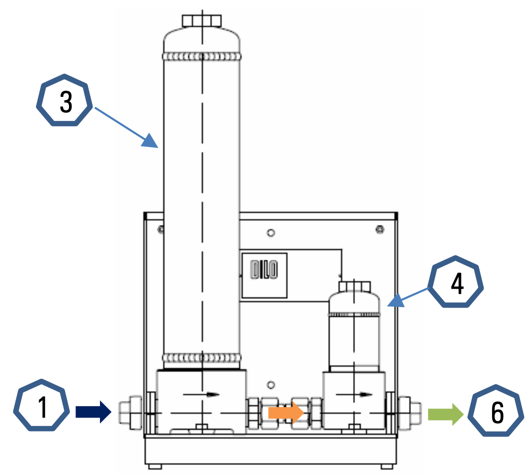

FIG: 1b - Side View typical standard size SF_6 gas filtration system using only one filter for adsorption and absorption and one particle filter.

1. Input from Source (GIE or Storage cylinder/tank)
2. Activated Charcoal Filter
3. Combined Aluminum Oxide/Molecular Sieve Desiccant Filter
4. Molecular Sieve Desiccant Filter
5. Particle Filter

- (dark blue arrow) Output to recovery system
- (red arrow) Contaminated SF_6 Gas
- (orange arrow) SF_6 Gas post filtered clean of oil contamination
- (green arrow) SF_6 Gas post filtered clean of moisture & by-product (i.e. SO_2)

FIG: 1c – Descriptions of major components and gas flow indication on SF_6 gas filtration system

Note that in "fig 1a," the gas is passed through an Activated Charcoal filter first. This is in the event the gas is suspected to have oil contamination. Otherwise, an Activated Charcoal filter is not required if the SF_6 gas is only being filtered of moisture and gas by-products. This is important as oil will not only contaminate the filter system but can damage the Aluminum Oxide and Molecular Sieve Desiccant Filters and the Particle filter, rendering them all useless.

In this filter system design, the first two Aluminum Oxide/ Molecular Sieve Desiccant Filters are designed to be in parallel to ensure optimum adsorption of contaminants because it is required that minimal contact with SF_6 gas is experienced by the filters to ensure adsorption of contaminants by the filter is achieved. This is important when the expected volume of gas is high and/or the contamination is high (or a combination of both). The filter following the two parallel filters is a Molecular Sieve Desiccant Filter to ensure adsorption of moisture. The last filter is a particle filter which will trap solids, including by-product and GIE or source container particles suspended in the vapor. Note that the absorbability and capturing of particles by the filters are dependent on the concentration of contamination of the SF_6 gas at the input of the filter system.

In consideration of the prior point, it is important that an analysis of the filtered SF_6 gas is performed to ensure that the gas has been filtered of contaminants and that the analysis is well within the specifications for use in new or in service GIE.

It is also important to note that this filtration process does not and cannot improve the purity of the SF_6 gas. Thus, other vapors will remain and not be removed as a result. This requires a different process known as reconditioning.

SF_6 Gas Reconditioning

Reconditioning is a process used to separate SF_6 gas from other vapors (i.e. N_2, O_2, CF_4) by applying high pressure (>700psi) with extremely low temperatures (≤ -20°C). As the SF_6 gas liquifies because of the increased pressure and low temperatures, other vapors present will remain suspended, thus separating from the liquified SF_6 gas. These other vapors are then released into a separate chamber for further processing or to atmosphere (such is the case with N_2 & O_2).
Note that the SF_6 gas must first be recycled as outlined in the section above "SF_6 gas Filtration." This will help to ensure moisture is well below the standards and that the gas is free of any oil or by-products before processing through the reconditioning process.

Analysis of Recycled and Reconditioned SF_6 Gas

As is the requirement with the filtration process, it is important to perform analysis of the gas pre and post reconditioning to determine the starting purity and the ending purity of the SF_6 gas. Any deviation from the expected results (i.e. ≥99% purity) should be investigated.

Reconditioning, in combination with filtration, will result in SF_6 gas that meets, and in most cases, exceeds the industry standards for SF_6 gas use in new or existing GIE.

The following is an example of typical analysis comparisons of SF_6 gas analysis pre- filtration and separation/reconditioning process and post filtration and separation/reconditioning process.

	Pre- Filtration & Reconditioning	Post- Filtration & Reconditioning
Purity in %	96%	99.55%
Moisture in PPMv	1,095 PPMv	40 PPMv
SO_2 in PPMv	12 PPMv	0 PPMv
Oil Content in PPMm	0 PPMm	0 PPMm

FIG: 2 - Typical SF_6 gas analysis results data

To further support the typical results tested locally, an annual or bi-annual analysis using an independent 3rd party laboratory should be used to ensure the process is consistent with the results realized during local analysis of processed gas. A sample of a 3rd party analysis can be as follows (unit of measure is ppmV) as it compares to a typical industry standard.

H2	Hydrogen	(ppm) :	0
O2	Oxygen	(ppm) :	583
N2	Nitrogen	(ppm) :	2164
CF4	Carbon tetraflouride	(ppm) :	36
CO2	Carbon dioxide	(ppm) :	77
SF6	Sulfur hexaflouride	(ppm) :	997141
SO2F2	Sulfuryl flouride	(ppm) :	0
SOF2	Thionyl flouride	(ppm) :	0
SOF4	Thionyl tetraflouride	(ppm) :	0
COS	Carbonyl sulfide	(ppm) :	0
SO2	Sulfur dioxide	(ppm) :	0
CCl2F2	Freon R-12	(ppm) :	0
WF6	Tungsten hexaflouride	(ppm) :	0
	Total	(ppm) :	1000000
	Moisture	(ppm) :	16
D2477	Dielectric BV	(kV) :	16

FIG: 3 – Independent 3rd lab SF_6 gas analysis

Maximum acceptable impurity levels for reuse of SF_6 at all use pressures (IEC 60480)

Impurity	Specification
Air and/or CF_4	3% volume [a]
H_2O	25 ppmw [b] (see NOTE 1)
Mineral oil	10 ppmw (see NOTE 2)
Total reactive gaseous decomposition products	50 µl/l total or 12 µl/l for (SO2 + SOF2) or 25 µl/l HF

NOTE 1—Converted to ppmv these levels should also apply to mixtures until a suitable standard becomes available.

NOTE 2—If gas-handling equipment (e.g., pump or compressor) containing oil is used, it may be necessary to measure the oil content of the SF_6. If all equipment in contact with the SF_6 is oil-free, then it is not necessary to measure oil content.

[a] In case of SF_6 mixtures, the equipment manufacturer should specify the levels for these gases.

[b] 25 mg/kg (25 ppmw) is equivalent to 200 ppmv (200 µl/l) and to a dew point of –36 °C (–32.8 °F), measured at 100 kPa and 20 °C (14.5 psi and 68 °F).

FIG: 4 – Excerpt SF_6 gas specifications table from IEC 60480

The results illustrated above show that the delta between the 3rd party analysis and the typical industry standard for the purity of the sampled gas is <0.99%. Thus, indicating that the processes used for purification are resulting in SF_6 gas that can be safely used in new or existing GIE.

Filter Service Life

It is difficult to determine the service life of a filter element as it is dependent on the amount of gas and contaminants it is exposed to over the course of its service life. As a result, gas analysis must be performed prior to and post filtration. If the results show that filtration performance is below expectations (i.e. moisture: -51°C/41ppmV post filtration), replacement of the filter core(s) is/are required.

Another consideration is that SF_6 gas by-products such as tungsten trioxide (WO_3), cupric fluoride CuF_2) and other related decomposition products are effectively captured in the particle filters. However, SO_2 and SOF_2 may be adsorbed by the Aluminum Oxide and Molecular Sieve Desiccant filter(s). These elements can greatly reduce the service life of a filter element. Hence why it is important to analyze the and compare results with what the target analysis should be post filtration.

Health and Safety

As part of the 3-R's process and SF_6 gas reconditioning, adherence to industry, state, federal and local health, and safety policies must be practiced. Application and proper use of PPE is required when ever handling any SF_6 gas. This is specifically important when handling SF_6 gas that has been subject to high temperatures (i.e. arcing or arcing events due to GIE fault(s).

SF_6 gas by-products are harmful to human life. Refer to industry gas handling guides and policies for more information.
It is important that all gas handling techniques are performed by trained and experience operators, using equipment and accessories that are designed for zero emissions. Proper equipment, processes and training will ensure that users do not contribute to SF_6 gas emissions and will aid in maintaining a 1% or less emission rate.

Summary

The history of filtration has come a long way since the days of water purification. Improvements and technological advancements with filtration materials not only contribute to ensuring the health and safety of humans and animals alike, but also to help to ensure the designed use and serviceability of equipment and machinery is guaranteed. And of course, helps to restore materials so they may continue to be used or to be re-used one or many times over.

Filters which are designed to adsorb or absorb contaminants or even capture particles aid to improve the quality of materials passed through the filters for several applications. And SF_6 gas is no exception.

Such as the case with the 3-R's process which is designed to filter out contaminants from used SF_6 gas for immediate reuse. And is also the case when performing reconditioning of SF_6 gas so it may be introduced into the supply stream for future use.

When these processes are properly performed with the correct tools and equipment and in parallel is performed by properly trained personnel following set processes, SF_6 gas can be filtered and purified to easily meet the standards set by the industry for SF_6 gas to be re-used in new and existing GIE.