

SF₆ Maintenance Equipment Fundamentals

Eric Campbell
DILO Company, Inc.
11642 Pyramid Drive
Odessa, FL

Introduction

Used as a dielectric and arc-suppression medium, sulfur hexafluoride (SF₆) has countless redeeming values. However, as environmental consequences of gas emissions are brought to light, it is becoming evident that users must exercise responsibility in testing, maintaining, and reusing existing SF₆ inventories.

Over the past few years, advances have been made that encourage and simplify the reuse of existing gas, as well as lower the cost of recovery and test equipment. Recent world-recognized publications have surfaced that resolve many questions as to the viability of used gas. As the volumes of SF₆ gas within insulated equipment (GIE) are reduced, a larger proportion of SF₆ inventories are distributed in smaller equipment. And, as larger, older equipment is replaced, many users are finding themselves with excess inventory of “used” SF₆.

Fortunately, the technology used in the SF₆ maintenance equipment industry has advanced as well. Today, recovery and test equipment can be as small as a suitcase-sized container. No longer must users drive triple-axle trailers from across their division to pump down 15 lbs. of SF₆.

Testing SF₆

Most original equipment manufacturers (OEMs) recommend maximum and minimum tolerances for certain variables within the gas. These include moisture, gas decomposition, and purity of SF₆. Though there has been past debate on what numbers are acceptable for reused gas, a consensus has been reached by the majority of OEMs. As such, it is important that end users have reliable, cost-effective, and durable testing equipment.

Currently, all test devices require that the sample gas be “sacrificed.” Consequently, the longer a test device requires an accurate reading, the more gas is vented. Fortunately, devices exist that limit gas losses to rates less than a few ounces.

Moisture

Moisture levels must be kept to a minimum to reduce the formation of acidic by-products, such as HF, SO₂, SOF₂, etc. Hygrometers, or moisture-measuring devices, built to work in the corrosive environment of arced SF₆, will quantify the level of moisture vapor in gas. Because the amount of moisture present in the vapor state will fluctuate depending on the temperature and pressure of the gas, most devices are dependent on pressure and temperature. Ideally, the sensor used in a hygrometer should be capable of handling arced SF₆ and should not require that the gas be pre-filtered.

It is extremely important to exclude moisture from any system employing SF₆ as a dielectric. Moisture can react with SF₆ under the influence of electrical discharges to form toxic and corrosive compounds. Although moisture does not affect the dielectric strength of SF₆, it can have a harmful effect on the reliability of GIE (Air Products and Chemicals, 1983).



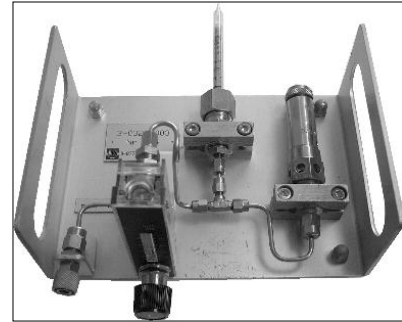
Moisture-Measuring Device

Moisture values can be interpreted in several units; parts per million by volume (PPM_v), parts per million by weight/mass (PPM_w or PPM_m), dew point (C° or F°), and relative humidity (RH).

Decomposition

Although SF₆ is non-toxic in its pure form, it will decompose when exposed to high temperature or electrical arcing – especially in the presence of moisture. The amount of decomposition that occurs is linked directly to the intensity and duration of the temperature and the materials used in the construction of the GIE. The two principal gaseous decomposition products are SF₄ and S₂F₂. These sulfur fluorides further react with the trace amounts of contaminants typically found in all systems (Air Products and Chemicals, 1983).

Decomposition testing equipment and analytical services help users determine the levels of decomposition within sampled gas. Off-site analysis involves capturing a sample of gas and sending it to a laboratory where gas chromatography or spectrometry can be performed. The sample containers used to capture the gas must be completely evacuated to ensure that all moisture and air are removed. Any initial residual moisture will cause subsequent reactions en-route to the testing facility. Test results will indicate specific levels of various by-products, as well as air, nitrogen, and oxygen content.

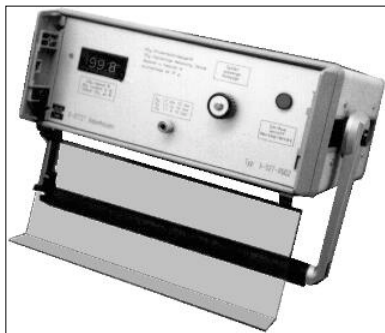


Decomposition Detector

On-site test devices offer instant indication of the level of decomposition (generally measured in SOF₂, or HF). Using small glass ampules that contain a reactive element, the user can quickly and accurately determine approximate levels of decomposition. Because these types of devices are purely mechanical, they are very simple to use, and provide an extremely cost-effective means for determining the amount of decomposition present.

Purity

Decomposition and moisture are two contaminants that can be removed by passing the gas through desiccant filters and molecular sieves. However, other contaminants, which reside in a gaseous state, such as air, nitrogen, oxygen, and CF₄, cannot be removed by filtration alone. Fortunately, most gaseous contamination occurs through gas handling, and not through the operation of the equipment. As concentrations increase, dielectric strength and handling characteristics of the gas change. As such, OEMs have established minimum SF₆ purity values that must be maintained.



Purity Meter

Off-site analysis can provide a very accurate means for documenting SF₆ purity levels. However, typical limitations include waiting several days for lab results, possible sample container contamination, and cost. On-site test equipment can provide reliable and accurate readings. The acoustical

technology used to sample the purity of SF₆ provides for fast, repeatable results.

SF₆ Recovery Equipment

Compared with older oil-based technology, GIE has far longer maintenance cycles – often times 10 years or more. Over time, moisture and decomposition levels increase and must be kept within industry-recognized limits. Testing and benchmarking these levels will provide the user with a means of scheduling gas maintenance.

SF₆ gas recovery systems are used in several capacities: as a means to store the gas during GIE maintenance, to clean and dry the gas, and to perform cylinder consolidation. Various technologies exist that can achieve similar results.

Compressed to liquid form, larger amounts of SF₆ can be stored in smaller volume storage containers. For example, a typical 1.6 ft³ (44 liter) type-b cylinder is capable of storing approximately 115 lbs. (52 kg.) of SF₆ in liquid form. In gaseous form, the same cylinder will store only approximately 25 lbs. (11 kg.). Because liquid storage is considerably more efficient, nearly all recovery systems are designed to liquefy.

Liquefaction

There are currently three approaches to liquefying SF₆: direct high-pressure liquefaction, refrigeration-assisted liquefaction, and heat-exchanged liquefaction. All three designs have advantages and disadvantages.

Direct High-Pressure Liquefaction

Using this approach, the main transfer compressor is used to generate sufficient pressure, generally 700 PSIG (48 bar), causing the SF₆ gas to condensate and liquefy. Because liquefaction is not based on temperature, any vessel capable of 725 PSIG (50 bar) can be used for storage. This eliminates the need for dedicated storage, and allows the user to directly fill any empty SF₆ cylinder with liquid. Lack of additional components allows the system to be simplified – often allowing for one-button, unsupervised operation.

Because there is no supplemental cooling (i.e., refrigeration, or re-circulating heat exchangers), the compressor must be able to overcome the heat of compression. Thus, high-pressure liquefaction systems are typically slower than refrigerated systems.

Refrigeration-Assisted Liquefaction

Rather than relying on compressors to generate enough pressure to liquefy, refrigerated systems extract the heat of compression from the SF₆, causing it to condensate. At 40°F, the main compressor need only generate 200 PSIG (13.8 bar) to liquefy. A refrigeration system that is properly sized for the maximum capacity of the storage tank can provide enough heat dissipation to allow gas to liquefy at lower pressures and faster rates than the other technologies.

However, maintenance of the refrigeration system must be considered. Also, operation of the unit is considerably more complex, requiring a delicate balance between temperature and pressure. As part of the lower pressure design, the SF₆ compressor is unable to liquefy gas that is not cooled. Therefore, all liquefaction is limited to the on-board storage tank. Because external cylinders cannot be cooled using the refrigeration system, liquefaction within un-cooled cylinders (or cylinder consolidation) is also not possible.

Heat-Exchanged Liquefaction

As a hybrid of the high-pressure and refrigeration process, heat-exchanged systems rely on a series of forced-air coolers to extract heat from the compressed SF₆. As a benefit of reduced temperatures and pressures, this approach allows gas to be liquefied at a slightly faster rate than the direct high-pressure approach. Additionally, such systems utilize compressors that can achieve pressures much higher than the refrigerated designs. Most, however, still fall short of the required 700 PSIG (48 bar) to liquefy without the use of the heat exchangers. As with any radiator, maximum cooling effect is achieved by repeatedly circulating the gas. This requires a storage tank that allows gas to flow both in and out simultaneously. Although the user is not

limited to the on-board storage vessel, additional vessels must be designed with two ports. As such, SF₆ cannot be directly liquefied into un-cooled cylinders at higher ambient temperatures.

Compressors

The main component in any gas recovery system is the compressor. It is used to transfer SF₆ from the GIE to the storage tank. Depending on design, it may also be used to transfer gas from the storage tank back to the GIE. There are several compressor designs that are currently used: oil-based, oil-free, and oil-less. Among these are direct-drive, belt-driven, and pneumatic-driven units.

Oil-based compressors rely heavily on oil traps, scrubbers and filters to remove compressor oil from the SF₆. Arguably, some oil will remain in the gas and transfer to the GIE.

Oil-free compressors contain oil in the crankcase, but provisions are made to keep the oil from seeping into the compression chamber. In such system, oil traps, scrubbers, and filters are not built into the system. Guarantees cannot be made that no oil will migrate to the compression section.

Oil-less compressors contain absolutely no oil. Using greased-for-life bearings, Teflon® and graphite seals and rings, oil contamination is eliminated.

Direct-drive compressors are designed with the electric motor directly attached to the compressor crankshaft. Such configurations are available in which both motor and compressor are in one statically sealed housing.

Belt-driven compressors stand independent of the drive motor. The compressor crankshaft is connected to the motor via flywheel and belt. Such systems require maintenance to prevent the dynamic crankshaft seal from wearing and allowing the possibility of air intrusion or SF₆ emissions.

Pneumatically driven compressors use compressed air or nitrogen to move the SF₆ compressor – similar to an air ratchet. Though effective, concerns about cross contamination of air/N₂ and SF₆ must be addressed.

Compression Ratio

When working with compressors and booster pumps, efficiency and capability can be determined by assessing the compression ratio of the compressor. Any given piston compressor has a factory-determined maximum outlet, as well as an optimal inlet suction pressure. For example, a given compressor may be rated to generate 500 PSIG (35 bar) on the outlet, and, independently, 200 mmHg (150 mbar) on the inlet. However, the maximum output pressure is always dependent on the inlet pressure. With a 20:1 compression ratio, the referenced compressor would only be able to pull to 10.5 PSIG (0.72 bar) on the inlet while maintaining the maximum outlet pressure.

Using the same formula with a 50:1 compression ratio, the inlet pressure during recovery will drop as low as 524 mmHg (700 mbar). Even with final pressures this low, a sizeable percentage of SF₆ is left behind. On GIE with an initial pressure of 87 PSIG (6 bar), 524 mmHg represents

Using compression ratio to determine final vacuum:

To determine the best possible vacuum that a compressor can generate while achieving its maximum output pressure, apply this formula:

$$\left(\frac{P_{MO}}{Ratio} \right) \times 760 = vacuum (mmHg)$$

or

$$\left(\frac{P_{MO}}{Ratio} \right) - 14.5 = suction pressure (PSIG)$$

To apply this formula, divide the maximum output pressure (P_{mo}) by the compression ratio (ratio). Divide this value by 14.5 (or one atmosphere). Take this value, and multiply by 760 (millimeters of mercury in one atmosphere). The final value displayed is the best achievable vacuum the compressor can obtain.

9.8% residual gas being left behind. Because piston compressors cannot generate a sufficient vacuum, an additional component is required to remove the residual gas.

Booster Compressor

Usually routed in series with the main compressor, booster compressors are designed to increase the overall compression ratio of the entire system. Functioning purely as a vacuum device, the exhaust of the booster is directed to the main compressor. Again, technology differs from using oil-less boosters to using standard oil-based vacuum pumps. Some systems allow the booster compressor to automatically turn on and plumb itself into the system, while others require the operator to open valves at specific pressures.

Because vacuum components are sensitive to positive pressure, the system should prevent accidental over-pressurization.

Filter

Aside from transferring and storing SF₆, gas recovery systems are capable of returning the gas to like-new condition. All modern recovery systems use desiccant dryers to remove moisture. Filter location, type, and pressure are important in determining its efficiency.

Most gases, SF₆ included, filter better under higher pressures and temperatures. Placing the filter directly after the compressor, but before the storage tank, will allow for this to happen. Regulating the filter pressure, or locating before the compressor, will limit the amount of filter material exposed to the gas.

Aluminum oxide (AL₂O₃) and a four-angstrom (4A) molecular sieve are used successfully in desiccant towers. In contrast, a 13X molecular sieve, used for decades, can produce carbon dioxide and excessive heat resulting from chemical reactions. This heat, in extreme cases, can cause the material to melt, resulting in damage to equipment.



SF₆ Filter

Regenerative filters, or filters that contain heating elements, are not to be used. Heating of the contaminated desiccant can lead to a catalytic reaction between the desiccant materials and the corrosive by-products. This reaction is known to be exothermic, and can generate sufficient heat to cause equipment damage. Reactivation of desiccants, after application in an SF₆ environment known to contain traces of arc by-products, is not recommended.¹

Storage Vessel(s)

Most SF₆ recovery systems include a medium in which SF₆ is stored. Depending on the technology used to liquefy, storage will range from ASME-approved tanks to Department of Transportation (DOT) approved cylinders.

Refrigerated Storage

For refrigerated systems, a large evaporator coil is housed inside an ASME-approved tank. This allows the contents of the tank to be cooled during recovery and storage of SF₆. When removing gas from the storage vessel, heat is added by turning on a large heating element located inside the tank. Because of size and weight, these types of systems typically do not have weight scales to determine the mass of SF₆. Instead, refrigerated tanks have a liquid level sight glass that is useful in approximating capacity. Temperature of the tank will have an effect on the level of liquid

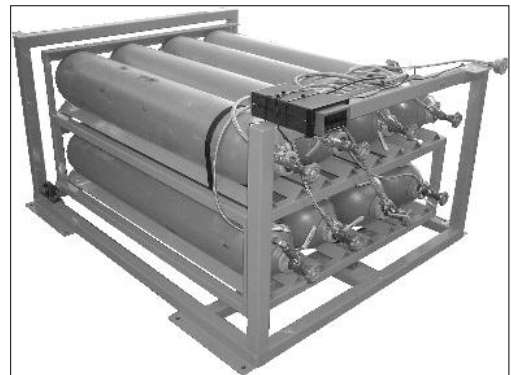
indicated. As the tank temperature increases, more of the stored SF₆ will be in the vapor phase. As the gas is cooled, more will revert back to the liquid phase. These types of tanks are not approved by the DOT.

Heat-Exchanged Storage

Because of the need to re-circulate the compressed gas through forced-air radiators, this technology requires ASME tanks. However, unlike refrigerated systems, no cooling or heating coil is located in the tank. Because the tanks do not contain fragile cooling coils, they can be set on a pivot and electronic scale, which indicates the weight of gas. The ASME tank is not approved by DOT.

Direct High-Pressure Storage

Without the requirement for cooling, high-pressure liquefaction can occur in any pressure tested vessel. The ideal method for packaging and transporting SF₆ is in the DOT-approved cylinders in which the gas was originally delivered. Such systems allow for unlimited storage capacity, and legal transportation with full storage vessels. Manifold cylinders, all located on a weighing tray, provide increased flexibility. In the event that all internal cylinders are full, the operator can simply attach additional empty cylinders.



8-bottle Storage Tray

DOT Approval

49CFR173.115(b) states that any Class 2.2 (non-flammable, non-poisonous compressed gas – i.e., SF₆) that exerts in the packaging an absolute pressure of 40.6 PSIA (2.8 bar) or greater at 68°F must be in a DOT-approved vessel with a working pressure of at least 1000 PSIG (69 bar). As interpreted by DILO, any gas recovery system with any storage medium other than DOT-approved cylinders and with more than 25 PSIG (1.7 bar) in the storage tank is illegal to be transported over the public roadways.

Other Items

There are many other issues that require attention when reviewing the fundamentals of SF₆ maintenance equipment. These include automation, plumbing, speed, longevity, leakage rates, and cost.

Systems exist that eliminate the need for operator supervision, while automation eliminates costly mistakes associated with learning curves.

Plumbing considerations include stainless and copper tubing runs. Copper tubing reduces stress vibration from transporting equipment at highway speeds. Stainless, which is much more rigid, pass most vibration on to the fittings. This requires regular preventative maintenance to periodically check and retighten fittings. Though issues have been raised about possible reaction between copper and by-products, all have centered on the corrosiveness of tin solder. All copper-plumbed recovery systems currently use silver solder, which is unaffected by the SF₆ by-products.

SF₆ Separation

Recent technology is allowing users with contaminated SF₆ to return the product to a vendor for reprocessing. As a result, gas that was not previously usable can be returned to like-new condition.

Conclusion

With inexpensive, efficient, and cost-effective equipment available, all users of SF₆ have the ability to test, maintain, and reuse their inventory of SF₆. A recent study funded in part by NEMA and DILO Company, Inc. revealed that global production of SF₆ has been steadily falling since 1997. Although GIE installations have been increasing, and most SF₆ users have increased their inventory levels, it is becoming apparent that recovery and recycling efforts are resulting in lower demand.

IEEE Guide for Moisture Measurement and Control in SF₆ Gas-insulated Equipment, IEEE Std 1125-1993, Insulated Conductors Committee of the IEEE Power Engineering Society