SF$_6$ & ALTERNATIVES COALITION

Alternative Insulation Technologies

Introduction

In the Electrical Sector, Sulfur Hexafluoride (SF_6) is primarily used for insulation and arc quenching in medium voltage and high voltage equipment[1]. Electrical equipment manufacturers first started experimenting with the use of SF_6 as an equipment insulator in the late 1930's albeit for only a few specific applications. Large scale production of the gas began in the 1950's and by the end of the 1960's its use was widespread in high-voltage switchgear and circuit breakers. Use of SF_6 to insulate medium-voltage equipment followed a few decades later.

Today, equipment most commonly insulated by SF_6 includes switchgear, circuit breakers, gas insulated substations (GIS) and gas-insulated lines (GIL). But other equipment such as transformers, instrument transformers and medium- and high-voltage electrical bus may also be insulated by the gas. Besides insulation with ambient air, SF_6 is by far the most common insulation technology used for switching and breaking devices, particularly in the high voltage class. For medium voltage equipment, it is most common in equipment with relatively low interrupting or switching ratings.

SF_6 History

SF_6's widespread use in the electrical sector for the last several decades is due to a range of properties. It is non-toxic, non-flammable, inert, non-corrosive to the equipment it insulates, thermally stable (i.e. it does not decompose until 500 degrees Celsius) and it naturally recombines after decomposition so that the permanent decomposition rated due to arcing is very low. These are all advantages over one of SF_6's historical competitors as an interruption medium – oil. Additionally, SF_6 is a far better insulator than its other historical competitor – air. It is an electronegative gas which, along with other properties, makes it much more suitable for both arc interruption[2] and insulation[3]. Other properties that make SF_6 a prime insulator include: 1) an Ozone Depletion Potential of zero[4]; 2) a broad temperature operating range without the need for heaters or gas mixtures; and 3) a relatively high OSHA Permissible Exposure Limit of 1,000 PPM as a time-weighted average over an eight-hour period[5].

For all of its strengths, recent years have marked the emergence of a trend in market demand (some of which has been stoked by regulatory pressure) for industry to either move away from SF_6 or develop measures to prevent its emission. This has been primarily, if not exclusively, due to SF_6's environmental footprint. With a global warming potential of approximately 23,900 over a 100-year time horizon[6], SF_6 is

---

[1] See definitions for "medium voltage" and "high voltage" in IEEE std. C37.100.1-2018, Section 1.1 SCOPE, NOTE 2
[2] SF_6 is approximately 100 times more effective than air.
[3] The dielectric strength of SF_6 is about 2.5 times higher than air under the same conditions.
[4] See U.S. Environmental Protection Agency, "Ozone-Depleting Substances," https://www.epa.gov/ozone-layer-protection/ozone-depleting-substances
[5] See U.S. Occupational Safety and Health Administration, "OSHA Annotated Table Z-1," https://www.osha.gov/dsg/annotated-pels/tablez-1.html#osha_pel1
[6] See United Nations Framework Convention on Climate Change, "Global Warming Potentials," https://unfccc.int/process/transparency-and-reporting/greenhouse-gas-data/greenhouse-gas-data-unfccc/global-warming-potentials

the most potent greenhouse gas regulated under the Kyoto Protocol. And its long life-time of 3200 years means that levels will likely only increase over time, assuming further emissions.

Why Are There So Many Alternative Insulating Technologies?

Insulating gases are asked to perform a variety of functions, all of which SF_6 has historically performed well. While some alternative insulating gases, many of which are new in development, have proven to be comparable to SF_6 in one or more of these functions, no alternative gas currently compares favorably to SF_6 in ***each*** of these categories. Below are some examples:

- Dielectric Performance: SF_6 is an excellent insulator because it has high dielectric strength that is a result of its high electronegativity and its high density. For example, SF_6 has a dielectric strength that is three times higher than air at 0.1MPa. This property means that electrical contacts within GIE can be much closer to each other when insulated by SF_6, allowing manufacturers to reduce the size of the GIE while keeping the same electrical properties. This is particularly advantageous for urban and underground installations with tight spacing constraints.

- Switching and Short Circuit Performance: SF_6 has excellent arc quenching capabilities allowing it to interrupt high short-circuit current at lower blast pressures. Without good arc-quenching capabilities of the interrupting medium, reignition or restrikes occur between the contacts and interruption fails. SF_6's excellent quenching capabilities are due to its thermal properties, high electronegativity and low ionization temperature. Like SF_6's dielectric qualities, it's arc-quenching performance also allows GIE insulated with the gas to be smaller in size than they might otherwise be.

- Temperature Rise Performance: An insulating gas must also be able to transfer the heat from the conductors to the environment to cool the busbars and other components inside the equipment. The better the heat transfer of the gas, the lower the steady-state temperature of the GIE will be, and the quicker it will cool down during transient events. SF_6 has an excellent heat transfer property due to its high volumetric specific heat. This allows higher current ratings of SF_6 equipment without exceeding the max steady state temperature outlined in applicable standards[7]. SF_6's good temperature rise performance increases equipment longevity.

- Chemical Stability: SF_6 does not react with materials used in switchgear like metals, epoxies, thermoplastics, elastomers, gaskets, greases, etc. This allows GIE designers flexibility in choosing the materials to be used inside the equipment without having to run long term material compatibility testing.

- Recombination: The SF_6 molecule decomposes at higher temperatures that occur during switching and arc quenching. In the presence of an arc, the decomposition of SF_6 produces toxic by-products such as SF_2 and SF_4 that largely recombine to form (nontoxic) SF_6 immediately after arc extinction. This reversible chemical reaction during arc generation and extinction processes allows SF_6 to maintain its excellent level of interruption performance through a high volume of arc events. Other

[7] IEEE C37.100.1-2018 IEEE Standard for Common Requirements for High Voltage Power Switchgear Rated Above 1000V; IEC 62271-2017 "High-voltage switchgear and controlgear—Common specifications for alternating current switchgear and controlgear."

SF_6 decomposition byproducts exist but are minimal. Not every component of certain alternative gas mixtures has the same ability to recombine after switching and arc quenching.

- Reconditioning: In the event a certain volume/quantity of SF_6 becomes contaminated and is no longer fit for use, reconditioning procedures are well established: the gas can be reconditioned on site for immediate use with a gas cart using filtration that removes moisture and reactive decomposition byproducts (and oil if necessary[8]) from the SF_6 gas. In some cases, SF_6 gas must be shipped offsite to remove vapors and other impurities when such are present and reduce gas purity to below 97%[9]. In both cases, the reconditioned gas continues to be an effective dielectric. Research is ongoing for many alternatives to SF_6 to assess their viability for reconditioning.

- Homogeneity: Insulating gases must remain homogenous for long periods of time to retain rated performance. As noted in the chart above, many alternatives to SF_6 require proper mixing of two or more gases. This can be a more complex task for gas handlers and users than simply filling with SF_6. In addition to handling complexities, gas mixture equilibrium may be delayed for a period of time under certain operating parameters.

Summary

In short, the insulating gas market currently accommodates a range of options because, given their respective properties, some alternatives have specific advantages for certain applications while others do not. For example, an alternative gas with high dielectric performance but low chemical stability may be well suited for higher voltage applications with infrequent switching/breaking requirements, but not the other way around.

This is not to say, of course, that any or all SF_6 alternatives are inferior to SF_6. It simply means that the "one-size-fits-all" approach to gas insulation that has historically worked with SF_6 is not appropriate (yet) for alternatives. With that context in mind, insulating gas producers have collectively developed a range of technologies to ensure that alternatives exist that are suitable for a range of applications. These developers continue to innovate and may one day be able to provide SF_6 alternatives for all applications.

About the Coalition

The SF_6 & Alternatives Coalition is comprised of 16 members who are producers and distributors of SF_6 and SF_6 alternatives, manufacturers of gas-insulated equipment (GIE), California utilities using GIE, and other SF_6 stakeholders. Our mission is to: 1) provide a forum for equipment manufacturers using SF6, SF6 producers and distributors, and transmission and distribution equipment owners for discussion of environmental concerns of SF6 as a greenhouse gas; 2) develop best practices and recommendations related to sustainable SF_6 usage in electric power transmission and distribution; 3) advocate the Coalition positions to federal, state, and local policymakers; 4) educate public and private stakeholders on SF_6 alternatives; and 5) maintain liaisons with government and industry groups such as U.S. EPA,IEEE, EEI, IEC, CIGRE, and EPRI.

Please contact Jonathan Stewart for further information at 703-841-3245 or jonathan.stewart@nema.org.

[8] A different type of filtration system is used for oil.
[9] SF6 RECYCLING GUIDE, CIGRE, August 1992

Bibliography

1. Koch, Denis. "SF_6 Properties and use in MW and HV Switchgear." Electrical Engineering Portal. Accessed November 12, 2019. https://electrical-engineering-portal.com/download-center/books-and-guides/schneider-electric/sf6-mv-hv-switchgear

2. "SF_6 Gas or Sulfur Hexafluoride Gas Properties." Electrical 4 U. Accessed November 12, 2019. https://www.electrical4u.com/sulfur-hexafluoride-sf6-gas-properties/

3. Csanyi, Edvard. "Maintenance of SF_6 Gas Circuit Breakers." Electrical Engineering Portal. Accessed November 12, 2019. https://electrical-engineering-portal.com/maintenance-of-sf6-gas-circuit-breakers

Annex I

Examples of Alternative Insulation Technologies

A range of alternative technologies are now on the market in hopes of meeting increasing demand for a more environmentally friendly alternative to SF_6. While not exhaustive, the table below is meant to present some information about known insulating gases and mixtures.

Gas/Mixture	**Voltage[10]**	**GWP**	**Typical/Proposed Minimum Operating Temp (deg C)**	**Typical/Proposed Minimum Operating Gauge Pressure (MPa)**
SF_6	Medium and High	23,500	-30	0.5
			-25	0.6
$SF_6 + N_2$	High	14,100 (SF_6 60%)	-50	0.5
$SF_6 + CF_4$	High	16,752 (SF_6 60%)	-50	0.7
VI+ $N_2 + O_2$	Medium	0	-25	0.1
VI + N2 + O2	High	0	-50 (outdoor)	0.4
			-25(GIS)	0.6
VI + solid	Medium and High	N/A	< -25	Atmospheric
$CO_2 + O_2$	High	< 1	< -30	0.7 – 1.2
$N_2 + O_2 + C_5F_{10}O$	Medium	< 1 (1 for pure $C_5F_{10}O$)	< -25	0.12 - 0.15
	High			0.5 - 1.0
$CO_2 + O_2 + C_5F_{10}O$	High	< 1 (1 for pure $C_5F_{10}O$)	< -15	0.7 - 1.0
$CO_2 + CF_3I$	Medium	< 1 (0.4 for pure CF_3I)	-20	0.1
$CO_2 + 0_2 + C_4F_7N$	High	400	-30 (Outdoor)	0.7
			-25 (GIS)	0.8

[10] Based on primary use application at date of publication