Chapter 18
Eliminating SF_6 from Switchgear

Emily Yedinak, Kathleen Lentijo, and Isik C. Kizilyalli

1 Introduction

Today, the electric grid in the United States is responsible for distributing over 4 trillion kWh per year of electricity from generators to consumers. It forms an integrated network that has become an indispensable asset to the nation's economy, infrastructure, and security. The physical infrastructure of this network depends on a combination of specialized equipment including transformers, power converters, power factor correctors, and switchgear. A critical component for the safety and reliability of the electric grid is a man-made gas, sulfur hexafluoride (SF_6). In 1937, General Electric (GE) introduced SF_6 as an insulation gas to the electric industry; since then, SF_6 has become ubiquitous in medium-voltage (MV) and high-voltage (HV) equipment. Among its many key attributes are its intrinsic nontoxic, noncorrosive, and nonflammable nature, in addition to its superior stability over a wide operating window, good thermal conductivity, high dielectric strength, and excellent arc-quenching capabilities. These properties make it particularly amenable as an insulating and arc-quenching gas in electrical equipment [1]. As a result, over 90% of gas-insulated switchgear globally uses SF_6 as the insulating gas [2]. However, SF_6 emissions from the electric transmission and distribution sector pose a significant climate risk as a potent and long-lived greenhouse gas (GHG) source. One ton of SF_6 emitted to the atmosphere has an equivalent 100-year global warming potential (GWP) of 22,800–26,700 tons of carbon dioxide and has an

E. Yedinak · I. C. Kizilyalli (✉)
Advanced Research Projects Agency – Energy, Washington, DC, USA
e-mail: emily.yedinak@hq.doe.gov; kizilyalli@ieee.org

K. Lentijo
Booz Allen Hamilton, McLean, VA, USA
e-mail: kathleen.lentijo@hq.doe.gov

I. C. Kizilyalli et al. (eds.), *Direct Current Fault Protection*, Power Systems,
https://doi.org/10.1007/978-3-031-26572-3_18

estimated atmospheric lifetime of 3200 years [3]. As a result of its strong radiative forcing and long atmospheric lifetime, SF_6 was designated as one of the six main greenhouse gases in the 1997 Kyoto Protocol.

As countries set increasingly ambitious emission targets in accordance with the Paris Agreement, emissions of all GHGs, particularly from the electric grid, will be scrutinized. Furthermore, regulations being considered in places like California and the European Union (EU) aim to completely phase out SF_6 from electrical equipment, necessarily setting a timeline to develop alternative solutions to SF_6-insulated equipment. Alternative solutions developed today could define the market for decades to come, both in the United States and globally.

Equipment leaks are a major source of SF_6 emissions from the electrical transmission and distribution sector. This fact is particularly true for aging equipment which, due to natural deterioration, is more prone to gas leaks [4]. A study presented at the 2000 International Conference on SF_6 and the Environment suggests that 10% of circuit breakers in the United States leak; of that 10%, 15% were identified as minor leaks and 85% were identified as major leaks or leaks that required operations to schedule repairs [5, 6]. The National Electrical Manufacturers Association (NEMA) estimates leak rates of 0.1% per year, while the International Electrotechnical Commission (IEC) standard 62271-1 (2004) sets the standard for equipment leakage at 0.5% [7]. Across the entire life cycle of the equipment, however, SF_6 emissions may be as high as 15% and potentially underreported by at least a factor of two [8, 9]. In addition to the emissions associated with equipment service life, losses due to poor gas handling practices are to blame. The operation and maintenance of SF_6 gas carts are considered a major source of handling-related losses [4], and some in industry say the eventuality that all created SF_6 will ultimately end up being released into the atmosphere should be considered [10].

Today, significant effort is dedicated toward supplanting fossil fuel-derived electricity generation with wind and solar power, with the concomitant effect of the grid becoming increasingly decentralized. The electrification of transport, heating, and cooling will also require grid expansions [11]. Barring any disruptive technological advances or policy-driven trends, more gas-insulated equipment (GIE) employing SF_6 will be added to the grid, increasing the emission risks and, ironically, potential climate impacts. Between 1994 and 2022, the measured SF_6 in the atmosphere has increased 3.5-fold [12], and as more clean energy is integrated onto the grid, SF_6 emissions from the transmission and distribution (T&D) sector (0.25% of combined emissions from SF_6 and power generation, 0.07% of total GHG emissions from the United States in 2019) will likely continue to rise and constitute a larger proportion of emissions from the electric grid [13] (Fig. 18.1).

In addition, a large portion of the US grid was built in the 1960s and 1970s, implying that the equipment currently in use is approaching or exceeding its useful life span [11]. The aging infrastructure has two important implications. First, older equipment tends to leak more SF_6 or require more volumes of SF_6 which pose a significant climate risk [4]. Second, within the next few decades, much of this equipment will be replaced and will require large investments. Precluding any market-ready alternatives, this equipment will be replaced with new equipment that

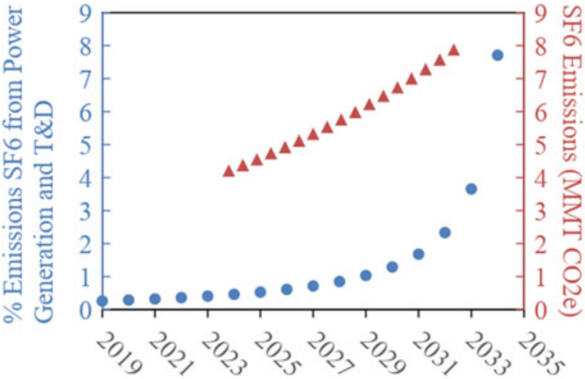

Fig. 18.1 Projected SF_6 emissions as a percentage of the emissions from power generation and T&D and in real terms, expressed as MMT CO_{2e}. Calculations based on emissions from power generation decreasing linearly to zero by 2035 and SF_6 nameplate capacity increasing by 4% per year (consistent with the average historical increase between 1999 and 2013) and SF_6 emission rates of 1.5% consistent with EPA reported values (recent SF_6 emission rates have plateaued since 2015) [14, 15]. Note: SF_6 emission rates may be underreported by a factor of two, as one study suggested, based on atmospheric concentrations [9]

still uses SF_6, potentially locking in this potent greenhouse gas in the grid for the next 20–50 years and increasing the risk of future SF_6 emissions. Because of the environmental challenges associated with using SF_6 in the electric grid, a few states, including California and Massachusetts, are updating their legislation to address SF_6 emission reporting and to set new, more stringent, emission limits. Given the age of the equipment, the investment needed to update and expand the grid, and the stricter policy measures, new technologies and/or alternative gases that minimize or eliminate SF_6 and SF_6 emissions from gas-insulated equipment (GIE) will be required.

2 The Search for SF_6 Substitutes

SF_6 is used extensively as the insulating and arc-quenching medium in MV and HV (12–720 kV) electrical power systems due to its high dielectric strength, nontoxicity, nonflammability, chemical inertness, excellent thermal interruption and heat transfer properties, high vapor pressure at low temperatures, and “self-healing” or fast recovery properties when exposed to an electrical arc. It is an excellent and reliable gas for gas-insulated equipment, were it not for its outsized impact on global warming.

The search for SF_6 alternative gases with a lower environmental impact has been an area of focus for decades [16]. The most critical property for alternative insulating gases is a high dielectric strength, implying that the gas molecules are

Table 18.1 Relative DC uniform field breakdown strengths, V_s^R, of some dielectric gases[a]

Gas	$V_s^{R\ b}$	Comments
SF_6	1	Most common dielectric gas to date besides air
C_3F_8	0.90	Strongly and very strongly electron-attaching gases, especially at low electron energies
n-C_4F_{10}	1.31	
c-C_4F_8	~1.35	
1,3-C_4F_6	~1.50	
c-C_4F_6	~1.70	
2-C_4F_8	~1.75	
2-C_4F_6	~2.3	
c-C_6F_{12}	~2.4	
CHF_3	0.27	Weakly electron-attaching; some (CO, N_2O) are effective in slowing down electrons
CO_2	0.30	
CF_4	0.39	
CO	0.40	
N_2O	0.44	
Air	~0.30	
H_2	0.18	Virtually non-electron-attaching
N_2	0.36	Non-electron-attaching but efficient in slowing down electrons
Ne	0.006	Non-electron-attaching and not efficient in slowing down electrons
Ar	0.07	

[a] See also Table 2 in Christophorou and Datskos [111]

[b] Some values are for quasi-uniform fields and may be somewhat lower than their uniform field values

strongly electronegative. Practically speaking, the dielectric strength of the gas is an indication of its ability to reduce the number of free electrons in an electrically stressed dielectric gas. An appropriate substitute, therefore, must be able to scavenge free electrons with a wide range of energies and over a range of temperatures, have favorable electron slowing down properties which reduce additional electron generation from electron impact ionization, and be characterized by a low ionization cross-section/high ionization onset [17].

If the only concern for an SF_6 alternative was the dielectric strength, several alternatives would have been identified decades ago. As can be seen from Table 18.1, which has been reproduced from a 1997 NIST report, there are several gasses with higher dielectric strengths than SF_6.

However, the many gases with high dielectric strengths were ruled out because they did not meet other performance requirements [17]. In addition to dielectric strength, gas insulators must have a high vapor pressure to ensure they stay in the gas phase, even at low temperatures. They must have high thermal conductivity, high specific heat, and long-term thermal stability (i.e., no significant degradation when exposed to elevated temperatures over long periods of time) which is essential for managing the significant thermal loading during an arcing event. They must also feature high breakdown voltages under uniform and nonuniform electric fields, be robust to factors like surface roughness or moisture content, and be compatible with the materials of construction used for gas-insulated equipment. For safety reasons, gas insulators must be nonflammable and nonexplosive and must have low toxicity to minimize adverse impacts during gas handling or in the event of a gas leak. The chemical compatibility and toxicity levels of the breakdown products after a gas insulator is exposed to an arc must be considered, as these will impact performance and safety over the lifetime of the gas-insulated equipment. These stringent performance and property requirements, on top of environmental considerations like a low GWP and zero ozone depletion potential (ODP), have challenged the search for a suitable gas insulator alternative to SF_6 for decades.

Early candidates considered as possible SF_6 substitutes included carbon dioxide, nitrogen, and mixtures of carbon dioxide and/or nitrogen with SF_6 [17]. A key driver in selecting mixtures based on SF_6 was to find a "universal" drop-in replacement that could be used across all types of gas-insulated equipment with only minor equipment modifications. For some applications, like gas-insulated transmission lines, comparable performance with modest increases in gas pressures relative to pure SF_6 were observed for 50/50 and 40/60 SF_6-N_2 mixtures with the added benefit of slightly lower GWP and lower cost [18–21]. Under some conditions like nonuniform fields or in some interrupter applications, mixtures of SF_6-N_2 were even found to confer superior performance over pure SF_6 due to factors like nitrogen's better insulating properties at high pressures or because nitrogen has complimentary thermal properties at temperatures below 3000 K relative to SF_6 which is better at temperatures higher than 3000 K [22, 23]. However, SF_6 mixtures or pure N_2/CO_2/dry air were found to not be compatible as drop-in replacements for gas-insulated substation circuit breakers and switchgear without a significant thermal derating or redesign [24]. Additional concerns were raised regarding safety issues associated with the rate of pressure rise during an internal failure arc and additional costs associated with gas mixture recycling. It is perhaps because of these and other drawbacks that rollout of these early SF_6 alternatives was limited to MV (12 kV/24 kV) in the case of N_2 and dry air and HV gas circuit breakers up to 72.5 kV for CO_2 [25].

Later research sought to identify alternatives beyond gases like nitrogen and carbon dioxide. One study by Rabie and Franck compared the dielectric strength of SF_6 to 2611 carbonyl compounds as a preselection process to identify potential SF_6 alternatives [26, 27]. They focused their search on groups of hydrofluoro-ketones and hydrofluoro-aldehydes, acyl fluorides, and perfluoro-ketones and perfluoro-aldehydes. Figure 18.2 shows the 2611 molecules grouped into three classes of C_3-, C_4-, and C_5-carbonyl compounds and their predicted dielectric strength (E_r) relative to SF_6 and T_B, the molecules' boiling point. The most promising candidate molecules, due to their relatively high values of E_r and low values of T_B, are captured in the black box. Fluorinated compounds have been of particular interest, in terms of their favorable dielectric strengths, but most had key drawbacks like high GWPs (5000–12,000 for perfluorocarbons) and/or high toxicity (CF_3I) which excluded them from further consideration. Two of the most

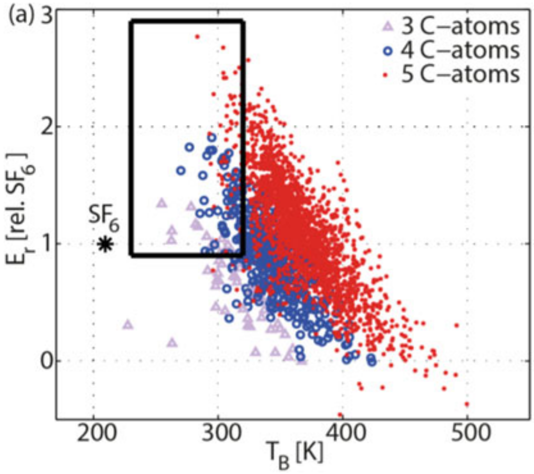

Fig. 18.2 Predicted dielectric strength E_r vs predicted boiling point T_B for 2611 carboxyl compounds. The complete list of molecules is split into carbonyl compounds containing three (triangles), four (circles), and five carbon atoms (dots) [27]

promising fluorinated compounds are a fluoronitrile (C_4F_7N or $(CF_3)_2$-CF-CN) and a fluoroketone ($C_5F_{10}O$ or $CF_3C(O)CF(CF_3)_2$) which have acceptable GWPs and low toxicities [25, 28]. Both are currently marketed under 3 M's Novec™ dielectric gases, Novec™ 4710 and Novec™ 5110, as SF_6 gas alternatives for power utility applications.

Original equipment manufacturers (OEMs) are currently testing mixtures based on the Novec™ dielectric fluids in high-voltage electrical equipment. For example, GE developed green gas for grid (g^3) using CO_2 and O_2 mixed with Novec™ 4710 for gas-insulated substation (GIS) and gas-insulated line (GIL) applications [29]. Testing to assess the performance of g^3 gas in 60 bays of 145 kV gas-insulated substations, over 2000 meters of 420 kV gas-insulated lines, and in 6 AIS 245 kV current transformers has produced promising results. ABB has also developed AirPlus™, which combines dry air with Novec™ 5110, for GIL and GIS applications.

Zhang et al. recently reviewed studies that have modeled and experimentally characterized the arc plasma and decomposition products of the Novec™ gas mixtures [25, 30]. The basic properties of the arc plasma produced from mixtures of C_4F_7N and $C_5F_{10}O$ are critical for understanding arc plasma behavior and evaluating arc-quenching capability. The main takeaway from a comparison of the composition of the arc plasmas calculated assuming local thermodynamic equilibrium conditions (LTE), non-LTE but local chemical equilibrium condition (LCE), and using chemical kinetics models with no equilibrium assumptions reveals a discrepancy at low temperatures. Chemical kinetics are more critical for low-temperature conditions where the impact of energy barriers for each decomposition pathway is expected to dominate; LTE assumptions ignore the influence of energy barriers. Regarding the decomposition products, the recognition that, unlike SF_6, the decomposition by-products of the proposed gas mixture alternatives do not recombine to form the original structure has necessitated studies that characterize the decomposition products under thermal degradation, spark discharges, corona discharges, and arcing. To this end, researchers have conducted experimental studies to characterize the decomposition products directly and developed computational models to understand the chemical kinetics and decomposition mechanisms [29, 31–46]. Erroneous or incongruous results are still prevalent, however, due to the limitations of the chosen methods. The detection methods most often used in experimental studies that characterize the gas composition are Fourier transform infrared spectroscopy (FTIR) and gas chromatography-mass spectroscopy (GC/MS). FTIR enables in-line gas composition analysis but is limited by a relatively high detection threshold. Conversely, GC/MS is excellent for detecting trace gasses but introduces a significant time delay, so the decomposition products are detected when they are no longer under their formation conditions. In the case of computational methods, the accuracy will necessarily depend on the input assumptions which should be documented carefully and provided with adequate rationale.

A few studies from the last decade focus on the materials compatibility of C_4F_7N and $C_5F_{10}O$ and their decomposition products with metals, metal oxides, common elastomers, and lubricating greases. Early computational results indicate, for example, that C_4F_7N may be more compatible with aluminum than copper, while experimental results from Pohlink et al. found no serious compatibility issues among the most common metals used in HV equipment over a period of several months at 120 °C [32]. The most prevalent compatibility issues for both C_4F_7N and $C_5F_{10}O$ were associated with polymers, particularly ethylene propylene diene monomer (EPDM) which is used as a gasket/sealing material. C_4F_7N can also have an effect on the degradation of other common materials found in circuit breakers such as nitrile O-rings and synthetic zeolite molecular sieves used to remove decomposition by-products [47]. In addition to material incompatibilities, the different decomposition pathways of these gases are important in order to design molecular sieves to capture by-products and to preserve the integrity of the dielectric and cooling properties of the gas in the chamber. In summary, research regarding arc plasma behavior, decomposition products, and materials compatibility are still at the early stages for both C_4F_7N and $C_5F_{10}O$ but are critical to understand before moving entirely away from SF_6.

Although potential gas alternatives like those previously mentioned are promising, several challenges exist in accomplishing full replacement of SF_6. Though some of the proposed alternatives can reduce the GWP by over 98% relative to SF_6, a 98% reduction still leaves many alternatives with a GWP >300 [48]. What's more, alternative gas and gas mixtures are not necessarily drop-in solutions for SF_6 under all conditions; some gas mixtures pose a potential performance risk in colder climate zones due to their higher boiling points, while some gas mixtures require modest increases in pressure to achieve equivalent performance to SF_6 [49]. Alternative gases and gas mixtures may require new or modified equipment specially designed to use these gases, new leak detection and monitoring equipment, and new practices to address end-of-life disposal or recycling. Like the work described earlier related to arc plasma characterization and decomposition products, toxicological studies are also at the beginning stages and reflect conflicting results, though some initial results are promising [28]. Finally, there is still a degree of uncertainty around the potential of future regulations which may impact adoption. Even if these points are addressed, market adoption will require overcoming challenges associated with workforce training and spacing constraints, in addition to the need to assess the connection compatibility with existing equipment/infrastructure.

A final comment regarding vacuum dry air or vacuum solid dielectric circuit breakers as another route to SF_6-free electrical equipment will be made, which is the route that OEMs like Siemens and Mitsubishi are currently pursuing [50]. A vacuum is used as the arc-quenching medium and insulator between the contacts as part of a vacuum interrupter (VI) and either dry air or a solid dielectric as the insulator around the VI and in the bushings, eliminating the need for SF_6 or related gases entirely. Several manufacturers already have vacuum technologies for 38 and 72.5 kV, while technologies at 145 kV are expected to become available within the next year. Although these vacuum or near-vacuum technologies have a higher dielectric strength compared to SF_6 circuit breakers, OEMs consider scaling to higher voltages (i.e., 245 kV) a difficult technical challenge.

3 SF_6 Life Cycle Considerations

There are other considerations in the life cycle of the equipment beyond developing alternatives for SF_6-insulated GIE. One of the most effective strategies for mitigating SF_6 emissions in existing equipment is to detect leaks early and to fix these quickly. The International Electrotechnical Commission sets the maximum allowable leakage rate of SF_6 at 0.5% per year [51]. Most new equipment achieves leakage rates far below this limit, but as the equipment (which has a useful lifetime of several decades) ages, the leakage rates may exceed 0.5% per year. To achieve this stringent requirement, it is necessary to continuously monitor for leaks; IEEE Guide for the Selection of Monitoring for Circuit Breakers also recommends monitoring SF_6 density which can fluctuate in response to thermal fluctuations. Several technologies are currently available on the market including portable point source nondispersive infrared (NDIR) detectors, NDIR room sensors which detect ppb and ppm SF_6 concentration levels in enclosed GIE substations, and pressure gauges interfaced with alarm systems that monitor changes in pressure in GIE [52–57]. While these technologies are mature and widely available, further improvements in continuous, sensitive, early-warning detection systems are merited. Developing sensors that combine lower cost, higher sensitivity, and continuous monitoring for all equipment settings could lead to advances in early detection technologies that reduce SF_6 emissions in the short and medium term as the electric grid transitions to non-SF_6 alternatives as well as lead to more accurate accounting of emission rates. Of particular interest are cost-effective detection technologies with remote notification systems or systems sensitive enough to detect slow leaks in small-capacity gas-insulated equipment which pose unique challenges that demand low detection limits and high accuracy under a variety of environmental conditions.

Today's continuous sensors primarily rely on pressure gauges that are not sensitive enough to detect slow leaks or leaks in small-capacity equipment. As a result, even with the technology that is on the market today, several small-capacity GIE owners responded to the proposed policy changes in the California legislation by noting that achieving 1% emission rates on a consistent basis is challenging [58]. One percent emission rate still corresponds to the equivalent of at least 1 megaton of CO_2 released per year in the United States; these emissions could potentially increase fivefold by the year 2035 if SF_6 nameplate capacity continues to increase at an average of 4% per year and the emission rate stay the same.[1] NDIR-based sensors offer higher sensitivity than pressure gauges, but they currently have several drawbacks. NDIR point source sensors are more sensitive and can detect ppm or ppb SF_6 concentrations but are not continuous, are cost-prohibitive, and require a technician to manually check all equipment for leaks. NDIR room sensors can continuously monitor dilute SF_6 concentrations but are still costly and are only applicable for equipment housed in an enclosure. Density and pressure sensors carefully located at optimal locations on the equipment and potentially supplemented with CFD models may enable NDIR-level accuracy at a similar cost and robustness of pressure gauges, thereby leading to more accurate leak rate monitoring [51]. Looking longer-term, cost-effective sensors for proposed gas and gas mixture alternatives will be required because the alternative gases on the market today have a GWP potential that is lower than SF_6 but still significant when compared with other greenhouse gases [59, 60]. Of note, alternatives based on gas mixtures may demand higher accuracy or bespoke sensors to monitor the conditions of the gas-insulated equipment where risks of changes in mixture composition will have major implications on the equipment operation. The gas composition must be always known to ensure the dielectric gas is within a safe operational window.

In addition to leak detection, there are other items to consider when using SF_6 alternatives. The characteristics of SF_6 replacements dictate changes to the mechanical structure of the breaker to accommodate variations in pressure and dielectric withstand. Because of this, several studies have been published regarding the life cycle impact of the manufacture, use, and disposal of the new GIE hardware. For example, hardware changes required for Novec 4710™ mixtures for a 145-kV, 40-kA breaker were found to have minimal impact relative to the equivalent SF_6-based switchgear when accounting for the emissions and waste generation from production of material, manufacturing, distribution, construction, operation and maintenance, and end-of-life destruction [61]. In contrast, while vacuum-based breakers will not have any deleterious emissions during use, compared to a Novec 4710™ -based circuit breaker, researchers in [62] conclude that the need for larger

---

[1] The emissions are estimated by using a 1% emission rate on the reported and projected SF_6 nameplate capacities (see Fig. 18.1). Of note, the EPA does not require SF_6 emission reporting for utility operators with a combined total of 17,820 lbs. SF_6 nameplate capacity, and therefore, the numbers available for nameplate capacity may not be complete.

equipment (a direct result from the vacuum's lower dielectric strength), the GWP, among other negative factors, is higher for vacuum-based breakers at 72.5 kV.

Finally, novel end-of-life processes for SF_6 must be considered as SF_6-insulated equipment is retired and replaced with non-SF_6 alternatives. While SF_6 is available, it poses a significant environmental risk. This represents an opportunity to develop novel SF_6 destruction pathways which are less energy-intensive and do not produce toxic and/or corrosive products [63–65]. Alternative pathways for efficient and complete destruction of SF_6 use strong reducing agents [66–68], low-valent transition metal complexes [69–76], strong nucleophiles [77], monovalent aluminum reagents [78], and catalytically enhanced dielectric barrier discharge processes [79]. A more recent approach has been to use SF_6 as a safe fluorinating agent in organic synthesis, opening new valorization routes for stranded SF_6 supplies when it is no longer needed in electrical equipment [70, 80–86]. For alternative gas and gas mixtures, end-of-life considerations are in their nascent stage.

4 SF_6-Free Circuit Breaker Hardware

Alternative dielectric mediums in HVAC switchgear and near drop-in replacements for SF_6 require changes to the system hardware that can involve significant research, development, design, and testing. While allowing for more significant hardware redesigns offers more options for dielectric mediums, trade-offs in size and life cycle impacts must still be taken into account. Ensuring safety aspects are considered and that the dielectric withstand capability of the circuit breakers can still pass power frequency, lightning impulse, and chopped wave dielectric tests according to IEEE C37-04 or other standards is also critically important when any changes to dielectric medium or hardware are made. Dynamic tests such as those in IEEE C37-04 serve to verify fundamental performance parameters critical for any new design such as how to extinguish the arc quickly and safely and ensure a speedy and full dielectric recovery. For reference, an example of a high-voltage SF_6-based dead tank AC breaker and a corresponding bushing and tank cutaway is shown in Fig. 18.3.

One of the initially more attractive options for SF_6-free switchgear is vacuum-based circuit breakers due to their ease of maintenance and zero GWP [88]. While vacuum interrupters (VI) perform well at lower voltages, at voltages above 72.5 kV, as a result of practical design limitations, there can be diminishing returns for increased gap lengths [89, 90]. As a result, multibreak VI designs are often proposed as a solution though this is still an active area of research and considerations for voltage balancing between the sets of electrodes, such as grading capacitors, must be considered [91]. Other active areas of research for increasing a single VI's interruption capabilities particularly beyond 72.5 kV are similar to those for other mediums such as new contact materials and geometries, improved speed and control of operating mechanisms, new solid insulator material, and improved designs for electric field control [92–95]. For dead tank breakers, an insulating medium must also be used in the tank that contains the VI as well as the bushings. While technical

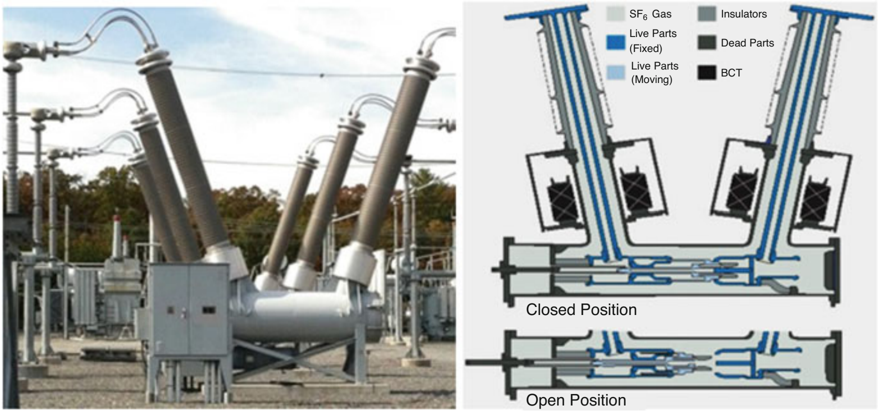

Fig. 18.3 Example of three-phase HVAC dead tank breaker (left) and cutaway drawing of example chamber, bushings, and contacts for a single phase (right) [87]

air is a common choice, VIs with technical air insulators could have weights and footprints 132% higher and 160% larger, respectively, than an SF_6 breaker of similar performance [62, 96]. Recent work has also looked at dielectric mediums primarily for the tank and bushings such as CF_3I-CO_2 to improve the footprint of VI-based breakers with technical air while maintaining lower GWP [97].

In [24], researchers demonstrated how non-vacuum dielectric mediums combined with circuit breaker redesigns can achieve design goals while maintaining a low GWP. Using a 72.5-kV breaker redesigned to use a 0.8-MPa CO_2, the researchers reduced the GWP of the circuit breaker significantly while still meeting the key fault and capacitive switching requirements of IEC 62271-100. The redesign included accounting for the lower heat capacity of 0.8 MPa CO_2 which causes a more rapid pressure rise and fall than SF_6 at similar starting temperatures and pressures. As a result, the CO_2 puffer pressure may not be adequately maintained for long-duration arcs, necessitating a larger puffer cylinder volume. The authors conclude that higher pressures of CO_2 as well as blends with O_2, which has better arc-quenching capability than CO_2, could possibly overcome some of these issues as well as further improve the GWP. Another option for higher-pressure CO_2, as demonstrated in [98], is to use it in its supercritical state. Supercritical carbon dioxide (scCO_2) at around 8 MPa has a dielectric strength of around three times that of SF_6 in addition to high heat transfer capability and low viscosity. scCO_2-based breakers have already been proposed for a compact, low-arcing, medium-voltage breaker [99]; however, scCO_2 breakers have their own challenges as they require the chamber, bushings, and all external seals to manage the 8-MPa pressure and a well-controlled temperature to maintain the CO_2 at supercritical levels. Additionally, during an AC fault, the great amounts of heat energy released from the arc over the course of several milliseconds or partial cycles could cause more overpressure in the switchgear enclosure and bushings, resulting in rupture. While this phenomenon has been studied at lower starting pressures for SF_6, CO_2, and N_2 [100], further analysis on the higher operating pressure effects over time and in operation during arcing faults in $scCO_2$ are needed.

In addition to looking to CO_2 at higher pressures, in [101], researchers demonstrated that N_2, with a combination of higher pressures and/or increased sparking distance, can achieve a dielectric insulation equivalent to SF_6 at 0.7 MPa. In [102], researchers further evaluated gaseous nitrogen at pressures up 2.6 MPa and with various mixtures of SF_6 and showed that, for example, with a working pressure of 1 MPa and only 5% SF_6 and 95% N_2, a similar insulation performance could be achieved to SF_6 at its typical working pressure of 0.7 MPa. As has been discussed, for application to circuit breakers, a suitable dielectric medium is dependent on many other variables besides dielectric strength, such as gas flow characteristics and various thermal properties, that should be considered to definitively evaluate the equivalency of the insulating medium as a replacement for SF_6 in switchgear.

Other work has also looked at nongaseous forms of nitrogen. If future substations have available liquid nitrogen (LN_2), then concepts proposed in [103] such as a 126-kV LN_2-cooled superconducting fault current limiter (SCFCL), which reduces the fault current energy, could enable a smaller, cryogenically cooled vacuum interrupter in series which would have the added benefit of an “on” resistance of less than a third of a traditional AC breaker. Alternatively, since LN_2 can have a higher breakdown voltage than SF_6 at its standard operating pressure, LN_2 has been proposed as the dielectric medium in the interrupter itself where it can both serve to greatly reduce steady-state losses due to reduced resistivity of the cryo-cooled contacts and extinguish the arc. In [104], the arc-extinguishing capability of LN_2 was tested up to nearly 3-kA peak with 50-mm-diameter contacts, opening at 1 m/s to reach a 25-mm gap. The LN_2 was shown to help successfully extinguish the arc at the zero crossing without reignition for root mean square currents of less than 2085 A. The two concepts of SCFCL and dielectric medium are combined in [105] where researchers have also proposed and tested at lower voltages with LN_2 as the dielectric medium in the interrupting mechanism combined with a SCFCL. The results indicate the system is fast-acting and results in lower current and therefore lower-energy faults, though many other items, including the hardware redesign, the logistics of cooling the LN_2, and how to deal with any GN_2 that is generated, must be considered. For those that envision liquid nitrogen and cryo-cooled elements as part of the solution for the future grid, demonstrating the value of fault current limiters and liquid nitrogen in switchgear could play a part but may require rethinking of traditional fault coordination systems.

Another area of research as it relates to SF_6 alternatives is in the materials, speed, and movement of the mechanisms that separate the contacts, determine the movement of the arc, and control gas flow. In [106], researchers demonstrate in a low-voltage circuit breaker the use of permanent magnets to help guide the arc toward a splitter stack that elongates and cools it. However, physical prototypes to prove the efficacy of these approaches on high-voltage equipment are costly, and theoretically evaluating the range of possible solutions also proves challenging. The simulation of such systems are complex due the multi-physics phenomena related to flow, pressure, contaminants, electrical operating points, mechanical structures, the shape and movement of contacts, and dielectric medium management mechanisms. Much research has been done to make the simulation problem more accurate and manageable such as defining the ignition of discharges and their lifetime transitions from corona to streamer or to Townsend avalanches by evaluating the discharge's stability mathematically as an eigenvalue problem [107] or defining an iterative calculation of streamer propagation with a dependence on pressure into an algorithm that helps simplify finite element simulation. A similar effort to simplify simulations in [108] uses computational fluid dynamics and detailed enthalpy flow simulations to determine the discharge coefficients of various geometries of gas valves during the circuit breaker operation that can then be plugged into enthalpy flow models of the full circuit breaker system. The need for high accuracy simulations and the multidisciplinary nature of the problem is apparent even in research related to existing high-voltage switchgear. For example, some 550-kV HVAC SF_6-based breakers must now manage higher short-circuit ratings than ever, such as 80 kA versus a previous maximum of 63 kA, as a result of new grid conditions. This increase in peak fault current is compelling researchers to explore electromagnetic- and mechanical-based solutions that can reduce contact travel time and guide the arc so that it extinguishes more effectively so as to not cause significant changes to equipment size and operation as a result of the increased fault current rating [109, 110].

5 Concluding Remarks

The risks of using SF_6 as the insulating medium on the grid due to its outsized GWP have long been recognized by researchers and regulators. The search for suitable alternatives to SF_6-insulated GIE has spanned decades and only recently has it achieved gains in the form of unique fluorinated gas mixtures, vacuum dielectrics pushing higher voltages, and cryo-insulators. Though early results are promising, there remain many open questions related to the life cycle impacts of new GIE or vacuum-based equipment, the performance of the dielectric medium when exposed to an arc, the safety and monitoring aspects that will be required, and the end-of-life handling practices. With much of the current grid infrastructure approaching end of useful life, the introduction of new renewable energy generation to the grid, and upcoming policy mandates, the need for alternatives to SF_6-insulated GIE has never been greater. Addressing these questions, analyzing the findings from ongoing pilot studies, and anticipating future needs for SF_6 alternative technologies are sure to be a top priority for stakeholders in this space and will be critical for achieving a zero-emission grid.

Acknowledgments The writing of this chapter was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof. Special thanks to Dr. Sade Ruffin for her contributions.

References

1. Y. Wang, D. Huang, J. Liu, Y. Zhang, L. Zeng, Alternative environmentally friendly insulating gases for SF6. Processes **7**(4), 216 (2019). https://doi.org/10.3390/pr7040216
2. Gas-insulated switchgear market worth $26.5 billion by 2025 – Report by MarketsandMarkets™. https://www.marketsandmarkets.com/PressReleases/gas-insulated-switchgear.asp. Accessed 23 June 2022
3. O. US EPA, Inventory of U.S. greenhouse gas emissions and sinks: 1990–2015, Apr. 24, 2016. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2015. Accessed 23 June 2022
4. J. Blackman, M. Averyt, SF6 leak rates from high voltage circuit breakers – U.S. EPA investigates potential greenhouse gas emissions source, p. 4
5. J.D. McCreary, *AEP: A Case Study* (San Diego, 2000)
6. D. Keith, J. Fisher, T. McRae, *Experience with Infrared Leak Detection on FPL Switchgear* (San Diego, 2000)
7. Management on SF6 gas for use in electrical power equipment, in *Ad-Hoc Task Group on SF6, Switchgear Section (8-SG)*, Feb. 1998
8. M. McGrath, Climate change: Electrical industry's 'dirty secret' boosts warming, BBC, Sept. 13, 2019. https://www.bbc.com/news/science-environment-49567197. Accessed 28 June 2022
9. R.F. Weiss, R.G. Prinn, Quantifying greenhouse-gas emissions from atmospheric measurements: A critical reality check for climate legislation. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. **369**(1943), 1925–1942 (2011). https://doi.org/10.1098/rsta.2011.0006
10. Industry Leader, Presented at the DOE ARPA-E grid hardware annual review, Pittsburgh, PA, Nov. 25, 2022
11. Power grid long-term outlook 2021, BloombergNEF, Feb. 2021
12. E. S. R. L. NOAA, NOAA global monitoring laboratory – Sulfur hexafluoride. https://gml.noaa.gov/hats/combined/SF6.html. Accessed 26 Nov 2022
13. Inventory of U.S. Greenhouse gas emissions and sinks 1990–2019, EPA, EPA 430-R-21-005, Apr. 2021. [Online]. Available: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks
14. V. Roshchanka, SF6 gas storage inventories: Strategies for tracking, EPA, May 08, 2019. [Online]. Available: https://www.epa.gov/sites/default/files/2019-07/documents/sf6storageinventories_webinar_050819.pdf
15. SF6 emission reduction partnership for electric power systems, EPA, 2014 annual report, Mar. 2015. [Online]. Available: www.epa.gov/electricpower-sf6
16. L. Niemeyer, A systematic search for insulation gases and their environmental evaluation, in *Gaseous Dielectrics VIII*, ed. by L.G. Christophorou, J.K. Olthoff, (Springer US, Boston, 1998), pp. 459–464. https://doi.org/10.1007/978-1-4615-4899-7_61
17. L.G. Christophorou, J.K. Olthoff, D.S. Green, *Gases for Electrical Insulation and Arc Interruption: Possible Present and Future Alternatives to Pure SF6* (NIST, Gaithersburg, 1997), Technical Note
18. Gases superior to SF6 for insulation and interruption, Electric Power Research Institute, EPRI EL-2620, Sept. 1982
19. D.W. Bouldin, D.R. James, M.O. Pace, L.G. Christophorou, Current assessment of the potential of dielectric gas mixtures for industrial applications, in *4th Intern. Symp. on Gaseous Dielec*, Knoxville, Tennessee, Apr. 1984. Accessed 28 June 2022. [Online]. Available: https://ui.adsabs.harvard.edu/abs/1984gadi.symp.....B
20. D.R. James, M.O. Pace, D.W. Bouldin, L.G. Christophorou, *Current assessment of research on insulating gas mixtures and their potential for industrial applications* (Oak Ridge National Lab., TN (USA), ORNL/TM-9017, 1984). Accessed 28 June 2022. [Online]. Available: https://www.osti.gov/biblio/5282616

21. N.H. Malik, A.H. Qureshi, A review of electrical breakdown in mixtures of SF6 and other gases. IEEE Trans. Electr. Insul. **EI-14**(1), 1–13 (1979). https://doi.org/10.1109/TEI.1979.298198
22. L.G. Chrisophorou, D.R. James, I. Sauers, M.O. Pace, R.Y. Pai, A. Fatheddin, Ternary Gas Dielectrics. New York, 151–165 (1982). Accessed 28 June 2022. [Online]. Available: https://www.osti.gov/biblio/5279201
23. K. Nakanishi, New Gaseous insulation. IEEE Trans. Electr. Insul. **EI-21**(6), 933–937 (1986). https://doi.org/10.1109/TEI.1986.349005
24. T. Uchii, Y. Hoshina, H. Kawano, K. Suzuki, T. Nakamoto, M. Toyoda, Fundamental research on SF6-free gas insulated switchgear adopting CO2 gas and its mixtures. Proc. Int. Symp. EcoTopia Sci. **ISETS07**, 5 (2007)
25. B. Zhang, J. Xiong, L. Chen, X. Li, A.B. Murphy, Fundamental physicochemical properties of SF_6 -alternative gasses: A review of recent progress. J. Phys. Appl. Phys. **53**(17), 173001 (2020). https://doi.org/10.1088/1361-6463/ab6ea1
26. M. Rabie, D.A. Dahl, S.M.A. Donald, M. Reiher, C.M. Franck, Predictors for gases of high electrical strength. IEEE Trans. Dielectr. Electr. Insul. **20**(3), 856–863 (2013). https://doi.org/10.1109/TDEI.2013.6518955
27. M. Rabie, C. Franck, Predicting the electric strength of proposed SF6 replacement gases by means of density functional theory, in *ISH – 18th Int. Symp. High Volt. Eng*, (2013)
28. J. Owens, A. Xiao, J. Bonk, M. DeLorme, A. Zhang, Recent development of two alternative gases to SF6 for high voltage electrical power applications. Energies **14**, 5051 (2021). https://doi.org/10.3390/en14165051
29. Y. Kieffel, A. Ficheux, R. Luescher, E. Laruelle, L. Maksoud, SF6 alternative – What to learn from the high voltage experience. AIM (2019). https://doi.org/10.34890/891
30. L. Chen, X. Li, J. Xiong, A.B. Murphy, M. Fu, R. Zhuo, Chemical kinetics analysis of two C5-perfluorinated ketone (C5 PFK) thermal decomposition products: C_4F_7O and C_3F_4O. J. Phys. Appl. Phys. **51**(43), 435202 (2018). https://doi.org/10.1088/1361-6463/aade62
31. X. Li, H. Zhao, A.B. Murphy, SF6-alternative gases for application in gas-insulated switchgear. J. Phys. Appl. Phys. **51**(15), 153001 (2018). https://doi.org/10.1088/1361-6463/aab314
32. K. Pohlink, F. Meyer, J. Owens, *Characteritics of Fluoronitrile/CO2 Mixture* (Paris, 2016), p. D1-204
33. P. Simaka, C.B. Doiron, S. Scheel, A. Di-Gianni, *Decomposition of Alternative Gaseous Insulation Under Partial Discharge* (Buenos Aires, 2017)
34. B. Zhang et al., Thermal and electrical decomposition products of C5F10O and their compatibility with Cu(111) and Al(111) surfaces. Appl. Surf. Sci. **513**, 145882 (2020). https://doi.org/10.1016/j.apsusc.2020.145882
35. B. Zhang, C. Li, J. Xiong, Z. Zhang, X. Li, Y. Deng, Decomposition characteristics of C4F7N/CO2 mixture under AC discharge breakdown. AIP Adv. **9**(11), 115212 (2019). https://doi.org/10.1063/1.5115588
36. B. Radisavljevic, P.C. Stoller, C.B. Doiron, D. Over, A. Di-Gianni, S. Scheel, *Switching Performance of Alternative Gaseous Mixtures in High-Voltage Circuit Breakers* (Bueno, 2017)
37. J. Mantilla, M. Claessens, M. Kriegel, Environmentally friendly perfluoroketones-based mixture as switching medium in high voltage circuit breakers, in *CIGRE*, (Paris, France, 2016), p. A3-348
38. P.C. Stoller, J. Hengstler, C.B. Doiron, S. Scheel, P. Simaka, P. Muller, Environmental aspects of high voltage gas-insulated switchgear that uses alternatives to SF6 and monitoring and long-term performance of a pilot installation, in *CIGRE*, (Paris, France, 2018), p. D1-202
39. Y.K. Bousoltane Kieffel, L. Maksoud, D. Vigouroux, D. Vancell, P. Teulet, P. Robin-Jouan, Investigation on the influence of the O2 content in fluoronitrile/CO2/O2 (g3) mixtures on the breaking in high voltage circuit breakers, in *22nd International Conference on Gas Discharges and Their Applications*, (Novi Sad, Serbia, 2018)

40. X. Yu, H. Hou, B. Wang, Mechanistic and kinetic investigations on the thermal unimolecular reaction of heptafluoroisobutyronitrile. J. Phys. Chem. A **122**(38), 7704–7715 (2018). https://doi.org/10.1021/acs.jpca.8b07189
41. L. Chen, B. Zhang, J. Xiong, X. Li, A.B. Murphy, Decomposition mechanism and kinetics of iso-C4 perfluoronitrile (C_4F_7N) plasmas. J. Appl. Phys. **126**(16), 163303 (2019). https://doi.org/10.1063/1.5109131
42. S. Xiao, Y. Li, X. Zhang, S. Tian, Z. Deng, J. Tang, Effects of micro-water on decomposition of the environment-friendly insulating medium $C_5F_{10}O$. AIP Adv. **7**(6), 065017 (2017). https://doi.org/10.1063/1.4990512
43. X. Zhang, Y. Li, S. Xiao, S. Tian, Z. Deng, J. Tang, Theoretical study of the decomposition mechanism of environmentally friendly insulating medium C_3F_7CN in the presence of H_2O in a discharge. J. Phys. Appl. Phys. **50**(32), 325201 (2017). https://doi.org/10.1088/1361-6463/aa783a
44. L. Chen, B. Zhang, T. Yang, Y. Deng, X. Li, A.B. Murphy, Thermal decomposition characteristics and kinetic analysis of C4F7N/CO2 gas mixture. J. Phys. Appl. Phys. **53**(5), 055502 (2020). https://doi.org/10.1088/1361-6463/ab56a0
45. Y. Li et al., Decomposition properties of C4F7N/N2 gas mixture: An environmentally friendly gas to replace SF6. Ind. Eng. Chem. Res. **57**(14), 5173–5182 (2018). https://doi.org/10.1021/acs.iecr.8b00010
46. X. Zhang et al., Decomposition mechanism of the C5-PFK/CO2 gas mixture as an alternative gas for SF6. Chem. Eng. J. **336**, 38–46 (2018). https://doi.org/10.1016/j.cej.2017.11.051
47. W. Gao et al., Materials compatibility study of C_4F_7N/CO_2 gas mixture for medium-voltage switchgear. IEEE Trans. Dielectr. Electr. Insul. **29**(1), 270–278 (2022). https://doi.org/10.1109/TDEI.2022.3146460
48. Y. Kieffel, T. Irwin, P. Ponchon, J. Owens, Green gas to replace SF6 in electrical grids. IEEE Power Energy Mag. **14**(2), 32–39 (2016). https://doi.org/10.1109/MPE.2016.2542645
49. H.E. Nechmi, A. Beroual, A. Girodet, P. Vinson, Fluoronitriles/CO2 gas mixture as promising substitute to SF6 for insulation in high voltage applications. IEEE Trans. Dielectr. Electr. Insul. **23**(5), 2587–2593 (2016). https://doi.org/10.1109/TDEI.2016.7736816
50. Siemens energy and Mitsubishi electric to develop high-voltage switching solutions with zero GWP, Energy Industry Review, June 08, 2021. https://energyindustryreview.com/environment/siemens-energy-and-mitsubishi-electric-to-develop-high-voltage-switching-solutions-with-zero-gwp/. Accessed 07 July 2022
51. L. Graber, Improving the accuracy of SF6 leakage detection for high voltage switchgear. IEEE Trans. Dielectr. Electr. Insul. **18**(6), 1835–1846 (2011). https://doi.org/10.1109/TDEI.2011.6118621
52. V. Hermosillo, M. Kelly, M. Broglio, Advances in leak detection in the manufacturing process, May 28, 2014. [Online]. Available: https://www.epa.gov/sites/default/files/2016-02/documents/hermosillo-kelly-broglio-alstom-grid-presentation-2014-wkshp.pdf
53. SF6 Gas Leak Detector (3-033-R501) | DILO Company, Inc. https://dilo.com/sf6-gas/products/measuring-devices/leak-detection-and-monitoring/portable-leak-detector. Accessed 28 June 2022
54. SF6 transmitter high voltage technology. Draeger, 2019. [Online]. Available: https://www.draeger.com/Products/Content/sf6-transmitter-pi-9107808-en-gb.pdf
55. T. Heckler, Mitigating potential SF6 leaks through early leak detection, Atlanta, GA, 2012. [Online]. Available: https://www.epa.gov/sites/default/files/2016-02/documents/conf12_heckler.pdf
56. NDIR Infrared (IR) gas sensor for CO2, methane, SF6, refrigerants, Nano Environmental Technology S.r.l. https://www.nenvitech.com/products/ndir-sensors/. Accessed 28 June 2022
57. Gas detector – GIR-10 – WIKA. https://www.wika.com/en-us/gir_10.WIKA? Accessed 28 June 2022
58. Public hearing to consider the proposed amendments to the regulation for reducing sulfur hexafluoride emissions from gas insulated switchgear. California, 2020. [Online]. Available: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2020/sf6/isor.pdf

59. S. Blázquez, M. Antiñolo, O.J. Nielsen, J. Albaladejo, E. Jiménez, Reaction kinetics of (CF3)2CFCN with OH radicals as a function of temperature (278–358K): A good replacement for greenhouse SF6? Chem. Phys. Lett. **687**, 297–302 (2017). https://doi.org/10.1016/j.cplett.2017.09.039
60. M.P. Sulbaek Andersen, M. Kyte, S.T. Andersen, C.J. Nielsen, O.J. Nielsen, Atmospheric chemistry of (CF3)2CF–C≡N: A replacement compound for the most potent industrial greenhouse gas, SF6. Environ. Sci. Technol. **51**(3), 1321–1329 (2017). https://doi.org/10.1021/acs.est.6b03758
61. D. Gautschi, R. Luescher, Comparative life cycle assessment of an environmentally friendly 145 kV gas insulated substation, p. 11
62. V. Hermosillo, E. Laruelle, L. Darles, C. Gregoire, Y. Kieffel, Environmental performance of dead-tank circuit breakers with SF6 and alternative gases, Aug. 2020
63. R. Kurte, H.M. Heise, D. Klockow, Analysis of spark decomposition products of SF6 using multivariate mid-infrared spectrum evaluation. J. Mol. Struct. **480–481**, 211–217 (1999). https://doi.org/10.1016/S0022-2860(98)00642-5
64. C.-H. Tsai, J.-M. Shao, Formation of fluorine for abating sulfur hexafluoride in an atmospheric-pressure plasma environment. J. Hazard. Mater. **157**(1), 201–206 (2008). https://doi.org/10.1016/j.jhazmat.2008.01.010
65. W.-T. Tsai, The decomposition products of sulfur hexafluoride (SF6): Reviews of environmental and health risk analysis. J. Fluor. Chem. **128**(11), 1345–1352 (2007). https://doi.org/10.1016/j.jfluchem.2007.06.008
66. H.C. Cowen et al., The reaction of sulphur hexafluoride with sodium. J. Chem. Soc., 4168–4188 (1953). https://doi.org/10.1039/JR9530004168
67. G.C. Demitras, A.G. MacDiarmid, The low temperature reaction of sulfur hexafluoride with solutions of sodium. Inorg. Chem. **3**(8), 1198–1199 (1964). https://doi.org/10.1021/ic50018a033
68. H.L. Deubner, F. Kraus, The decomposition products of sulfur hexafluoride (SF6) with metals dissolved in liquid ammonia. Inorganics **5**(4), 68 (2017). https://doi.org/10.3390/inorganics5040068
69. S. Bouvet et al., Controlled decomposition of SF_6 by electrochemical reduction. Beilstein J. Org. Chem. **16**, 2948–2953 (2020). https://doi.org/10.3762/bjoc.16.244
70. C. Berg, T. Braun, M. Ahrens, P. Wittwer, R. Herrmann, Activation of SF6 at platinum complexes: Formation of SF3 derivatives and their application in deoxyfluorination reactions. Angew. Chem. Int. Ed. **56**(15), 4300–4304 (2017). https://doi.org/10.1002/anie.201612417
71. P. Holze, B. Horn, C. Limberg, C. Matlachowski, S. Mebs, The activation of sulfur hexafluoride at highly reduced low-coordinate nickel dinitrogen complexes. Angew. Chem. Int. Ed. **53**(10), 2750–2753 (2014). https://doi.org/10.1002/anie.201308270
72. L. Zámostná, T. Braun, B. Braun, SÀF and SÀC activation of SF6 and SF5 derivatives at rhodium: Conversion of SF6 into H2S. Angew. Chem. Int. Ed. **53**(10), 2745–2749 (2014). https://doi.org/10.1002/anie.201308254
73. B.G. Harvey, A.M. Arif, A. Glöckner, R.D. Ernst, SF6 as a selective and reactive fluorinating agent for low-valent transition metal complexes. Organometallics **26**(11), 2872–2879 (2007). https://doi.org/10.1021/om070175i
74. R. Basta, B.G. Harvey, A.M. Arif, R.D. Ernst, Reactions of SF6 with organotitanium and organozirconium complexes: The 'inert' SF6 as a reactive fluorinating agent. J. Am. Chem. Soc. **127**(34), 11924–11925 (2005). https://doi.org/10.1021/ja052214s
75. M. Wozniak et al., Activation of SF6 at a Xantphos-type rhodium complex. Organometallics **37**(5), 821–828 (2018). https://doi.org/10.1021/acs.organomet.7b00858
76. D. Dirican, N. Pfister, M. Wozniak, T. Braun, Reactivity of binary and ternary sulfur halides towards transition-metal compounds. Chem. Eur. J. **26**(31), 6945–6963 (2020). https://doi.org/10.1002/chem.201904493
77. F. Buß, C. Mück-Lichtenfeld, P. Mehlmann, F. Dielmann, Nucleophilic activation of sulfur hexafluoride: Metal-free, selective degradation by phosphines. Angew. Chem. Int. Ed. **57**(18), 4951–4955 (2018). https://doi.org/10.1002/anie.201713206

78. D.J. Sheldon, M.R. Crimmin, Complete deconstruction of SF $_6$ by an aluminium(I) compound. Chem. Commun. **57**(58), 7096–7099 (2021). https://doi.org/10.1039/D1CC02838C
79. X. Zhang, G. Zhang, Y. Wu, S. Song, Synergistic treatment of SF $_6$ by dielectric barrier discharge/γ-Al_2O_3 catalysis. AIP Adv. **8**(12), 125109 (2018). https://doi.org/10.1063/1.5054729
80. M. Rueping, P. Nikolaienko, Y. Lebedev, A. Adams, Metal-free reduction of the greenhouse gas sulfur hexafluoride, formation of SF5 containing ion pairs and the application in fluorinations. Green Chem. **19**(11), 2571–2575 (2017). https://doi.org/10.1039/C7GC00877E
81. T.A. McTeague, T.F. Jamison, Photoredox activation of SF6 for fluorination. Angew. Chem. Int. Ed. **55**(48), 15072–15075 (2016). https://doi.org/10.1002/anie.201608792
82. D. Rombach, H.-A. Wagenknecht, Photoredox catalytic α-alkoxypentafluorosulfanylation of α-methyl- and α-phenylstyrene using SF6. Angew. Chem. Int. Ed. **59**(1), 300–303 (2020). https://doi.org/10.1002/anie.201910830
83. P. Tomar, T. Braun, E. Kemnitz, Photochemical activation of SF6 by N-heterocyclic carbenes to provide a deoxyfluorinating reagent. Chem. Commun. **54**(70), 9753–9756 (2018). https://doi.org/10.1039/C8CC05494K
84. P. Tomar, T. Braun, E. Kemnitz, Preparation of NHC stabilized Al(III)fluorides: Fluorination of [(SIMes)AlMe3] with SF4 or Me3SnF. Eur. J. Inorg. Chem. **2019**(44), 4735–4739 (2019). https://doi.org/10.1002/ejic.201900921
85. S. Kim, Y. Khomutnyk, A. Bannykh, P. Nagorny, Synthesis of glycosyl fluorides by photochemical fluorination with sulfur(VI) hexafluoride. Org. Lett. **23**(1), 190–194 (2021). https://doi.org/10.1021/acs.orglett.0c03915
86. D. Rombach, H.-A. Wagenknecht, Photoredox catalytic activation of sulfur hexafluoride for pentafluorosulfanylation of α-methyl- and α-phenyl styrene. ChemCatChem **10**(14), 2955–2961 (2018). https://doi.org/10.1002/cctc.201800501
87. H. Wilson, D. Dufournet, H. Mercure, R. Yeckley, History of circuit breakers, in *Switching Equipment*, ed. by H. Ito, (Springer International Publishing, Cham, 2019), pp. 157–198. https://doi.org/10.1007/978-3-319-72538-3_5
88. L.T. Falkingham, The strengths and weaknesses of vacuum circuit breaker technology, in *2011 1st International Conference on Electric Power Equipment – Switching Technology*, (Xi'an, China, Oct. 2011), pp. 701–703. https://doi.org/10.1109/ICEPE-ST.2011.6122975
89. M. Godbole, A.M. Jain, Double break vacuum circuit breaker — A brief overview, in *2016 10th International Conference on Intelligent Systems and Control (ISCO)*, (Coimbatore, India, Jan. 2016), pp. 1–4. https://doi.org/10.1109/ISCO.2016.7727112
90. H.C. Miller, Surface flashover of insulators. IEEE Trans. Electr. Insul. **24**(5), 765–786 (1989). https://doi.org/10.1109/14.42158
91. D. Huang, W. Gaobo, J. Ruan, Study on static and dynamic voltage distribution characteristics and voltage sharing design of a 126-kV modular triple-break vacuum circuit breaker. IEEE Trans. Plasma Sci. **43**(8), 2694–2702 (2015). https://doi.org/10.1109/TPS.2015.2449075
92. G. Ge et al., Experimental investigation into the synergy of vacuum circuit breaker with double-break. IEEE Trans. Plasma Sci. **44**(1), 79–84 (2016). https://doi.org/10.1109/TPS.2015.2502241
93. H. Kojima, T. Takahashi, N. Hayakawa, K. Hasegawa, H. Saito, M. Sakaki, Dependence of spark conditioning on breakdown charge and electrode material under a non-uniform electric field in vacuum. IEEE Trans. Dielectr. Electr. Insul. **23**(5), 3224–3230 (2016). https://doi.org/10.1109/TDEI.2016.7736889
94. C.-H. Lee, B.H. Shin, Y.-B. Bang, Designing a permanent-magnetic actuator for vacuum circuit breakers using the Taguchi method and dynamic characteristic analysis. IEEE Trans. Ind. Electron. **63**(3), 1655–1664 (2016). https://doi.org/10.1109/TIE.2015.2494006
95. B. Zhang et al., A relationship between minimum arcing interrupting capability and opening velocity of vacuum interrupters in short-circuit current interruption. IEEE Trans. Power Delivery **33**(6), 2822–2828 (2018). https://doi.org/10.1109/TPWRD.2018.2838344
96. ABB, *Circuit Breaker Basics* (Orlando, 2019)

97. P. Widger, A. Haddad, H. Griffiths, Breakdown performance of vacuum circuit breakers using alternative CF_3I-CO_2 insulation gas mixture. IEEE Trans. Dielectr. Electr. Insul. **23**(1), 14–21 (2016). https://doi.org/10.1109/TDEI.2015.005254
98. J. Wei, A. Cruz, A. West, F. Haque, C. Park, L. Graber, Theoretical modeling and experimental testing on the electrical breakdown in supercritical fluids, in *2021 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, (Vancouver, BC, Canada, Dec. 2021), pp. 179–182. https://doi.org/10.1109/CEIDP50766.2021.9705453
99. C. Xu, J. Wei, L. Graber, Compatibility analysis of piezoelectric actuators in supercritical carbon dioxide, in *2020 IEEE Electrical Insulation Conference (EIC)*, (Knoxville, TN, USA, June 2020), pp. 171–174. https://doi.org/10.1109/EIC47619.2020.9158670
100. M. Li, P. Gong, H. Yang, P. Guo, Investigation on the pressure rise and energy balance due to fault arcs in a closed container filled with different insulating gases. IEEE Trans. Plasma Sci. **47**(12), 5226–5233 (2019). https://doi.org/10.1109/TPS.2019.2950331
101. A. Hopf, M. Rossner, F. Berger, U. Prucker, Dielectric strength of alternative insulation gases at high pressure in the homogeneous electric field, in *2015 IEEE Electrical Insulation Conference (EIC)*, (Seattle, WA, USA, Aug. 2015), pp. 131–136. https://doi.org/10.1109/ICACACT.2014.7223575
102. A. Hopf, M. Rossner, F. Berger, U. Prucker, Dielectric strength of alternative insulation gases at high pressure in the inhomogeneous electric field, in *2015 IEEE Electrical Insulation Conference (EIC)*, (Seattle, WA, USA, Aug. 2015), pp. 369–374. https://doi.org/10.1109/ICACACT.2014.7223618
103. J. Wang, Y. Tan, L. Zhang, Y. Geng, Z. Liu, S. Wang, Conceptual design of a liquid-nitrogen-insulated metal-enclosed switchgear. IEEE Trans. Appl. Supercond. **26**(7), 1 (2016). https://doi.org/10.1109/TASC.2016.2587480
104. B. Xiang et al., AC current interruption by liquid nitrogen in a superconducting fault current limiting switchgear, in *2020 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD)*, (Tianjin, China, Oct. 2020), pp. 1–2. https://doi.org/10.1109/ASEMD49065.2020.9276340
105. M. Junaid, B. Xiang, J. Wang, Z. Liu, Y. Geng, Experimental test of superconductor fault-current switchgear using liquid nitrogen as the insulation and arc-quenching medium. IEEE Trans. Appl. Supercond. **29**(5), 1 (2019). https://doi.org/10.1109/TASC.2019.2898523
106. H. Hofmann, C. Weindl, M.I. Al-Amayreh, O. Nilsson, Arc movement inside an AC/DC circuit breaker working with a novel method of arc guiding: Part I—Experiments, examination, and analysis. IEEE Trans. Plasma Sci. **40**(8), 2028–2034 (2012). https://doi.org/10.1109/TPS.2012.2200697
107. M.S. Benilov, P.G.C. Almeida, N.G.C. Ferreira, R.M.S. Almeida, G.V. Naidis, A practical guide to modeling low-current quasi-stationary gas discharges: Eigenvalue, stationary, and time-dependent solvers. J. Appl. Phys. **130**(12), 121101 (2021). https://doi.org/10.1063/5.0057856
108. A. Smajkic, B.B. Hadzovic, M. Muratovic, M.H. Kim, M. Kapetanovic, Determination of discharge coefficients for valves of high voltage circuit breakers. IEEE Trans. Power Delivery **35**(3), 1278–1284 (2020). https://doi.org/10.1109/TPWRD.2019.2939746
109. H. Zhang, Z. Wang, M. Li, Y. Yao, J. Li, J. Zhao, Simulation analysis of the breaking process of 550kV 80kA SF6 circuit breaker, in *2022 4th Asia Energy and Electrical Engineering Symposium (AEEES)*, (Chengdu, China, Mar. 2022), pp. 1–5. https://doi.org/10.1109/AEEES54426.2022.9759699
110. S. Tan, H. Zhang, M. Li, X. Duan, Z. Wang, B. Zhang, Simulation research on breaking performance of 550 kV 80 kA SF_6 circuit breaker under different opening characteristics, in *2021 11th International Conference on Power and Energy Systems (ICPES)*, (Shanghai, China, Dec. 2021), pp. 47–51. https://doi.org/10.1109/ICPES53652.2021.9683917
111. L.G. Christophorou, P.G. Datskos, Effect of temperature on the formation and autodestruction of parent anions. Int. J. Mass Spectrom. Ion Processes **149**(150), 59–77 (1995)