Analysis of Alternative Insulating Gases to Replace SF_6 in Electric Power Equipment

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Abstract

SF_6 gas is an excellent electrical insulator that has been widely used in the power industry for decades, but its status as a powerful greenhouse gas has led to increasing pressure to find an alternative. The objective of this paper is to compare the properties of two novel replacement insulators, Novec 4710 and Novec 5110, and show that Novec 5110 is marginally superior in warm climates. The analysis will be performed using three criteria: electrical properties, assessed through dielectric strength and using boiling point to determine suitable operating temperatures, toxicity, evaluating mainly the median lethal dose and operational exposure limit, and environmental impact, established through the gas' global warming potential. The analysis will show that for climates where the temperature does not fall below 0, Novec 5110 is the ideal choice because it results in a 99.996% reduction in warming potential and is the safest substance to handle. It is therefore recommended that Novec 5110 be adopted for insulating purposes in warm climates, while Novec 4710 is an excellent second choice with better insulating potential and a lower environmental impact relative to SF_6 that is more suitable for colder regions.

Introduction

Electrical insulation plays a vital role in ensuring the proper functioning of electric power equipment. Although there is an abundance of solid, liquid, and gaseous insulating materials to choose from today, an industry favorite has emerged over the last few decades in the form of sulfur hexafluoride (SF_6) gas. Widely used in circuit breakers, transformers, and switchgear, SF_6 earned its place thanks to its excellent electrical performance, chemical inertia, and low toxicity. It is particularly popular for installations in densely populated areas, as equipment using gas insulation is more compact [1]. All these qualities make it an ideal product to meet the rising energy demands of an increasingly urbanized global population.

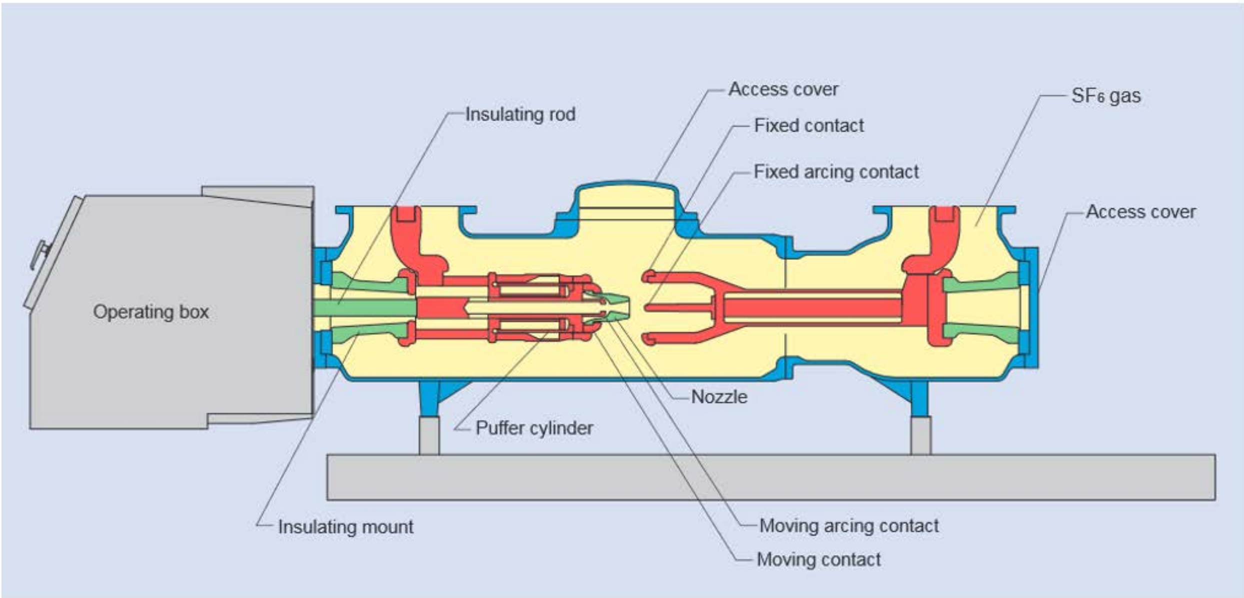
Unfortunately, SF_6 suffers from a major drawback: it is the most potent greenhouse gas ever to be identified by the UN Intergovernmental Panel on Climate Change (IPCC) [1]. As the threat of climate change becomes more serious with each passing year, the electric power industry is facing mounting pressure to introduce a greener alternative to SF_6 to meet the growing demand for insulation materials. Despite ongoing research, finding a replacement gas that has the same balance of chemical and electrical properties as SF_6 and a lower environmental impact has proven difficult. Among several recently proposed solutions, the gases C_4F_7N and $C_5F_{10}O$, better known by their trade names Novec 4710 and Novec 5110 respectively, have shown the most promise, with Novec 5110 being a marginally superior choice under certain temperatures. Using SF_6 as the current standard, this paper will compare the performance of both potential substitutes by analyzing their electrical insulating properties. Subsequently, the safety and toxicity of both propositions will be examined, and their environmental impact will be assessed primarily in terms of their global warming potential (GWP).

Background

The use of SF_6 as an insulation material in the electric power industry first became widespread in the 1950's; companies began gradually shifting away from air-based insulation towards gaseous insulation, which enabled more compact and reliable switchgear design [1]. Consequently, the power industry has been the largest consumer of the gas since the 1970's, now accounting for approximately 80% of total demand [1]. Concerns over its use did not arise until 1992, when the UN first classified it as a greenhouse gas. To this day, SF_6 remains the most powerful greenhouse gas ever evaluated, being 23,500 times more potent than CO_2 over a 100-year period [1], [2].

While SF_6 remains contained throughout its useful life as an insulator, emissions still occur due to unintended leakage [1]. As Figures 1 and 2 illustrate, the gas is meant to be entirely encased in the electrical equipment so it can fill the space between two components when a switch opens and interrupt the flow of current. Small gas amounts escape gradually during operation,

Figure 1: Example of an SF_6 gas-insulated circuit breaker [3].



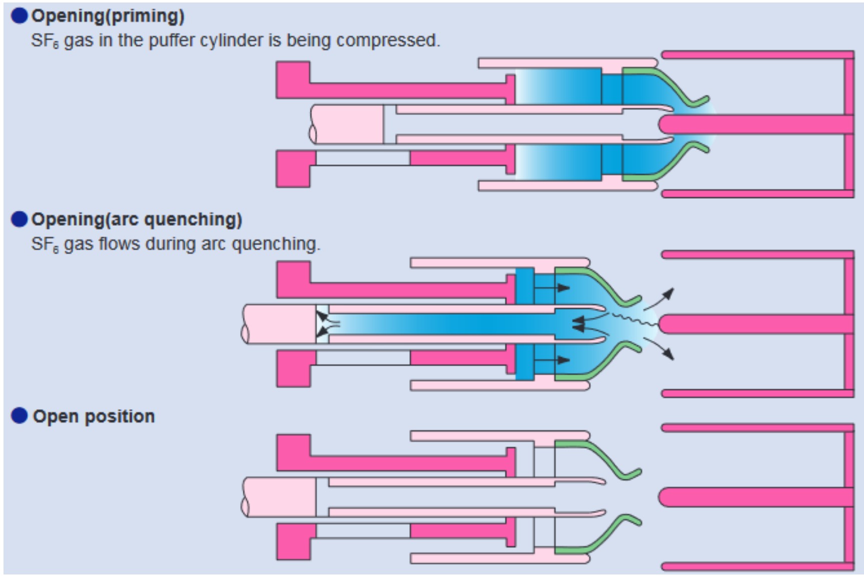


Figure 2: Operation of an SF_6 gas-insulated circuit breaker [3].

but leaks may also occur during installation, maintenance, or disposal. In countries with well-established gas collection infrastructure, much of the SF_6 could be reclaimed when the equipment reaches the end of its life. However, many countries like China have a rapidly expanding grid with almost no recovery measures in place, potentially leading to the release of the full quantity of sealed gas in the future [1]. The desire to avoid this kind of proliferation has contributed to the industry's push for a greener solution.

The two novel replacement gases identified, Novec 4710 and Novec 5110, will be examined relative to SF_6 using three criteria. The first and most important factor to consider will be their electrical insulating properties. These gases need to be able to withstand extremely high voltages without breaking down and allowing current to flow. This is known as their dielectric strength, and it should be as close to that of SF_6 as possible or higher. The gases must also be safe enough to handle without having harmful health effects. Their toxicity will therefore be assessed through their median lethal dose (LC_{50}), which is the concentration of the gas that would kill 50% of a group of subjects. For a more practical idea of toxicity, the 8-hour workday operational exposure limit (OEL) concentration as well as potential breakdown substances will also be investigated. Finally, the environmental footprint of both proposals will be presented in terms of their effect on atmospheric ozone as well as their global warming potential (GWP). Simply put, this quantity indicates how much more CO_2 would have to be released to result in the same amount of warming as the substance in question over a 100-year period; if SF_6 has a GWP of 23,500, then it would take 23,500 tons of CO_2 to warm the earth as much as 1 ton of SF_6.

Analysis

In order to have a clear picture of how well an SF_6 replacement should perform, the gas itself will first be evaluated. SF_6 has a dielectric strength of 14.0 kV at a pressure of 1 bar measured across a gap 2.5 mm wide, as well as a sublimation point of -63.9°C [4]. Since it sublimes at such low temperatures, the gas can be used in its pure form even in extremely cold climates. The advantage of this is that its dielectric strength is not diluted by the addition of a more conductive gas such as N_2 or CO_2. It is also non-flammable and chemically inert, so it will not combust during electrical discharges and will not corrode the equipment encasing it [5].

In terms of toxicity, SF_6 has a LC_{50} in excess of 100,000 ppm by volume [6]. According to the Canadian Centre for Occupational Health and Safety (CCOHS), a LC_{50} of this magnitude would be given the lowest toxicity rating of “relatively harmless” [7]. Similarly, the Environmental Protection Agency assigns a high OEL of 1000 ppm to the gas. Although SF_6 itself is quite safe, the same cannot be said of its breakdown by-products. Following an electrical discharge, the insulator may decompose into several substances, the most dangerous being the highly toxic and corrosive HF and $S_2O_2F_{10}$ [8]. These gases are usually only present in very small quantities however, because SF_6 recombines almost entirely after a discharge [5]. This has the added benefit of preserving the gas’ purity and consequently, its insulation properties.

SF_6' greatest shortcoming lies in its environmental impact. While it has no effect on atmospheric ozone, its GWP of 23,500 is higher than any other greenhouse gas, and it has an atmospheric lifetime of 850 years [1]. By 2100, the IPCC projects that in the worst-case scenario, leakage of SF_6 could cause a 0.03°C global temperature increase [1]. In the collective effort to keep temperatures from rising more than 2°C to avoid the most catastrophic impacts of climate change, this represents 1.5% of that target: a small yet nevertheless significant amount.

Using SF_6 as a basis for comparison, the two substitute gases will now be assessed, beginning with Novec 4710. The major advantage associated with this gas is its insulating potential; it has a dielectric strength of 27.5 kV under 1 bar pressure across a 2.5 mm gap, almost double that of SF_6. However, its relatively high boiling point of -4.7°C means that it cannot be used in pure form to operate equipment in sub-zero temperatures, as it will turn into a liquid under these conditions [4]. To circumvent this problem, Novec 4710 can be mixed with CO_2 to lower its boiling point, but doing so also dilutes its dielectric strength. As figure 3 shows, mixtures of 6% mol Novec 4710 with CO_2 are safe to use at temperatures as low as -25°C, but the resulting dielectric strength would drop to around 80% that of SF_6. With 10% mol Novec 4710, the dielectric strength rises to almost 90% that of SF_6, but this mixture would only be suitable for temperatures above -10°C [9]. Other factors such as pressure can also be changed in conjunction with the ratio of Novec 4710 to CO_2 to lower the boiling point and maintain an adequate insulating strength [4]. For most high-voltage applications, a modest overpressure of the mixture would be enough to replicate SF_6 performance in colder conditions, while in warmer climates the performance is expected to be superior [5].

In terms of toxicity, pure Novec 4710 has a LC_{50} between 10,000 and 20,000 ppm by volume [1]. The CCOHS would therefore label it as "practically non-toxic", one degree of toxicity

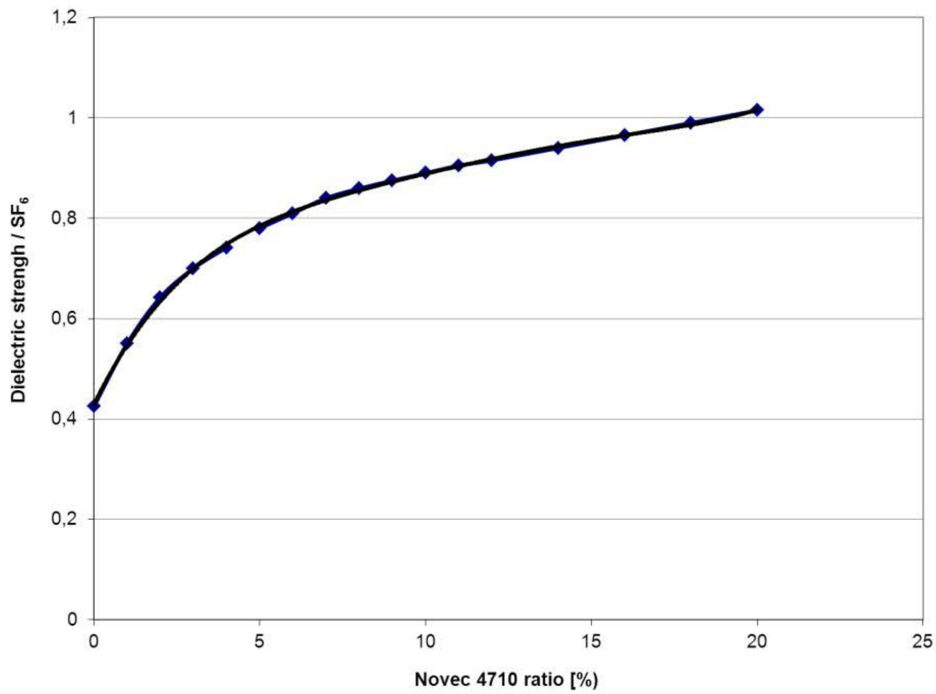


Figure 3: Dielectric strength relative to SF_6 of Novec 4710 in CO_2 mixture for varying concentrations of Novec 4710 [9].

above SF_6 [7]. Similarly, it has an OEL of 65 ppm by volume, which also makes it approximately one order of magnitude more toxic than SF_6 [4]. However, since Novec 4710 must be mixed with CO_2 to attain a lower boiling point, the overall toxicity of the mixture is reduced. A solution of 10% mol Novec 4710 has a LC_{50} closer to 100,000 ppm, the same as pure SF_6 [9]. Following electrical discharge, the gas decomposes mainly into CO, but traces of HF and the extremely poisonous HCN were also detected after repeated breakdowns [10]. As a result, special care must be taken when handling the mixture after many discharges, but otherwise it is no more toxic than SF_6.

With regards to its climate impact, Novec 4710 offers a substantial improvement. Just like SF_6, it has no effect on atmospheric ozone, and its GWP is 1490 [1], [9]. Although this is high in absolute terms, it pales in comparison to SF_6' GWP of 23,500. Furthermore, when used in a 10%

mol mixture with CO_2, the GWP drops even further to 690, resulting in a 97.1% overall reduction in warming potential [9]. One case study conducted on the EU-28 high voltage grid determined that replacing SF_6 with Novec 4710 as an insulating material beginning in 2020 would result in a median cumulative emission cut of 14 Mt CO_2 equivalent by 2070 [11]. Even with such a large emission savings potential, the GWP of this gas is still significantly higher than many well-known problematic greenhouse gases like methane, whose GWP is only 28 in comparison [2].

The second alternative, Novec 5110, has perhaps shown the most potential for replacing SF_6, despite the fact that its electrical properties are inferior to Novec 4710. $C_5F_{10}O$ has a dielectric strength of 18.4 kV under 1 bar pressure across a 2.5 mm gap: more conductive than C_4F_7N, but less than SF_6. It is also plagued by a boiling point of 26.9°C, significantly higher than that of Novec 4710, which eliminates any possibility of using the pure form of the gas in most climates [4]. Nevertheless, it still performs well when used in a mixture with CO_2 or air; 7-14% mol Novec 5110 in air is suitable for insulating medium-voltage equipment up to -25°C, while a 6% mol mixture has been found to perform adequately for high-voltage applications in temperatures above 5°C [1]. For high-voltage equipment in colder regions, the gas is outperformed by Novec 4710 in CO_2 mixtures, which can more closely replicate the behaviour of SF_6 in such conditions. The performance of Novec 5110 can be improved, however, by sealing the gas in at higher pressure. Figure 4 demonstrates that at a given temperature, a 2.5% mol Novec 5110 in air mixture has 71% the dielectric strength of SF_6 at 3 bar pressure. If the mixture's pressure is increased to 5.2 bar though, the two solutions become equal in insulating capacity [4].

The toxicological assessment of Novec 5110 is very similar to that of Novec 4710. It has a LC_{50} of 20,000 ppm by volume, equivalent to the uppermost estimate of the LC_{50} of Novec 4710

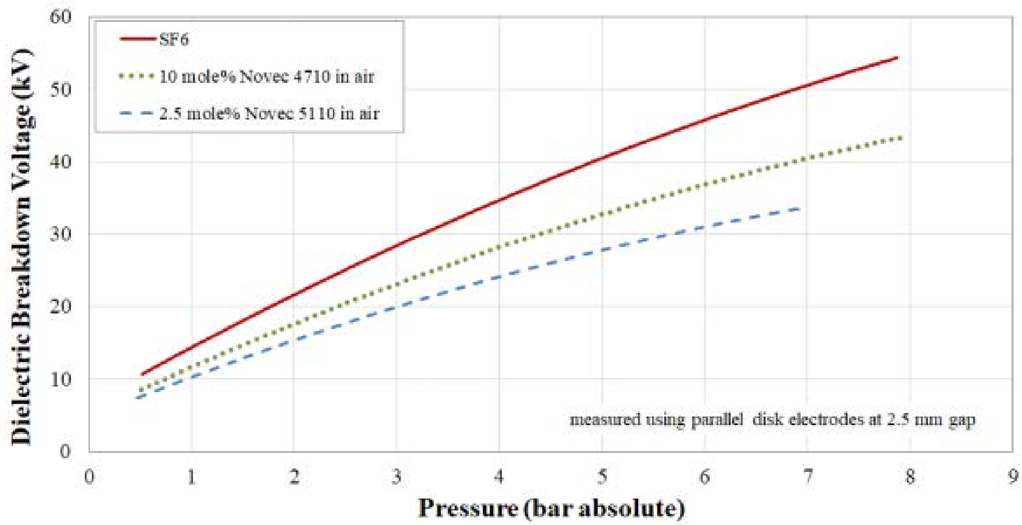


Figure 4: Effect of increasing pressure on the dielectric strength of Novec 4710 and Novec 5110 [4].

[1]. This means that it falls in the same category of toxicity according to the CCOHS, though it is marginally less dangerous because it has a higher OEL of 225 ppm by volume [4]. As with Novec 4710, its toxicity is reduced by an order of magnitude when it is mixed with air or CO_2 so that it effectively falls under the "relatively harmless" CCOHS category in practice. The most significant difference comes from the decomposition gases of Novec 5110. After undergoing electrical discharge, the insulator decomposes primarily into CO and CF_3, neither of which are particularly toxic in the amounts they are formed [12]. The lack of poisonous or corrosive by-products like HF or HCN make Novec 5110 slightly safer to handle than SF_6 or Novec 4710.

In contrast with both SF_6 and Novec 4710, the environmental impacts of Novec 5110 are its most appealing quality. In addition to having no effect on atmospheric ozone levels just like the other two gases, the GWP of Novec 5110 is less than 1 [1], [4]. Its warming potential is therefore 99.86% lower than that of Novec 4710, and substituting it for SF_6 would result in 99.996% less potent greenhouse gas emissions. In the study of the EU-28 high-voltage grid, it was found that replacing SF_6 with Novec 5110 instead of Novec 4710 would yield approximately the same median cumulative emissions reduction, but the probability density function for cumulative savings was shifted slightly to the right for Novec 5110 [11]. The implications of this are that there is a marginally greater probability of achieving higher reductions using this gas than by using Novec 4710.

Conclusion

Table 1: Summary of the key characteristics of the two proposed alternatives.

	Novec 4710	**Novec 5110**
Dielectric strength at 1 bar pressure across 2.5 mm gap	27.5 kV	18.4 kV
Boiling Point	-4.7°C	26.9°C
LC_{50}	10,000-20,000 ppm	20,000 ppm
8-hour workday OEL	65 ppm	225 ppm
GWP in mixture	690 (10% mol in CO_2 mixture)	<1 (CO_2 mixture)

Table 1 lays out the main properties of each of the 2 insulating alternatives examined. Based on the criteria laid out, the optimal replacement for SF_6 would be Novec 5110 gas mixtures because of its slightly better environmental impact and the lower toxicity of the by-products it forms after a discharge. However, Novec 5110 is only suitable for use in high-voltage applications in relatively warm climates; more research is needed to find the ideal concentration and pressure balance for it to work well in cold climates. In the interim, Novec 4710 is an excellent choice for operating equipment in sub-zero temperatures, as it performs almost as well as SF_6 while drastically reducing the impact of greenhouse gas emissions.

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