EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology 2023, 24(3), 60–70
https://doi.org/10.12912/27197050/159630
ISSN 2719-7050, License CC-BY 4.0

Received: 2022.12.16
Accepted: 2023.01.27
Published: 2023.02.25

Comparison Between Different Gases Used as Insulation Medium in High Voltage Technology and their Effect on the Environment

Rami S. Rzouq[1*], Mohammad K. Alrashdan[2], Elias Y. Suleiman[3], Joud M. Elmanaseer[4], Roa'a S. Abu Karsh[5]

[1] Department of Electrical Engineering, Al-Balqa Applied University, Salt, Jordan
* Corresponding author's e-mail: drrami.rzouq@bau.edu.jo

ABSTRACT
Since the 1960s, SF_6 gas has been a common gas insulation medium used in gas-insulated switchgear (GIS). As an insulating gas, Sulphur hexafluoride (SF_6) has a high insulation ability and is suited for a variety of climatic situations. However, the use of Sulphur hexafluoride (SF_6) gas as an insulating medium in power system components is restricted by its high global warming potential (GWP). Since SF_6 is one of the most potent greenhouse gases and is chemically stable, an alternative is required to reduce environmental risks. (GHGs) that cause significant global warming. In this regard, R12, R134, Novec 4710, and Novec 5110 gases seem to be better alternatives for SF_6 gas. Keeping in mind the performance, safety, and environmental aspects of four alternative-gas SF_6 components in electrical power applications, these are reviewed in this study, along with updates.

Keywords: SF_6 alternative gases, dielectric strength, global warming, Novec gases, Gaseous insulation.

INTRODUCTION

Sulfur hexafluoride (SF_6) gas has strong dielectric strength and the ability to quench arcs. SF_6 has an octahedral geometry, consisting of six fluorine atoms attached to a central sulphur atom. SF_6 gas is stable at normal temperatures and does not react with its surroundings. Due to its useful qualities, SF_6 gas has been utilized as an insulating medium in high-voltage applications for a long time. which is non-toxic, colorless, odorless, has good chemical stability, is non-flammable, has a breakdown strength that is over three times greater than air's, is thermally stable at temperatures below 500 °C, and has low boiling point. The use of SF_6 in electric power equipment, specifically GIS, gas-insulated transmission lines (GIL), and breakers, is fraught with problems due to its high global warming potential (GWP) and high liquification temperatures. SF_6 has a high atmospheric lifetime and a GWP of 22800 over 100 years, both of which have an adverse effect on the environment [Rajneesh, 2012; Rahmat et al., 2017]. Since SF_6 has a high liquification temperature, mainly frigid climates such as Siberia, western Canada, and China may use it. Therefore, the introduction of an eco-friendly alternative for SF_6 as a high-voltage application that uses an insulating medium is urgently needed. Since the 1970s, when it became clear that mixed gas has a higher dielectric strength than pure gas, research and development on finding an alternative to SF_6 have been underway. Since the 1990s, there have been trends in the emission of SF_6 from electrical equipment. The electric equipment sector in China accounted for over 70% of SF_6 emissions [Rahmat et al., 2018]. The purpose of this research is to find a gas-insulating medium that is an alternative to SF_6 and has the following properties: (a) dielectric strength; (b) nontoxicity; (c) nonflammability; (d) chemical stability; and (e) economic feasibility. Accordingly, R12, R134, Novec 5110, and Novec 4710 will all be thoroughly evaluated. These characteristics are shared by all of these gases. At a given pressure, Novec 4710 gas has a relative dielectric strength that is two times greater than SF_6.When compared to SF_6, R134 gas's GWP is determined to be 5.5%; Novec 5110 mixes with air by 95% and has a low density compared to the rest of the gases at 10.67, which is good for high altitudes; g^3 gas significantly reduces environmental worries about global warming and the atmosphere's lifetime; and R12's self-recovery is good [3M™, 2022; 3M™, 2017; Ang Xiao et al., 2017; Shafqat et al., 2018]

DEVELOPMENT OF NEW ALTERNATIVE TO SF_6

In earlier decades, many alternatives, including common gases like R12, R134, Novec 5110, and Novec 4710, were investigated as SF_6 replacements. The benefits and limitations of each of these gases are discussed.

R12 and R134

R12"Dichlorodifluoromethane" with the chemical formula (CCl_2F_2), and R134 "Tetrafluoroethane" with the chemical formula (CH_2FCF_3), are inert gases that have a long history of acting as refrigerants. Additionally, because they are an electronegative gas, breaking them down demands a lot of ionization energy. These two gases can be used as insulation in electrical components like switch gears because of their high electron affinities. They also contribute to global warming, albeit less significantly than SF_6.

Novec 5110 and Novec 4710

"Fluoroketone "with the chemical formula $C_2F_5C(O)CF(CF_3)_2$, and Novec 4710 "fluoronitrile" with the chemical formula $(CF_3)_2$ CFCN, are sustainable substitutes to SF6 for arc quenching and insulation applications, resulting in significant environmental impact reductions in gas-insulated equipment. When used as intended for the intended applications, they are a cutting-edge insulation medium with high electrical insulation performance, are non-flammable, offer a large safety margin for workers, have a GWP much lower than SF_6, and have strong dielectric properties.

BREAKDOWN VOLTAGE TESTING

A mixture of R12 & R134 with air

R134 and R12 are electronegative gases, which means the produced electrons attach to neutral molecules to produce negative ions. The production of positive ions occurs when electrons get attached to the molecule. Electron attachment and dissociation are dependent on the applied field. The detachment coefficient is provided by equation (1).

$$dN = N * (\alpha - \eta)dx \tag{1}$$

where: dx – the distance,
N – the initial number of electrons,
dN – the change in that number,
η – for the detachment coefficient.

Using equation (1), When α > η, there is exponential expansion, which causes gas to break down. The primary factor affecting the dielectric strength is the gap distance between the electrodes. According to the equation, increasing the electrode gap distance raises the breakdown voltage (2). There is a requirement for maximum potential for balancing the electric field between

Table 1. SF_6 compared to other gas properties

Object at 1 bar, 25 °C	Sulphur hexafluoride	4710 Novec	5110 Novec	R12	R134
Molecular formula	SF_6	(CF3)2CFCN	(CF3)2CFC(O)CF3	CCl_2F_2	CF3CH2F
Molecular weigh (g/mole)	146	195	266	120.94	102.03
Boiling point (°C)	-63.9a	-5	27	-29.8	-26.3
Vapor pressure (kPa)	2372	297	94	94.9	661.9
Freezing point (°C)	-50.8	-118	-110	-157.7	-103.3
Gas density (kg/m^3)	5.9	7.9	10.7	1.33	4.25
Breakdown voltage (kV), parallel electrodes, 2.5 mm gap	14.0	27.5	18.4b	Greater than SF_6 by 0.9	Greater than SF_6 by 0.85
Price/kg	(28-30)$	Can't be found	Can't be found	17$	10$

Note: [a] sublimation point, [b] at saturation.

electrodes in the case of increased distance between electrodes.

$$E = \frac{V}{D} \quad (2)$$

It is clear that increasing the R134 in the air by 50% significantly improves its breakdown strength, but adding more R134 does not have the same impact. This is due to R134's strong attachment properties at energies between 0–0.5 eV. This increased the breakdown strength by allowing a small amount of R134 gas to connect to practically all low-energy electrons. We may observe that as the mixtures' R12 content is raised, the breakdown voltage rises. Because R12 is a strong electronegative gas and air is less so, adding another strong electronegative gas to the combination will boost the breakdown strength. As you can see in Figures 1 and 2, adding 80% of R134 to air produces a good performance, while 80% R12 with 20% air produces the best result when compared to 80% R134 with 20% air [Rahmat et al., 2017; Shafqat et al., 2018].

A mixture of R12 & R134 with N2

A low level of R134 and R12 can significantly increase nitrogen's dielectric strength, according to an experimental examination of the aforementioned mixture. R134/N2 (80/20%) provides the greatest dielectric strength depending on testing setup and conditions [Rahmat et al., 2017] at 50 lb/in^2, which is 0.85 times that of SF_6, and

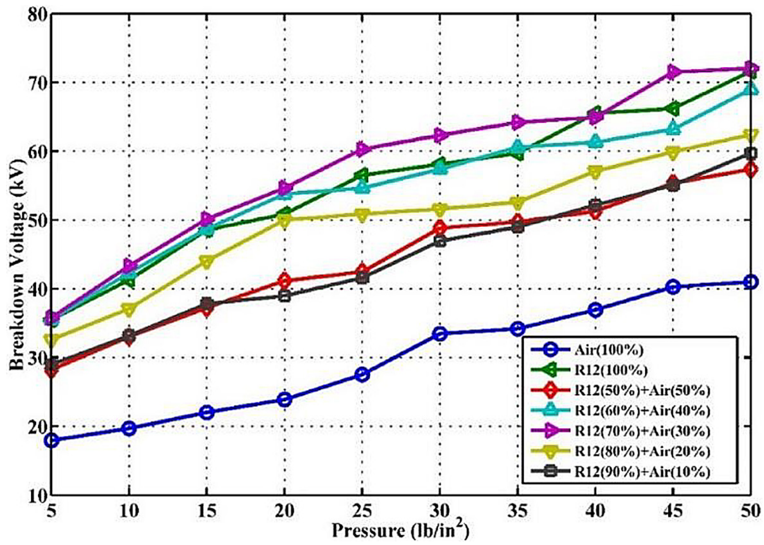

Fig. 1. AC breakdown characteristics of R12 and air and electrode gap is 6mm

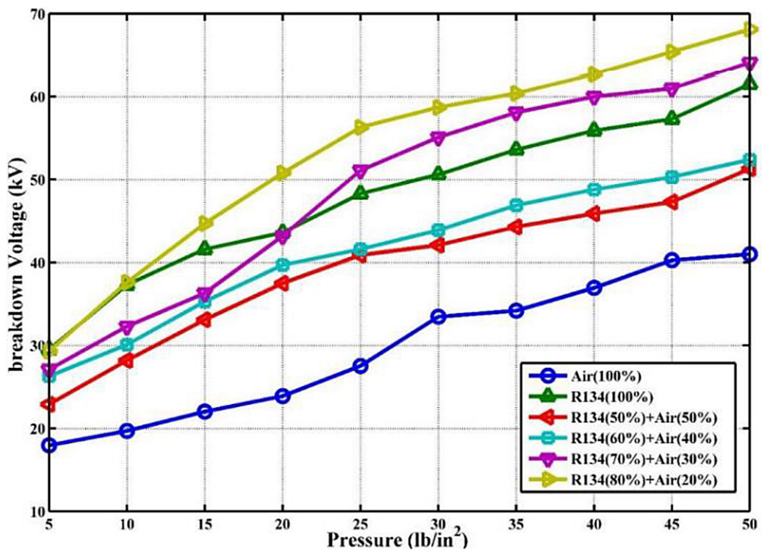

Fig. 2. AC breakdown characteristics of R134 and air with 6mm gap distance

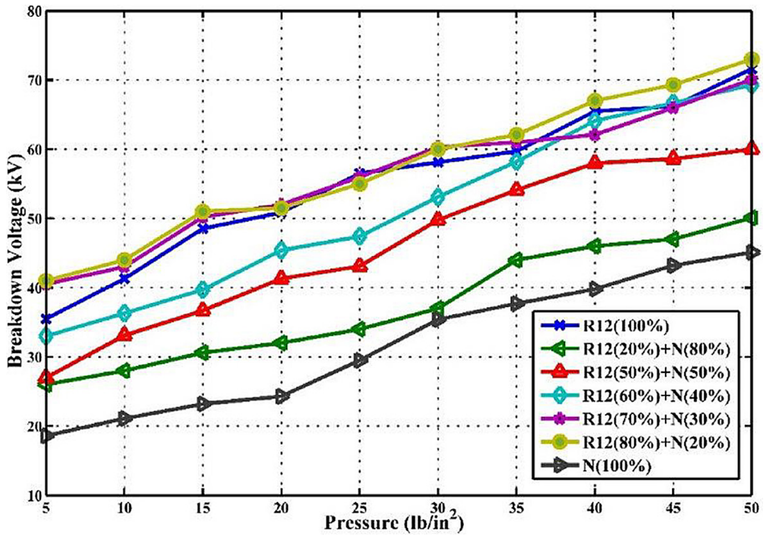

Fig. 3. Breakdown characteristics of R12 and Nitrogen gas and electrode gap is 6 mm

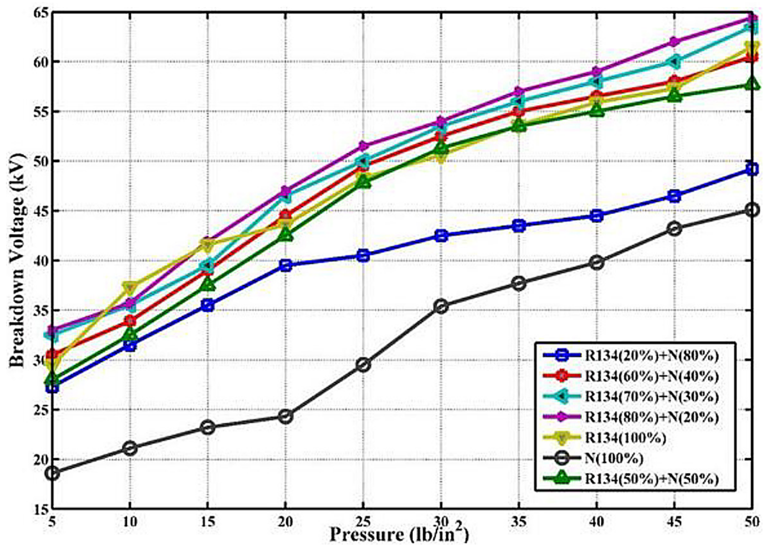

Fig. 4. Breakdown characteristics of R134, Nitrogen gas, keeping the 6mm electrode gap

the ideal ratio may be obtained using R12/N2 (80/20%), as shown in Figures 3, 4.

And comparing the dielectric strengths of the two gases in their pure forms, when R134 and R12 are compared to SF_6 in AC, R134 has a dielectric strength 0.85 times that of SF_6 and R12 has a dielectric strength 0.90 times that of SF_6, as shown in Figures 5, 6.

Pure Novec 5110 and Novec 4710

Numerous physical characteristics of SF6 are shared by the Novec insulating gases as well. They are non-flammable, highly fluorinated gases that have outstanding dielectric properties, great densities, and very low freezing temperatures. The dielectric breakdown voltages of the pure Novec gases are higher than SF6 at any given pressure (Fig. 7) [John et al., 2021].

Mixture of 5 mole% Novec 4710 in CO_2 and 5 mole% Novec 5110 in air

A gas mixture's total pressure, Novec gas concentration, and dielectric breakdown voltage all affect the mixture's breakdown voltage. By raising the overall gas pressure employed in the system, it is feasible to make up for the reduced dielectric strength of a diluted gas combination. In actuality, producers of gas-insulated equipment frequently use such a tactic. On the grid, there are many systems using Novec gas mixtures in operation, including GIS, GCB, and GIL installations. The performance of these systems

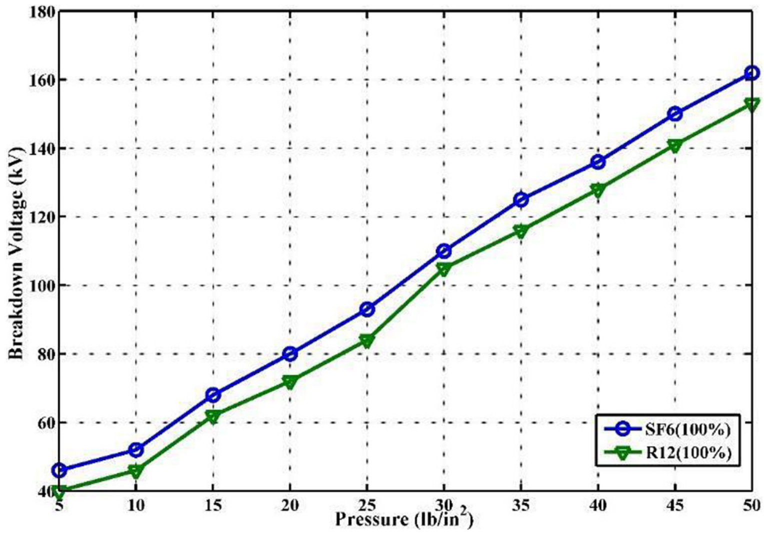

Fig. 5. Breakdown characteristics of SF6 and R12 and electrode gap is 10 mm

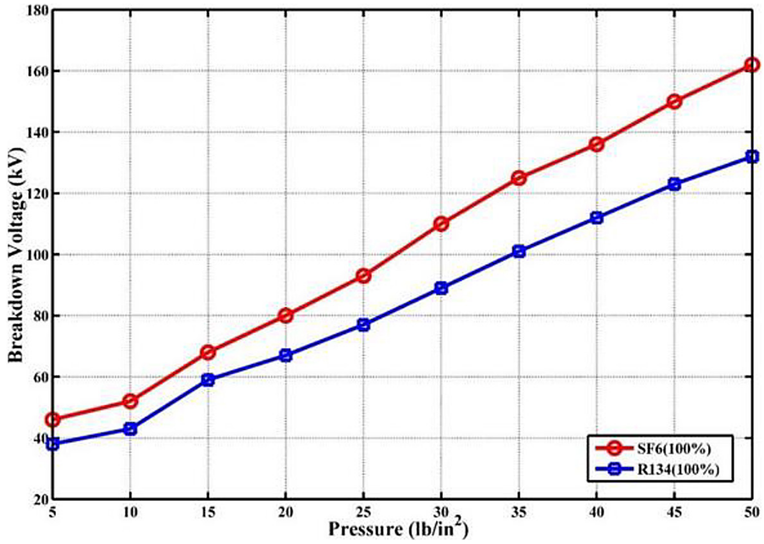

Fig. 6. Breakdown characteristics of SF6 and R134 and electrode gap is 10m

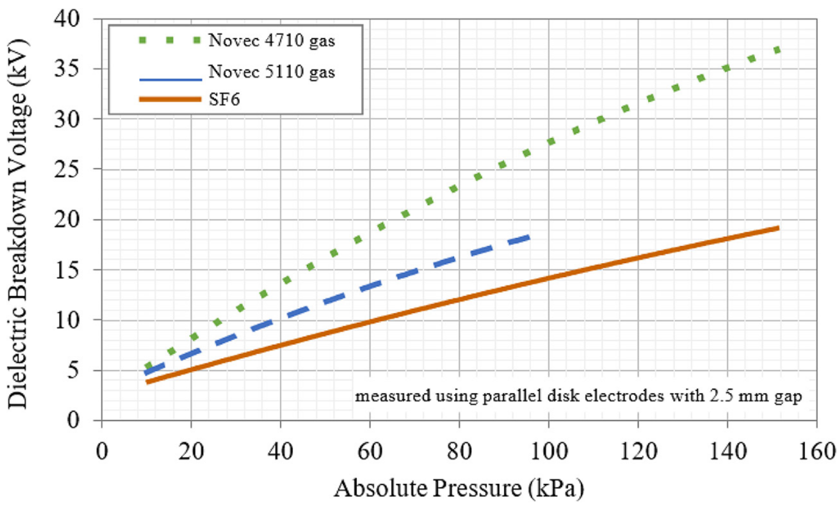

Fig. 7. Dielectric breakdown voltage of pure gases

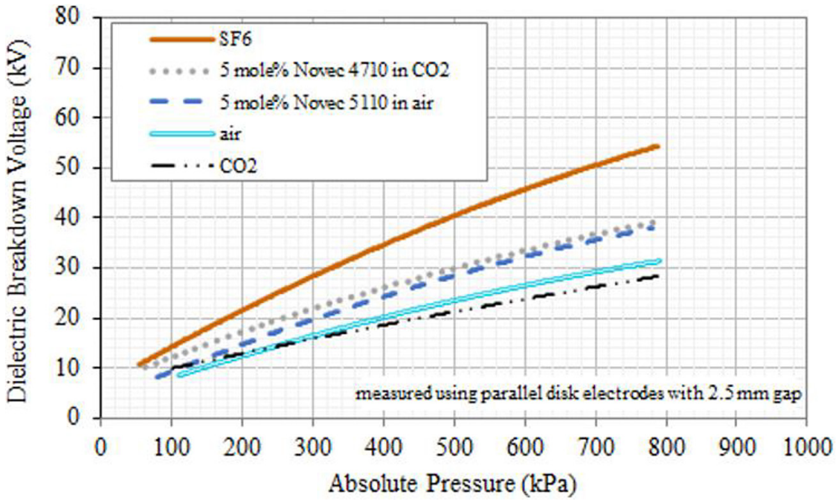

Fig. 8. Compared to pure SF6 gas, the dielectric breakdown voltage of gas mixtures

is intended to be comparable to that of similarly rated SF_6 equipment (Fig. 8) [3M™, 2022; Ang Xiao et al., 2020].

GENERAL SAFETY MEASURES FOR GASES

Any SF_6 replacement technology's ability to be used safely in gas-filled equipment is a crucial component. Employees may handle insulating gases when the system is being decommissioned, when it is being filled for the first time, when it needs to be maintained, or when it leaks naturally. Because of this, we must be concerned with safety issues and look for substitute gases that have less of an impact on dangerous substance cases than SF_6. When compared to pure SF6, the four gases' lower global harmonized dielectric breakdown voltages indicate lower acute toxicity hazards. SF_6 is a basic asphyxiant that is hazardous to humans. When SF_6 is exposed to high stress conditions, the potential for the development of extremely hazardous breakdown products exists; specifically, electrical discharges occurring in gas-insulated equipment may encourage the formation of highly reactive species of toxicological concern. The degradation products can be toxic and result in atelectasis, lung symptoms, nausea, and vomiting. It might contain other sulphate fluorides that are hazardous and irritating to the respiratory system, like sulphate pentafluoride and disulfur decay fluoride. The in vitro human lymphocyte chromosomal aberration assay revealed no genotoxic effects. Due to the substance's chemical inertness and extremely limited potential for accumulation, there is little cause for concern over its toxicity. Table 2 gives an overview of the most important findings for all gases.

R12

Overexposure might make you feel lightheaded and make it difficult to concentrate. At larger doses, exposure may cause heart arrhythmia and CNS depression. In small areas, vapors can asphyxiate people by displacing the air. At higher temperatures (more than 250 °C), decomposition products may include hydrochloric acid (HCI), hydrofluoric acid (HF), and carbonyl halides. A defatting action on tissue would cause skin irritation. Frostbite could result from liquid contact. Mist could aggravate Even at 5% doses, the inhalation of R-12 has negligible acute toxicity in animals (50,000 ppm). However, when oxygen levels in the air are reduced by displacement to 12–14%, asphyxiation symptoms, loss of coordination, a rise in heart rate, and deeper breathing occur. [Yalong et al., 2021]

R134

Breathing in large amounts of R134 vapor carries dangers to one's health, including the potential for acute central nervous system depression, narcosis, lethargy, and anesthetic effects. Continuous inhalation of high R134 vapor anesthetic concentrations can result in heart abnormalities, unconsciousness, and even death. Inhalation of R134 vapor in modest doses does not harm the respiratory system. Chemical risks When exposed to high temperatures, R134 vapors breakdown, forming poisonous and unpleasant substances like hydrofluoric acid, carbon monoxide, and carbonyl fluoride. [AFROX,2017]

Novec 5110 & Novec 4710

In repeat-dose inhalation toxicity studies, both Novec gases displayed a low hazard profile; however, irritant-associated effects were observed in tissues surrounding the portal of entry (mouth and nose), as well as in the respiratory and gastrointestinal tracts, at the highest exposure concentrations. Additionally, both gases have shown no genotoxic potential, with Novec 5110 gas showing no mutagenic potential in an in vitro genotoxicity assay, while Novec 4710 gas was shown to be non-mutagenic in both in vitro and in vivo assays. Even though Novec 5110 gas hasn't been tested in an in vivo study yet, in vivo testing on its closest homologue, an equivalent fluoroketone with a chain length one carbon longer, has demonstrated that it isn't carcinogenic. According to the weight of the evidence, the two Novec insulating gases should not be considered CMR risks based on all available information (carcinogenicity, mutagenicity, and reproductive toxicity). However, the only drawback shown by these two gases is that irritant-associated effects were observed in tissues surrounding the portal of entry (mouth and nose) [John et al., 2021]

ENVIRONMENTAL EFFECT

Three factors affect the environment, namely: global warming potential (GWP), atmospheric lifespan, and ozone depletion potential (ODP). The GWP is measured in terms of the amount of CO_2 that absorbs heat from the atmosphere. Since SF_6 has a high GWP and high environmental effects, it is not suitable for use as an insulation medium. According to equation (3), the GWP is determined by integrating the radiative forcing caused by the release of 1 kilogram of that compound in comparison to the warming caused by 1 kilogram of CO_2 during the same time period. Additionally, the ozone layer's thinning is brought on by the greenhouse gas ODP. Table 3 demonstrates this. [Ang Xiao et al., 2017; Rahmat et al., 2017; John et al., 2021; Mohamed et al., 2018].

$$GWP_i = \frac{\int_0^{ITH} R_i C_{i0} exp(-t/\tau_i) dt}{\int_0^{ITH} R_{CO_2} C_{CO_2}(t) dt} \quad (3)$$

SELF-RECOVERABILITY

The "self-recoverability of insulation" occurs if the insulation is not damaged when a breakdown happens as a result of increased temperature and overvoltage. In an AC power frequency breakdown test, twenty shots of breakdown are visible being applied to the gas insulation every minute, which results in a 10–12 shot decrease in the breakdown voltage of R134. However, the breakdown voltage drastically decreases after the 12th shot as a result of the electrode developing a carbon deposit. Because carbon is a good conductor of electricity, the presence of carbon deposits causes the insulator to fail. This limitation prevents R134 from being used in high-voltage applications. self-recoverability of R12, applying breakdown voltage per minute, shows a very small decrease in breakdown voltage. Carbon dioxide, hydrogen fluoride, hydrogen chloride, and carbon monoxide are the byproducts produced by the breakdown of R12. In order to bridge the insulation, a small quantity of carbon is generated

Table 2. Important toxicological effects of other insulating gases

R12	R134	Novec 4710 Gas	Novec 5110 Gas
LC50 : Cardiac Sensitization threshold (dog): 50,000 ppm; Inhalation 4 hours (rat): > 760,000 ppm EC50 in 10 minutes: 254,000 ppm	1000 ppm for Acute Toxicity (TWA 8+12 hr)	Low acute inhalation toxicity (4-h LC50 > 10,000 < 15,000 ppmv)	Low acute inhalation toxicity (4-h LC50 > 148,213 mg/L)
Male rats exposed to inhalant exposure over their lifetime had a slight rise in fibrosarcomas of the salivary gland.	Small amounts of R134a vapour inhaled do not harm the respiratory system.	Low toxicity with repeated inhalations (based upon 28-day study)	Low toxicity with repeated inhalations (based upon 28-day study)
There are no substances in the contents of this product that the State of California is aware of that cause cancer, birth defects, or any other type of reproductive harm.	Reproductive Hazards – no known effect	Negative for reproductive and developmental toxicity	Based on reading across from the next closest homologue, it is anticipated to be safe for use during pregnancy and during development.

Table 3. Environmental properties of alternative gases compared with SF_6

GAS	GWP	ODP	Atmosphere lifetime (years)
SF_6	22800	0	3200
R134	1300	0	14
R12	2400	0	12
Novec 5110	<1	0	15 days
Novec 4710	2240	0	30

on the electrode. R12 has this disadvantage when employed in high-voltage applications; however, there is a way to get around it by preventing carbonization. As illustrated in figures (9,10). While no studies have been tested or applied for the self-recoverability of any of the Novec gases [Rahmat et al., 2017].

LIQUEFACTION TEMPERATURE

Liquification of R134 and R12

Its liquification point must be taken into account when choosing an alternative gas insulation for SF_6 gas. Due to a drop in pressure brought on by a reduction in temperature, the gas loses some of its insulating strength. According to Eq. 4, R134 has a higher boiling point (BP) than SF_6 (-63 °C), but adding N2 will lower R134's overall BP, eliminating its disadvantage of having a high liquefaction point. The same is true for R12, as illustrated in figures (11,12,13). This implies that raising the base gas ratio will raise the liquefaction temperature.

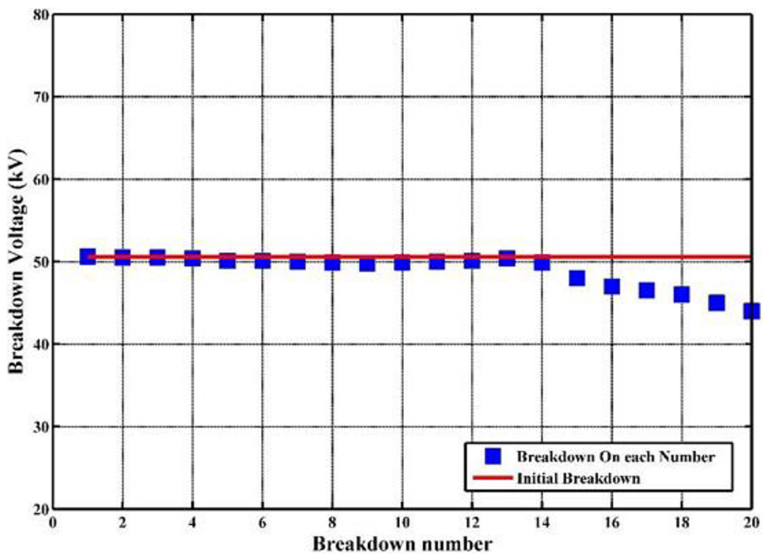

Fig. 9. Insulation self-recoverability of R134 gas

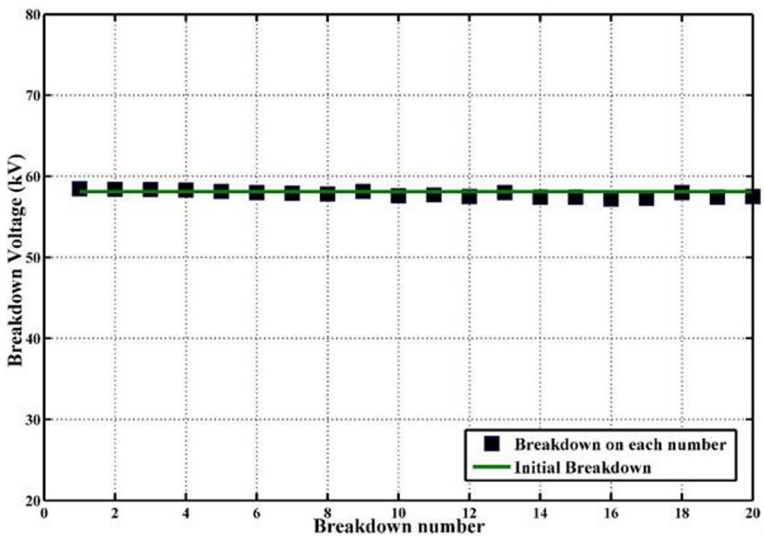

Fig. 10. Insulation self-recoverability of R12

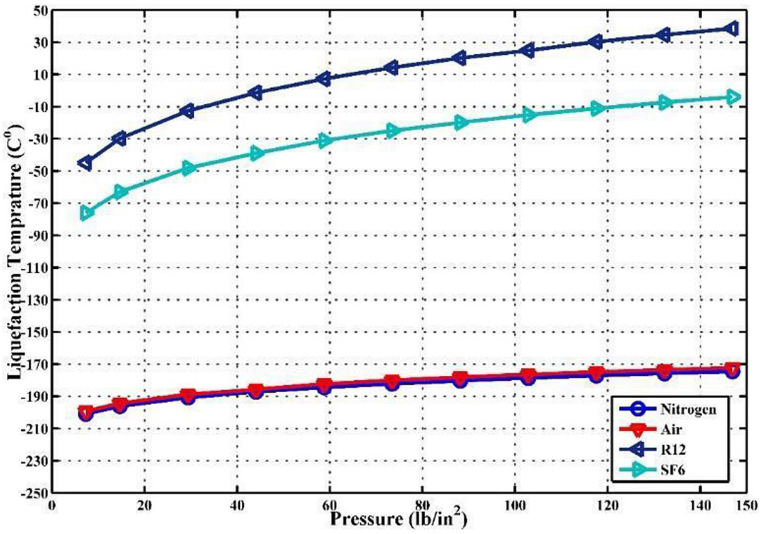

Fig. 11. Liquification temperature of pure gases

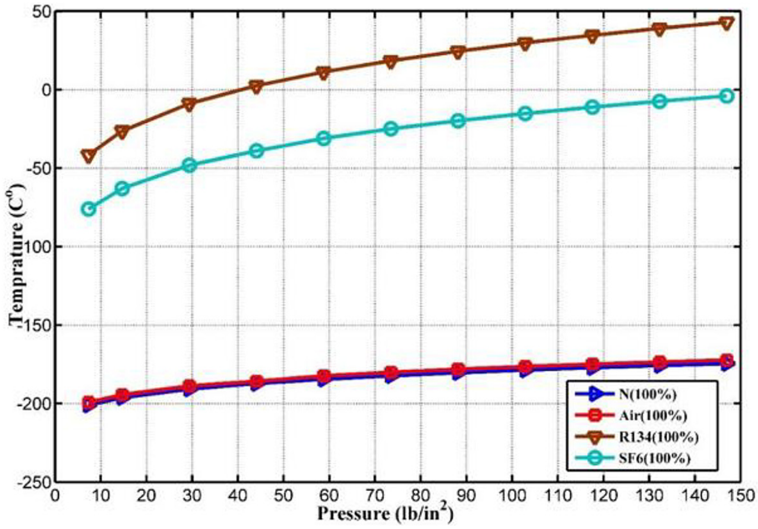

Fig. 12. Liquification temperature of pure gases

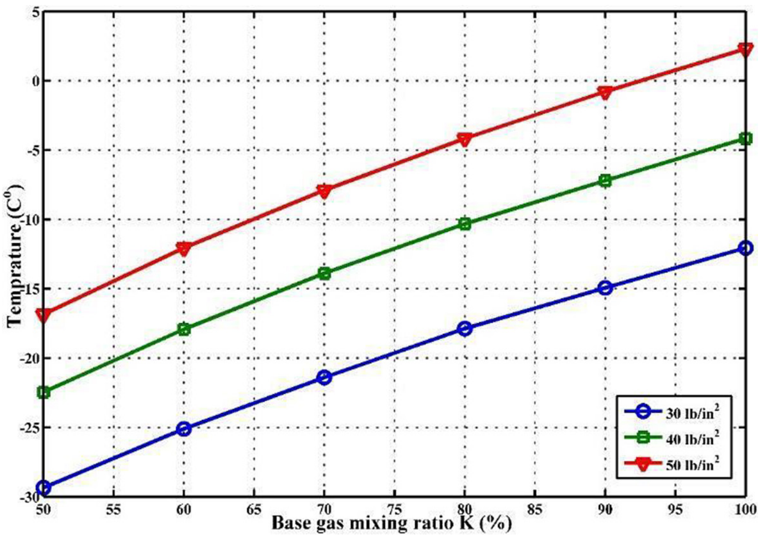

Fig. 13. Liquification temperature of mixed gases

$$p = exp\left(A\left(\frac{1-\frac{T_b}{T}}{R}\right)\right) \quad (4)$$

where: T_b – the liquefaction temperature at atmospheric pressure (K),
T – the liquefaction temperature of the base gas in mixed gases, and
P – the gas's boiling point pressure;
A – constant (21 Cal deg·1 mol), and
R – the gas constant (2 Cal deg·1 mol) [Rahmat et al., 2018].

Liquification of Novec 5110 & 4710

Due to the higher boiling temperatures and therefore lower vapor pressures of the Novec gases, they are used in gaseous mixtures rather than as pure components. Gases that have formed a homogeneous mixture cannot physically separate unless they are liquefied by cooling below the condensation temperature or being compressed to extremely high pressures. Novec 5110 and 4710 are not appropriate for all types of gas-insulated equipment because of their extremely high liquefaction temperatures and high use costs. Since Novec 5110 has a liquefaction temperature higher than 26.9 °C and Novec 4710 has a liquefaction temperature of around -5 °C, both must be combined with a buffer gas that has a lower liquefaction temperature. [John et al., 2021; National Refrigerants, 2021]

CONCLUSION

Sulfur hexafluoride gas has a strong dielectric strength. However, SF_6 usage is constrained due to the significant environmental risks. As a result, SF_6 needed to be replaced with more efficient, safe, and economical insulation. In light of this, many alternatives exist, including common gases such as R12, R134, Novec 5110, and Novec 4720, which have a lower GWP, the same ODP, and less environmental impact than SF_6, and that's what we need. The research shows that the dielectric characteristics of R12 and R134 mixtures with N2 and air were better compared to SF_6, where R134 and air/N2 reach 0.85-0.90 times that of SF_6 and R12 and air/N2 reach 0.90–0.95 times that of SF_6, respectively. The sole drawback of R134 and R12 gas that can be diminished by adding low-liquefaction gases like N2 and air is the high liquefaction temperature. R12 has good self-recoverability, but R134 does not. The concentration of Novec gas and the total mixture pressure both affect the dielectric breakdown voltage of a gas mixture. At any given pressure, pure Novec gases have higher dielectric breakdown voltages than SF_6. The results showed that Novec gases were classified as being less harmful than R12 and R134 when exposed to these gases in terms of toxicity. An evaluation was made for the table below, which shows a group of important factors in relation to insulating gases, and we chose the method of preference based on the marking system, where poor get 25%, good get 50%, very good get 75%, and excellent get 100%. As compared in Table 4, the ideal substitute is R12. Due to its low GWP and strong dielectric strength, R12 gas with a different gas composition, including carbon dioxide and helium, can instead be examined in the following investigation. Furthermore, there are studies about a mixture between Novec 4710 and CO2 in certain proportions called "g^3" (green gas for grid) [Yannick,2016]. According to these studies, g^3 may be a better alternative to SF_6 because it has a lower environmental impact and has more than 99% less global warming potential (GWP) compared to SF_6 [Ficheux et al., 2019].

Table 4. Final comparing between the gases

Comparison	SF_6	R12	R134	Novec 5110	Novec 4710
Global warming potential (GWP)	Poor	Good	Very good	Excellent	Good
Ozone depletion potential (ODP)	Excellent	Excellent	Excellent	Excellent	Excellent
Atmospheric lifetime	Poor	Excellent	Very good	Excellent	good
Self-recoverability	Excellent	Excellent	Good	_	_
Liquefaction temperature	Excellent	Very good	Good	Poor	Poor
Breakdown voltage testing (pure gas)	Excellent	Good	Good	Very good	Excellent
Breakdown voltage testing (mixture gas)	_	Excellent	Excellent	Poor	Poor
General safety measures for gases	Poor	Poor	Poor	Good	Good

REFERENCES

1. Budania, R. 2012. Sf6 gas properties. Retrieved from SlideShare:https://www.slideshare.net/RajneeshBudania/sf6-gas-properties
2. Ullah, R. 2017. Experimental Analysis of Dichlorodifluoromethane (R12), Tetrafluoroethane (R134) Gas and Mixtures with N2/Air as an alternate of SF6. https://www.researchgate.net/publication/329521486_Experimental_Analysis_of_Dichlorodifluoromethane_R12_Tetrafluoroethane_R134_Gas_and_Mixtures_with_N2Air_as_an_alternate_of_SF6
3. Ullah, R., Ullah, Z., Haider, A., Amin, S., Khan, F. 2018. Dielectric properties of tetrafluoroethane (R134) gas and its mixtures with N2 and air as a sustainable alternative to SF6 in high voltage applications. Electric Power Systems Research, 163, 532–537. DOI: 10.1016/j.epsr.2018.04.019
4. 3M™. (n.d.). 3M™ Novec™ 4710 Insulating Gas. Retrieved from 3MScienceAppliedtoLife:https://multimedia.3m.com/mws/media/1132124O/3m-novec-4710-insulating-gas-tech-data-sheet.pdf
5. 3M™. (n.d.). 3M™ Novec™ 5110. Retrieved from 3M Science. Applied to Life.: https://multimedia.3m.com/mws/media/1539521O/3m-novec-5110-ehs-summary.pdf
6. Xiao, A., Owens, J.G., Bonk, J., Zhang, A., Wang, C., Tu, Y. 2019. Environmentally friendly insulating gases as SF 6 alternatives for power utilities. In 2019 2nd International Conference on Electrical Materials and Power Equipment (ICEMPE) IEEE, 42–48. DOI: 10.1109/ICEMPE.2019.8727308
7. Kharal, H.S., Ullah, R., Ullah, Z., Asghar, R., Uddin, W., Azeem, B., Kamran, M. 2018. Insulation Characteristic of CCl 2 F 2 with mixtures of CO 2/N as a Possible Alternative to SF 6 substitute Gas for High Voltage Equipment's. In 2018 International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET) IEEE, 1–5. DOI: 10.1109/PGSRET.2018.8685961
8. Kharal, H.S., Kamran, M., Qureshi, S.A., Ahmad, W. 2019. Dichlorodifluoromethane (R12)/CO2/Air Gas Mixtures a Competent Gaseous Insulator as Surrogate of SF6 Dichlorodifluoromethane (R 12)/CO 2/Air Gas Mixtures a Competent Gaseous Insulator as Surrogate of SF 6. DOI: 10.14447/jnmes.v21i4.a09
9. Owens, J., Xiao, A., Bonk, J., DeLorme, M., Zhang, A. 2021. Recent development of two alternative gases to SF6 for high voltage electrical power applications. Energies, 14(16), 5051. DOI: 10.3390/en14165051
10. Xiao, A., Zhang, A., Bonk, J., Owens, J., DeLorme, M. (2020). Recent Development of Alternative Gases to SF6for High Voltage Electrical Power Applications. In 2020 IEEE International Conference on High Voltage Engineering and Application (ICHVE) IEEE, 1–4. DOI: 10.1109/ICHVE49031.2020.9279952
11. Rabie, M., Franck, C.M. 2018. Assessment of eco-friendly gases for electrical insulation to replace the most potent industrial greenhouse gas SF6. Environmental science & technology, 52(2), 369–380. https://doi.org/10.1021/acs.est.7b03465
12. SAFETY DATA SHEET – R12. (n.d.). Retrieved from National Refrigerants, inc.: https://refrigerants.com/wp-content/uploads/2019/12/SDS-R12.pdf
13. Xia, Y., Liu, F., Wei, Z., Zhang, X., Han, P., Xiao, S., Li, Y. 2021. Effect of O 2 on Partial Discharge Characteristic of C 5 F 10O/CO 2 Gas Mixture. In 2021 International Conference on Advanced Electrical Equipment and Reliable Operation (AEERO) IEEE, 1–4. DOI: 10.1109/AEERO52475.2021.9708368
14. AFROX. (n.d.). Material safety data sheet oxygen. Retrieved from AFROX A Linde Company https://www.afrox.co.za/en/images/Oxygen%20MS027266_27704_tcm266-490310.pdf
15. Kieffel, Y. 2016. Characteristics of g 3-an alternative to SF 6. In 2016 IEEE International Conference on Dielectrics (ICD) IEEE, 2, 880–884. DOI: 10.1109/ICD.2016.7547757
16. Ficheux, A., Luescher, R., Laruelle, E., Maksoud, L. 2019. SF6 alternative–what to learn from the high voltage experience. DOI: 10.34890/891