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Environmental and Physiochemical Properties of Gaseous Dielectrics Alternatives to SF_6

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Abstract: Research on alternative dielectric gases to eliminate the disadvantages of SF_6, which is widely used in GIS and switching systems in the power system engineering, has been an important study topic in the literature for nearly 40 years. Because of environmental priorities defined by international agreements such as the Kyoto Protocol and Doha Amendment, the restrictions on the use of SF_6 make these studies an obligation. Although the number of alternative dielectric gases studied for this purpose is quite high, these gases can be classified under the titles of non-synthetics, hydrocarbons (HCs), fluorocarbons (FCs), hydrofluorocarbons (HFCs), fluoronitriles (FNs), fluoroketones (FKs) and other synthetic gases. In this study, the gases classified under these titles are compared using the dielectric constant relative to SF_6, Global Warming Potential (GWP), atmospheric lifetime, boiling point and toxicity parameters used in the comparison of dielectric gases. When compared with these parameters, non-synthetic air, CO_2, and N_2, C_3F_7CN from FNs, and $C_5F_{10}O$ and $C_6F_{12}O$ from FKs stand out among alternative gases to SF_6. These alternatives are used in some innovative power system industry applications and have a widespread use potential in the insulating gas industry instead of SF_6.

Keywords: Gaseous dielectrics, sulfur hexafluoride (SF_6), global warming potential, dielectric strength

SF_6 Alternatifi Yalıtkan Gazların Çevresel ve Fizyokimyasal Özellikleri

Öz: Güç sistem mühendisliğinde GIS ve anahtarlama sistemlerinde yaygın olarak kullanılan SF_6'nın dezavantajları nedeniyle alternatif yalıtkan gaz araştırmaları, yaklaşık 40 yıldır literatürde önemli araştırma konularından birisidir. Kyoto Protokolü ve Doha Değişikliği gibi uluslararası anlaşmalarla tanımlanan çevresel önceliklerin bir sonucu olarak, SF_6'nın kullanımına ilişkin sınırlamalar bu çalışmaları bir zorunluluk haline getirmektedir. Bu amaçla alternatif yalıtkan gazlarla ilgili çalışmalarının sayısı oldukça fazla olmasına rağmen, bu gazlar sentetik olmayan, hidrokarbonlar (HCs), florokarbonlar (FCs), hidroflorokarbonlar (HFCs), floronitriller (FNs), floroketonlar (FKs) ve diğer sentetik gazlar başlıkları altında sınıflandırılabilmektedir. Bu çalışma, bu başlıklar altında sınıflandırılan gazları yalıtkan gazların karşılaştırılmasında kullanılan SF_6'ya göre yalıtkanlık katsayısı, küresel ısınma potansiyeli, atmosferik yaşam ömrü, kaynama noktası ve toksiklik parametrelerini kullanarak karşılaştırmaktadır. Bu karşılaştırmada, SF_6'ya alternatif gazlar arasında sentetik olmayan gazlardan hava, CO_2 ve N_2, floronitrillerden C_3F_7N ve floroketonlardan $C_5F_{10}O$ ve $C_6F_{12}O$ öne çıkmaktadır. Bu alternatifler bazı yenilikçi güç sistem endüstrisi uygulamalarında kullanılmaktadır ve SF_6'nın yerine yalıtkan gaz endüstrisinde yaygın bir kullanım potansiyeline sahiptir.

Anahtar Kelimeler: Gaz yalıtkanlar, kükürt hekzaflorür (SF_6), küresel ısınma potansiyeli, yalıtkanlık kuvveti

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1. Introduction

The distance between the points where electricity is produced and consumed and the regional energy demand that changes rapidly throughout the day makes it an imperative to establish an integrated transmission and distribution system on a global scale [1]. Competitive design and production of the circuit components used during the transportation of the voltage increased by transformers in transmission and distribution systems, depending on the cost and size criteria, is an important research area in power systems [2-4].

Sulfur hexafluoride, SF_6 is non-toxic, odorless, nonflammable and chemically stable. In addition to its chemical stability, it is also an effective absorber in heat and light source energy emissions [5-7]. SF_6, which is an electronegative gas with high dielectric constant since the electron attachment cross section is larger than the total ionization cross section even in high electric fields, is widely used in power system transmission and distribution equipment since the 1950s [5]. Owing to these properties, the breakdown voltage is three times higher compared to air at the unit distance provided that the product of the pressure and electrode gap remains constant, approximately 89 kV/cm [8]. SF_6 gas is used in almost 80% of gas-insulated applications in transmission and distribution systems such as circuit breakers, disconnectors, busbars and transformers [9]. In addition to this extensive use in power systems, it also has a wide range of industrial uses such as laser and semiconductor technology, plasma physics, magnesium and aluminum casting [10-11]. With the use in the power system industry, the size of switching elements such as circuit breakers and sectionalizers is reduced, the areas required for substations are reduced and supply processes such as transportation and installation are simplified [12]. In addition to these advantages of SF_6, its major disadvantages can be listed as follows,

- Disruption of discharge characteristics for high pressure and wide electrode gaps in non-homogeneous electric field configurations [9],
- Partial liquefaction depending on the high pressure in cold climatic conditions [9],
- The occurrence of corrosive and toxic decomposition products as a result of partial discharge and breakdown mechanisms [13, 14],
- Since it is a synthetic gas, its relatively high cost [9], and
- As it is an important greenhouse gas, its use causes important environmental problems [15].

Global Warming Potential (GWP) value, which is one of the greenhouse gas indicators, is 23.500 times of CO_2 for 100-year period [16]. The use of SF_6, which has one of the highest GWP among the synthetic gases used for industrial purposes, is recommended to be limited to the countries that are parties to the United Nations Framework Convention on Climate Change (UNFCCC) with the 1997 Kyoto Protocol and the 2012 Doha Amendment to the Kyoto Protocol agreements [17, 18]. The atmospheric lifetime of SF_6 is about 3200 years, making these environmental effects more important [19, 20]. Despite these agreements that recommend restricting the use of SF_6, its proportion in the atmosphere continues to increase. While the rate in the atmosphere was 3.94 ppt (parts-per-trillion) in 1997 when the Kyoto Protocol was signed, this rate increased to 8.61 ppt in 2015 [15]. The concentration of SF_6 in the atmosphere has more than doubled in 20 years.

Considering these disadvantages, producing switching and substation equipment with alternative gases to SF_6 in the power system industry becomes an economic and environmental requirement [4]. Since alternative gases to SF_6 have been the subject of significant discussion in the literature for nearly forty years, the number of alternative gases is quite high. These alternative gases are examined in the study by classification in non-synthetics, hydrocarbons (HCs), fluorocarbons (FCs), hydrofluorocarbons (HFCs), fluoronitriles (FNs), fluoroketones (FKs), and other synthetics [19; 21, 22].

SF_6 and other gaseous dielectrics are used in the power system industry to meet economic, safety and size constraints and to minimize faults caused by electrical breakdowns, partial discharges, coronas etc. Within the scope of this study, gas insulator alternatives used in power system transmission and distribution systems, especially in switching equipment, are examined in detail in terms of their environmental and physicochemical properties. These properties examined during the evaluation of these alternatives are GWP and lifetime in terms of environmental effects, and dielectric strength, boiling point and toxicity in terms of their physicochemical properties.

2. Alternative Gaseous Dielectrics

2.1. Non-Synthetics

Stable molecules and noble gases in the atmosphere are often used as pure or gas mixtures in search of an alternative to SF_6 due to their almost no greenhouse effects, they can be used in cold climates without risk of liquefaction independent of pressure and low costs [23-25]. The relative dielectric coefficient of dry air, N_2, N_2O, CO_2, O_2, H_2, Ar, He and Ne gases, which are frequently used in the literature among non-synthetic gases, varies between 0.37-0.40, 0.34-0.43, 0.44-0.50, 0.33-0.37, 0.20-0.22, 0.04-0.10, 0.02-0.06 and 0.01-0.02 ranges, respectively, see Table 1. Although the dielectric strength of these gases is significantly less compared to SF_6, the prominent advantages of these non-synthetic alternatives are the lower GWP values, boiling temperatures, costs and non-toxicity except CO. In order to increase the dielectric strength of these alternatives, binary or ternary mixtures with different gases, especially SF_6, can be used [2, 7]. This feature can also be improved by applying a magnetic field in the perpendicular direction to the electric field that causes the breakdown [23, 26]. Dry air, N_2 and CO_2 insulating medium switching and Gas Isolated System (GIS) designs are used by important manufacturers in the industry as transmission and distribution system equipment [2, 4, 25, 27]. In applications where these gases are used in GIS and circuit breakers, important technical parameters such as rated voltage, rated normal current, short circuit breaking current and rated filling pressure range between 24-175 kV, 800-3150 A, 16-40 kA and 1.3-7.7 bar, respectively [4].

Table 1. Main properties of non-synthetic alternative gaseous

	Gaseous	Dielectric constant relative to SF_6	GWP	Atmospheric Lifetime (Years)	Boiling point (ºC)	Toxicity
Non-synthetics	SF_6	1.00	23500 [16]	3200 [19, 20]	-64.0 [19, 22]	>50000 ppm for LC_{50} 4h [20]
	Air (Dry)	0.37-0.4 [19, 25]	~0 [4, 26]	∞ [26]	-194.0 [4]	Non-toxic [19]
	N_2	0.34-0.43 [19, 22]	0 [4, 26]	∞ [26]	-196.0 [4, 19]	Non-toxic [19, 27]
	N_2O	0.50 [19] 0.46 [28]	320 [19] 310 [26]	120 [26, 29]	-89.0 [19, 27]	Non-toxic [19]
	CO_2	0.32-0.37 [19, 22]	1	30-95 [19] 50-200 [26]	-79.0 [19, 22]	>300000 for LC_{50} 4h [19]
	CO	0.40 [19, 30]	1-3 [19]	0.08-0.25 [31]	-192.0 [27, 28]	1807 ppm for LC_{50} 4h [4, 19]
	O_2	0.33-0.37 [28] 0.33 [30]	0 [4]		-182.0 [4]	Hyperoxia [27]
	H_2	0.20 [19] 0.22 [28]			-253.0 [19, 27]	Non-toxic [19, 27]
	Ar	0.04-0.10 [19] 0.07 [26]	0 [26]	∞ [26]	-186.0 [19, 27]	Non-toxic [19, 27]
	He	0.02-0.06 [19]			-269.0 [19]	Non-toxic [19]
	Ne	0.01-0.02 [19] 0.006 [26]	0 [26]	∞ [26]	-246.0 [19, 27]	Non-toxic [19, 27]

2.2. Hydrocarbons (HCs)

Hydrocarbons, where carbon and hydrogen atoms combine with different geometrical sequences and the number of bonds, are a rich variety of organic compounds. When the literature on insulating gases is examined, it is seen that among the commonly used hydrocarbons are CH_4 and C_2H_2 [34, 35]. The relative dielectric coefficient of CH_4 relative to SF_6 is 0.43, its GWP is 23 times its CO_2 equivalent in a 100-year period, its atmospheric lifetime is about 10 years and its boiling point is -163.0 ⁰C, see Table 2. Through these features, it can be preferred for high pressure applications in cold climates, and it is known to be more suitable than N_2 and Ar for design in electron-beam controlled on/off switches [41]. Although the relative dielectric strength of C_2H_2 is almost at the same level as CH_4, the high boiling point compared to CH_4 is a disadvantage, see Table 2. There is diffuse discharge switching applications using ternary gas mixtures including C_2H_2 [35]. It is an advantage in terms of power system applications that these gases and possible decomposition products are non-toxic.

Table 2. Main properties of HCs, FCs, and HFCs

	Gaseous	Dielectric constant relative to SF_6	GWP	Atmospheric Lifetime (Years)	Boiling point (⁰C)	Toxicity
Hydrocarbons (HCs)	CH_4	0.43 [27, 28]	23 [31]	8.4-12 [31]	-163.0 [28]	Non-toxic [36]
	C_2H_2	0.42 [27]			-84.8 [27]	Non-toxic [36]
Fluorocarbons (FCs)	CF_4	0.42 [28]	6300 [37, 38]	50000 [19, 22]	-128.0 [4, 19]	40000 ppm for LC_{50} 4h [37]
	C_2F_4	0.50 [21]	0 [20]	1.9 days [20]	-76.3 [20]	40000 ppm for LC_{50} 4h [20]
	C_2F_6	0.78-0.79 [20, 38]	12200 [4, 22]	10000 [19, 22]	-78.0 [19, 38]	Non-toxic [19]
	C_3F_6	0.90-1.00 [4]	100 [4]	<10 [20, 38]	-28.0 [20, 38]	750 ppm for LC_{50} 4h [20, 37]
	C_3F_8	0.97-1.12 [37]	8830 [22, 39]	2600 [19, 39]	-37.0 [28, 38]	750 ppm for LC_{50} 4h [20]
	C_4F_6	1.71 [30]		-25.4 [27]	-25.0 [40]	82 ppm for LC_{50} 4h [4, 19]
	C_4F_8	1.32 [30]	8700 [19]	3200 [31]	-16.0/22.0 [21]	0.5 ppm for LC_{50} 4h [4, 19]
	C_4F_{10}	1.25-1.31 [38]	8860 [4]	2600 [31, 38]	-2.0 [28, 38]	
	C_5F_{12}	1.75 [30, 40]	8900 [31]	4100 [31]	28.0 [38]	
	C_6F_{14}	2.26 [40]	9000 [31]	3200 [29, 31]	52.0 [40]	
	c-C_4F_8	1.25-1.31 [26]	8700 [19, 22]	3200 [19, 22]	-6.0 [19, 20]	Non-toxic [19]
	n-C_4F_{10}	1.32-1.36 [26]	7000 [26]	2600 [26]	-2.0 [26]	
Hydrofluoro-carbons (HFCs)	CH_3F	0.28 [29]	97 [31]	2.6 [31]	-74.0 [28]	Non-toxic [36]
	CH_2F_2	0.27 [28] 0.50 [21]	550 [31]	5 [31]	-52.0 [28]	520000 ppm for LC_{50} 4h [36]
	CHF_3	0.38 [38]	11700 [26]	264 [26]	-83.0 [27, 28]	663000 ppm for LC_{50} 4h [36]

2.3. Fluorocarbons (FCs)

Fluorocarbons are highly stable due to the carbon-fluorine bond, which is considered one of the strongest bonds in organic chemistry. Due to the partial ionic character of the fluorine(s), the molecules on which these bonds are formed also have an electronegative property. As the number of carbons that forms the body of the molecule increases in fluorocarbons, the stability of the molecule increases with the effect of fluorine atoms. In other words, fluorocarbons are more stable than other organic compounds such as hydrocarbons [19]. Because of these properties, fluorocarbons are an important alternative in gas insulating applications in the power system industry.

Prominent alternatives among FCs compounds in the literature are CF_4, C_2F_4, C_2F_6, C_3F_6, C_4F_6, C_4F_8, C_4F_{10}, C_5F_{12}, C_6F_{14}, n-C_4F_{10}, and c-C_4F_8, see Table 2. The dielectric constant of these gases relative to SF_6 tends to increase with the increase in the number of carbon and fluorine in its compound. This is one of the consequences of increased stability due to the growth of the molecule. While this relative dielectric coefficient is 0.42 for CF_4 [28], it increases to 2.26 for C_6F_{14} [40]. One of the characteristic features of fluorocarbons is that they are among the gases proposed to be restricted by the Kyoto Protocol and Doha Amendment [17, 18]. Fluorocarbons other than C_2F_4 and C_4F_6, which are alternatives to dielectric gas, have the potential to cause significant environmental problems with their high GWP value and long atmospheric lifetimes, such as SF_6, see Table 2. Another negative feature of these gases is the high boiling point, depending on the molecular size. Boiling points of fluorocarbons such as C_3F_6 and C_3F_8 with dielectric strength close to SF_6 are -28 ^{0}C and -37 ^{0}C, respectively. High boiling points make these alternatives inefficient in high pressure and/or cold climate applications.

LC_{50}, a unit of toxicity, indicates that half of all living things exposed to a gas over a certain concentration and time interval are killed. When FCs are examined for toxicity, C_3F_6, C_3F_8, C_4F_6 and C_4F_8 are toxic and their use in high amounts in industrial applications should be avoided [19, 20]. FCs are used in GIS and switching equipment in double or triple gas mixtures [42]. In these mixtures, gases such as SF_6, N_2 and Ar are used in different concentrations and their breakdown characteristics are examined in different electrical discharges [43]. The ratio of FCs in these gas mixtures ranges from 20% to 80% [44-45]. These rates are determined by the environmental and electrical limitations of power system equipment application.

2.4. Hydrofluorocarbons (HFCs)

Hydrofluorocarbons, which contain carbon, hydrogen and fluorine atoms in their compounds, are recommended to limit their use for industrial purposes due to their greenhouse gas effects, just like SF_6 and FCs [17, 18]. Although there are studies on different molecular structures such as CHF_3, CH_2F_2, CH_3F, $C_2H_2F_3$, $C_2H_2F_4$ and $C_4H_2F_6$, the HFCs frequently recommended as an alternative to SF_6 are CHF_3, CH_2F_2, and CH_3F, see Table 2 [21, 28].

The stability and dielectric constants of HFCs increase in relation to the increase in the number of carbon and fluorine in the molecular structure, similar to FCs [28, 46]. In the literature, CHF_3 has been frequently studied due to its nontoxicity, low boiling point, relatively low cost, and high electronegativity from fluorine atoms [47]. However, this gas cannot meet environmental priorities due to its high GWP [26].

2.5. Fluoronitriles (FNs)

The low dielectric coefficient of non-synthetic gases relative to SF_6 and the limitation of the use of FCs and HFCs due to their high GWP values make FNs and FKs prominent in the search for alternative dielectric gases. Due to their high dielectric strengths and low GWPs, these gases have recently become an important alternative in high power transmission and distribution system equipment.

FNs contain carbon, fluorine and nitrogen atoms. Unlike FCs, the nitrogen atom makes a double or triple bond with a carbon in the molecule. FNs commonly used in alternative dielectric gas studies include CF_3CN, C_2F_5CN, C_3F_7N, and C_3F_7CN (C_4F_7N) [37, 46]. The relative dielectric strengths of these alternatives increase due to the increase in the number of carbon and fluorine in the structure and vary between 1.46-2.70, see Table 3. Despite these high dielectric strengths and relatively low GWPs compared to SF_6, it is an important disadvantage that FNs other than C_3F_7CN are acute toxic [19, 37]. Considering the dimensions of power system equipment, it is an obligation to take precautions for human and environmental health in the use of these alternatives.

Table 3. Main properties of FNs and FKs

	Gaseous	Dielectric constant relative to SF_6	GWP	Atmospheric Lifetime (Years)	Boiling point (⁰C)	Toxicity
Fluoronitriles (FNs)	**CF_3CN**	1.46 [37, 46]			-62.0 [19, 40]	360 ppm for LC_{50} 4h [37]
	C_2F_5CN	1.80-1.85 [19] 2.00 [28]			-32.0 [19, 40]	High [19]
	C_3F_7N	2.20-2.35 [19]			-2.0 [19]	Toxic [19]
	C_3F_7CN	2.20 [4] 2.74 [30, 46]	2100 [46]	22 [22]	-4.7 [46]	10000-15000 ppm for LC_{50} 4h [19, 37]
Fluoroketones (FKs)	**C_4F_8O**	1.60 [4]	4100 [4]		0 [4]	200 ppm for LC_{50} [19]
	$C_5F_{10}O$	2.00 [4, 30]	1 [19, 22]	0.044 [22]	24.0 [19]	Non-toxic [19]
	$C_6F_{12}O$	2.70 [22, 38]	1 [22, 38]	0.014 [38]	49.0 [22, 38]	Non-toxic [19]

Alternative dielectric gas studies are concentrated on the C_3F_7CN molecule, which is nontoxic among nitriles and has a relative dielectric strength in the range of 2.20-2.70 [4, 48]. However, due to the high boiling point of C_3F_7CN such as -4.7 ⁰C, there is a risk of liquefaction in outdoor applications. In order to overcome this problem, binary mixtures with alternative non-synthetic dry air, N_2 and CO_2 gases are recommended [4, 49]. Due to partial discharges, arcs and breakdowns naturally occurring in power system equipment, decomposition products emerge depending on the molecular structure of the insulating gas. Decomposition products formed by the binary mixtures of C_3F_7CN with different gases and the effects of impurities such as H_2O and O_2, which are inevitably present in the environment, have been studied in detail recently [46, 48]. These main stable decomposition products include FKs such as C_2F_5CN, CF_3CN, and CH_2FCN, FCs such as CF_4, C_2F_6, C_3F_8, and C_4F_{10}, and HFCs such as CHF_3 [46, 48]. The electronegativity of these decomposition products is close to C_3F_7CN and therefore the insulation performance is not damaged. However, decomposition products such as COF_2, C_3F_7H, and HF are toxic and/or corrosive [46]. These decomposition products threaten the internal structure of the equipment and the safety of maintenance personnel, so they should be detected during service periods.

2.6. Fluoroketones (FKs)

Fluoroketones, which have similar properties with FNs, have an oxygen molecule in the molecular structure instead of a nitrogen molecule. Among the fluoroketones, C_4F_8O is more disadvantageous than $C_5F_{10}O$ and $C_6F_{12}O$ due to its 4100 equivalent CO_2 GWP value and highly toxic, see Table 3. The main disadvantages of $C_5F_{10}O$ and $C_6F_{12}O$, which have optimum data on almost all properties in the search for alternative dielectric gas, are the boiling points of 24.0 ºC and 49.0 ºC, respectively. This disadvantage is tried to be eliminated by mixing these gases with different gases and not using them in high pressure equipment [30, 50]. After the FKs are subjected to electrical discharges, decomposition products consisting of fluorocarbons are formed, such as CF_4, C_2F_6, C_3F_6, C_3F_8, C_4F_{10} and C_5F_{12} [38]. These products can be varied depending on the buffer gases and the concentration of impurities in the medium. These by-products may have undesirable properties in terms of GWP and toxicity parameters.

2.7. Other Synthetics

Other synthetic alternatives include chlorocarbon, bromocarbon and iodide-carbons molecules using chlorine, bromine, and iodine from 7A elements instead of fluorine.

The chlorocarbons commonly used in the literature are CF_3Cl, C_2H_5Cl, CH_2FCl, CHF_2Cl, C_2F_3Cl, C_2F_5Cl, CF_2Cl_2, $CHFCl_2$, $C_2HF_3Cl_2$, $C_2F_4Cl_2$, $C_2F_3Cl_3$, $CHCl_3$, $CFCl_3$, and CCl_4. The relative dielectric coefficient of these molecules ranges from 0.30-1.80 [28, 40, 51]. These molecules generally have undesirable properties in terms of environment and human health, such as high GWPs and toxicity [36]. However, some molecular structures, such as CF_3CHCl_2, are proposed as an alternative in switching designs [51].

Bromocarbons studied in the gas dielectric literature are CH_3Br and CF_3Br. The relative dielectric coefficient of these gases is only 0.45 and 0.76, respectively [28, 30]. The boiling point of CH_3Br at 2.7 ºC and the GWP value of CF_3Br at 5600 equivalents CO_2 restrict their use in the dielectric industry [27, 29].

c-CIF_3, CF_3I and CH_3I are important iodide-carbons. The relative dielectric coefficients of these molecules are 0.47-0.58, 1.27 and 1.15, respectively [19, 27]. Although CF_3I is the most widely used literature among these gases, its acute toxic feature prevents its use for industrial purposes. In order to reduce this toxic effect of CF_3I, double and triple gas mixtures with gases such as N_2, CO_2, CF_4 and Ar have been proposed in different studies [52-53]. In these studies, the ratio of CF_3I in these mixtures is kept in amounts not exceeding 10%. Despite this low rate, it significantly increases the dielectric strength of the mixture.

3. Conclusions and Perspectives

This study, in which alternative dielectric gases are examined in different parameters, focuses on the selection of the most suitable gas or gases in terms of environmental and physicochemical properties that can be used instead of SF_6 in the power system industry.

The environmental effect that causes the use of SF_6 to be limited is evaluated by examining the GWP and atmospheric lifetime properties of alternative gases, see Figure 1. In terms of these features, a better alternative gas is expected to have a low GWP and long atmospheric lifetime due to the nature of power system equipment. When Figure 1 is examined in terms of these requirements, it can be seen that non-synthetics, CH_4, C_3F_7CN and FKs may be alternative, and FCs and HFCs are not environmentally suitable due to their high GWP value. In terms of toxicity, another parameter in terms of human and environmental health, FCs, HFCs and FNs other than C_3F_7CN pose a threat and are not recommended for large-scale industrial use.

The dielectric characteristics of these alternatives are examined in terms of dielectric constants relative to SF_6 and boiling points, see Figure 2. It is desired that the dielectric coefficient of the gas dielectric material should be as big as possible due to reasons such as reduction in size, security and cost in power system equipment. On the other hand, boiling point should be as low as possible to avoid liquefaction since these equipment operate outdoors under cold climate conditions.

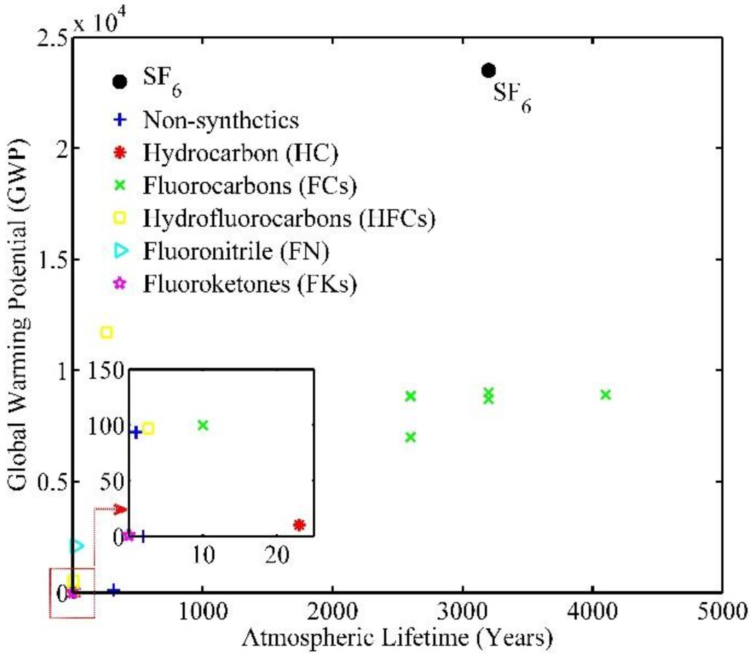

Figure 1. GWP and atmospheric lifetimes of alternatives to SF_6

According to Figure 2, HFCs, FNs and FKs stand out in terms of dielectric strength. However, the boiling points of these gases are quite high, and they are present as liquid in cold climate working conditions. To eliminate this disadvantage, these gases are mixed with non-synthetic gases such as air, N_2 and CO_2, where boiling points are considerably low.

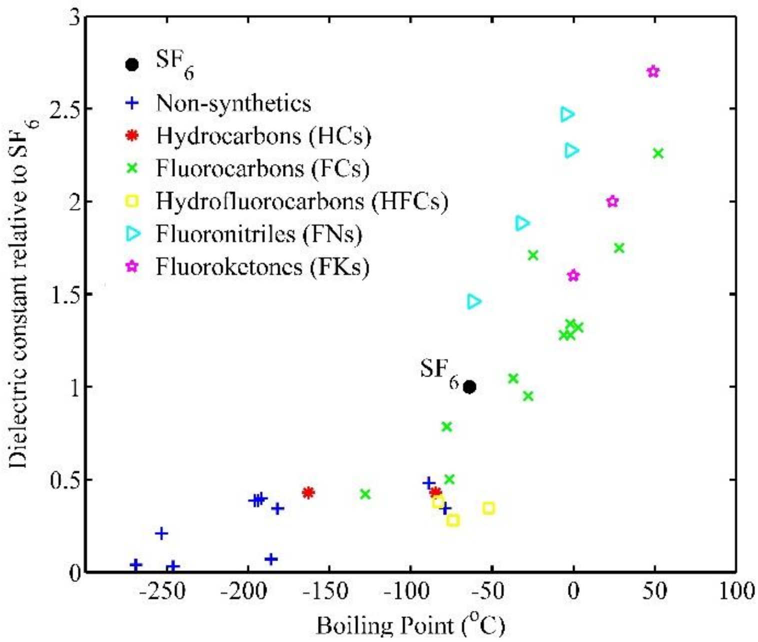

Figure 2. Dielectric constants relative to SF_6 and boiling points of alternatives

Among the gases that meet the requirements in terms of both environmental and electrical properties, non-synthetics, C_3F_7CN and FKs stand out. These gases are recently used by the leading companies of the power system industry sector in GIS and Circuit Breaker (CB) applications [4, 33, 49]. Non-synthetic gases in medium voltage equipment are preferred with high pressure applications to increase the insulating level of the system [4]. In applications where C_3F_7CN and fluoroketones are used, double or triple gas mixtures of non-synthetic gases such as air, N_2, CO_2, and O_2 are used to prevent liquefaction in the gas dielectric environment [49, 54]. These application examples and scientific studies, which have become widespread recently, show that a new era has started in the SF_6 alternative gas industry and applications will continue to increase.

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