VALIDATION METHODS OF SF6 ALTERNATIVE GAS

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ABSTRACT

This paper deals with the validation steps of alternative gases to SF6 for medium voltage switchgear applications. It is not only focused on technical properties capabilities of the most interesting candidates but also on the toxicity risk linked to the creation of by-products in some conditions.

INTRODUCTION

Among environmental concerns, the replacement of SF6 used in medium voltage switchgears represents an important challenge. Despite very interesting physical properties regarding its dielectric strength and electrical arc quenching ability, this gas is also known for its very high GWP value (Global Warming Potential). For this reason, studies have been in progress for many years to find alternatives for its substitution.

Considering the fact that it is not simple to quickly replace a gas used for 60 years in electrical power equipment with a lifetime of 40 years, the first target is to define a way to select the best candidate and to validate its application in medium voltage switchgear. Not only a good dielectric strength is necessary but many other performances are required.

This paper explains an approach to validate an alternative gas to SF6.

CHARACTERISTICS OF GAS CANDIDATES

The pure gas and gas mixtures must offer following features: non toxic, non corrosive, non flammable nor explosive, low GW, and no or very low ODP (Ozone Depletion Potential). Overall it must be environmental friendly.

Among the wide range of available gases, those from the family of hydrofluoroolefins (HFO1234ze and HFO1234yf), fluoroketones (C5FK and C6FK), fluoronitriles (iC4F7N), fluoroethers (HFE245cb2), fluorooxiranes and hydrochlorofluoroolefins (HCFO1233zd) were judged as the most interesting after a first selection based on flammability, GWP, ODP, boiling point and toxicity. Toxicity is defined as:

Acute toxicity is characterized by Lethal Concentration (LC50): standard measure of the toxicity of the surrounding medium that will kill half of the sample population of specific test animals (rat, mouse or worm for instance) in a specified period (often 4 hours) through exposure via inhalation (breathing). LC50 is measured in parts per million (ppm); low values correspond to high gas toxicity.

Chronic toxicity is characterized by Threshold Limit Values Time Weighted Average (TLV-TWA): recommended limits proposed by the American Conference of Governmental Industrial Hygienists (ACGIH) to which most workers can be exposed without adverse effect on the basis of a 8h/day, 40h/week work schedule. TLV-TWA is measured in parts per million (ppm). The TLV-TWA must be higher than the maximum value that can occur permanently in a factory in normal conditions due to normal leakage during gas handling. It should be higher than 50 ppm in order to be used in switchgear factories.

Medium and long term toxic effects characterized by the CMR data:

- Carcinogens (substance which can cause the development of cancer or increase its frequency)
- Mutagenic (substance which induces alterations in the structure or the number of chromosomes of cells)
- Repro-toxic (a substance which can involve an issue of fertility or of development of offspring
- The main toxicological data of gas or of pure gases in case of mixtures shall be communicated by the gas suppliers whose gases will have to be REACH registered.

Despite a severe specification sheet, it clearly appears that numerous potential candidates are available (cf. table 1). The main challenge is then to select the best ones and validate them.

PROPERTY / GAS	Boiling point at 1 bar (°C)	GWP	Flammability	Toxicity	
				LC50 (4h) on rats	TWA (ppm)
SF6	-64	22800	No		1000
C6 Fluoroketone	49	1	No	>98000	150
C5 Fluoroketone	26.5	1	No	>20000	225
HFO1234zeE	-19	6	No	>207000	1000
HFO1234yf	-29	4	Low	>405000	500
iC4 Fluoronitrile	-4.7	2210	No	>10000	85
HFE 245cb2	5.6	697	No		
HCFO1233zd	18.3	7	No	120000	800

Table 1: gas candidates for SF6 replacement

GAS PERFORMANCES AND VALIDATION TESTS

Dielectric aspects

From a technical point of view, one of the most important technical challenges during the selection of alternative gas to SF6 is related to the insulating properties of potential candidates.
Indeed, as SF6 is used for several decades, its insulating properties and consequently the theoretical rules to design products regarding their dielectric withstand are now well known. For instance, numerous papers can be found in the literature dealing with the influence of filling pressure and homogeneity of electrical field. Additionally, as SF6 has a very low boiling point (-64°C at 1 bar), it is possible to use it alone for medium voltage applications where the minimal temperature of use is generally comprised between -25°C and -5°C and where the filling pressure does not exceed 2 bars.
As it is not possible to perform tests on the whole range of pressures and temperatures during the pre-selection of the most promising candidates, it was decided to optimize the number of tests. Focus has been made on the most frequent minimal temperature requested by the main users of electrical switchgear (-15°C and -25°C) and on only two configurations of electrical fields: a homogeneous one and a heterogeneous one. The pressure is fixed at 1.3 bars, which is the most commonly used value in medium voltage applications.
Regarding the minimal temperature of use, as some candidates have a quite high boiling point at 1.3 bars (see table 1), a mixture has been done with a buffer gas in order to avoid any liquefaction until the lowest temperature of use. For instance, the vapor pressure curve of C5 clearly shows that it is not possible to use it alone while it is possible with HFO1234zeE (see figure 1).

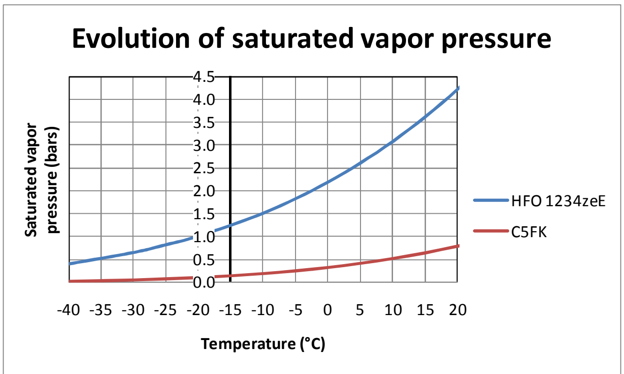

Figure 1: evolution of the satured vapor pressure of fluoroketone C5K and HFO1234zeE

So, in a first step, this minimum temperature of use permits to determine the partial pressure of the insulating gas insuring no liquefaction an then, the gas is completed with the selected buffer gas such as dry air, CO_2, Nitrogen for instance, up to a pressure of 1.3 bars which corresponds to a common filling pressure for medium voltage applications.
Concerning the electrical field distribution, two values of ratio “maximal electrical field / minimal electrical field” are chosen for the pre evaluation of selected candidates: factor 3 for homogeneous fields and factor 11 for heterogeneous fields.
Preliminary power frequency and lightning impulse tests are performed with SF6 and dry air as reference.
In a second step, tests in both configurations are made with several candidates at room temperature but with gas proportions corresponding to the minimal temperature of use. Figure 2 shows the BIL performances of different gases for gas proportion corresponding to -15°C conditions. That means the gas mixture has no liquefaction from high temperature down to -15°C. For lower temperatures part of the gas is liquefied, and as a consequence dielectric performances are reduced. Alternative gas performances are compared with those of SF6 and the best gases are selected for the next steps of validation: test in the whole range of electrical fields distribution, flashovers on surface of insulating materials tests, partial discharges tests, dielectric tests at low temperature, tests with barriers…
These preliminary tests highlighted a difference of behaviour depending on the kind of electrical field: some candidates are better in homogeneous field while others are better in heterogeneous field. Unfortunately, these tests also showed that it will be difficult to find an alternative to SF6 with similar or better performances on the whole range of electrical fields and temperature of use.

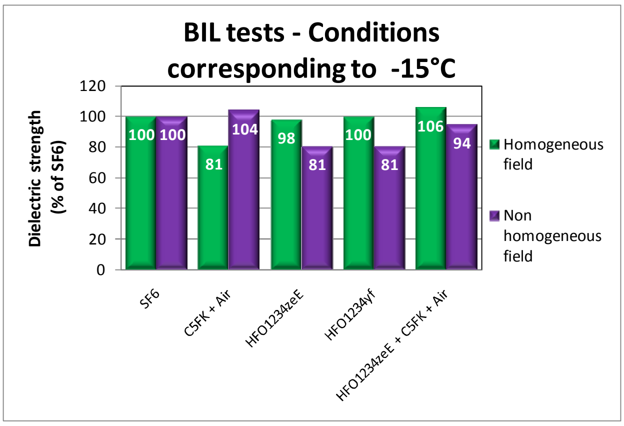

Figure 2: BIL dielectric withstand of different gases with gas mixture corresponding to -15°C conditions

Another interesting candidate is Fluoronitrile [1], it has higher dielectric properties than SF6 for MV use at 1.3 bar and -15°C but still a high GWP (2210).

Another solution could be to mix several gases together. Unfortunately this solution is not as obvious as it seems because at low temperatures the molecules interreact together and lead to a shift of boiling temperature. The

Raoult's law permits to take into account this phenomena and then to define the ratio between several gases for a selected minimal temperature of use (see figure 3).

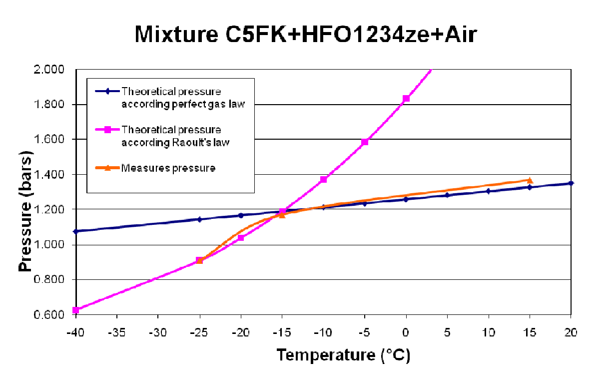

Figure 3: evolution of the pressure of a mixture C5FK + HFO1234zeE + dry air versus temperature

Tests with numerous mixtures are realized. In some cases a synergy effect regarding insulating properties is observed between the different gases that lead to an increase of the performances.

Then partial discharges tests on existing products are launched and compared to SF6 in order to complete the dielectric validation of the most interesting candidates. It appears that for instance, HFO1234ze and C5FK/Air mixtures give encouraging results with a small advantage for HFO1234ze compared to C5FK/Air mixture (see figure 4).

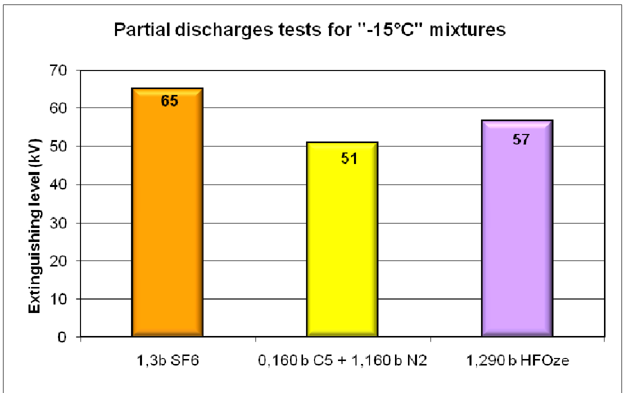

Figure 4: partial discharges tests with different gases with gas mixture corresponding to -15°C conditions

Long term behaviour must also be investigated: the candidates are put under several levels of partial discharges during several months, then, dielectric tests and gas analysis are done to check their stability. Finally, in order to validate this stability, long duration tests must be launched on real products: a regular pressure check and dielectric insulation follow up permit to conclude on the gas stability.

Temperature rise with permanent current

Temperatures rise tests with permanent currents have been performed on a switchgear mock-up filled with different gases or mixture of gases (see figure 5).

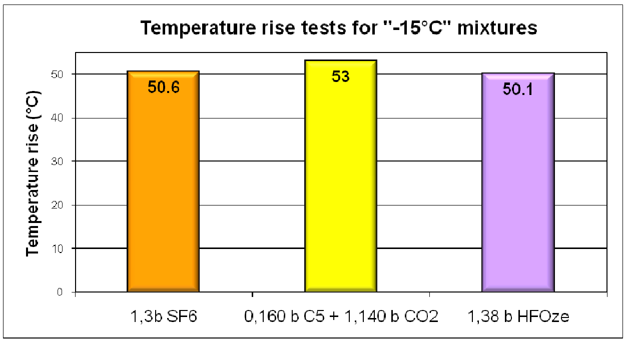

Figure 5: electrical contacts temperature rise with different gases with permanent current on a switchgear mock-up

The results with tested candidates are not so far from those obtained with SF6.

Pressure evolution

The means to check the pressure of gas inside the tank (measured by pressure sensor or densimeter) must be able to detect any leakage for the whole temperature range. The design of the switchgear tank and the safety membranes will have to take into account the pressure inside the tank on all the range of temperature (from the minimum temperature of storage up to the maximum temperature of gas in normal conditions) while complying to internal arc test.

Homogeneity of gases

In case of mix of gases, especially when the densities of gases are different, the homogeneity of gases must be checked. A good way to check it consists to fill a vertical pipe (for instance 2 meters) at a given temperature from its bottom, in starting by the less dense gases and continuing by the denser. The concentration of the different gas is measured from the both side of the pipe. It can be considered that the mixture is homogeneous when the different concentrations of gases measured from the top and the bottom are identical.

Flammability – Internal arc fault test

Whatever the gases (pure or mixture) used as dielectric medium, it is necessary to check that the gas is not explosive in the configuration of operating (filling, temperature rise test, partial discharge, making of disconnector, internal arc fault test, leakage) especially when the gas contains oxygen atoms. In the case of a mixture of gases, the non-flammability should be checked at different temperatures knowing that the pressure ratio

between gas and oxidant gas (dry air for instance) changes according to the satured vapor pressure of each gas.
Internal arc fault tests performed on switchboards filled with SF6, air, gases are necessary to compare the different gases in terms of energy liberated, and behaviour inside (reaction with materials) and outside the switchboard.

Permeability - Tightness

Keeping a sufficient pressure inside the tanks is another key point to ensure a constant level of performances for the whole life of the switchgear. With SF6 the shape and size of the molecule are favorable. Indeed SF6 is a quite big and massive molecule, which lead to a good permeability and tightness behaviour. Some of its alternatives have a too high boiling point that requires to use them with a buffer gas to ensure a fully gaseous state until the minimal temperature of use. This buffer gas may be a conventional gas media such as oxygen, nitrogen, carbon dioxide or a mix of them. Unfortunately these gases have smaller molecules and have then a higher ability to diffuse through materials (permeability) or to leak through small holes (tightness). The buffer gases and all the candidates must be tested alone in permeability at different temperatures and for different materials (thermoplastics, thermosets and elastomers). This problematic is important, especially with CO2, for which permeability factor is up to 5 orders of magnitude higher than that of SF6 for EPDM, the main elastomer used for seals and gaskets. This coefficient is not negligible with O2 and N2 for which it is about 3 orders of magnitude higher than that of SF6. A specific attention will then have to be taken during the design of the next generations of switchgears regarding the tightness/permeability aspect.

Interactions with materials

In medium voltage switchgears, the insulating gas is surrounded by numerous materials: e.g. insulating and conductive parts, greases, molecular sieves. The insulating gas must then be chemically compatible with all these materials. That means the gas must not be downgraded by surrounding materials and reciprocally.
Two types of tests must be done to validate this hypothesis. The first one consists in analyzing the gases set in contact during a long period, at high temperatures and pressures (to accelerate the phenomena) in order to determine if a gas degradation can be found. The second test consists in setting materials in contact during few months with gases at high temperatures. The mechanical and electrical properties are checked after exposition and compared to the initial ones.
For instance, C5FK is not compatible with greases and molecular sieves currently used and with more stable materials like aluminum (because of alumina) and some elastomers and plastics (because of their water content).
This degradation especially occurs when the temperature is high.

Making of disconnector

Electrical tests must be performed in identical conditions to the most severe operating conditions of the switchgear, i.e. with the partial pressures of gases at the minimal temperature of operating.

Risk of toxicity during the life of switchgear

By-products of gas are generated during the life of the product due to high temperature, partial discharge and reaction of materials. They can be present in the substation at a certain level of concentration in case of leakage or be present in the workshop during the end of life dismantling. Moreover, different by-products of gas may also occur in case of internal arc and be present in the substation. The toxicity of these by-products must be assessed and compared to acceptable levels. These acceptable levels must be defined according to possible concentration inside the substation depending on leakage level, substation volume, ventilation … and possible breathing duration by an operator. LC50 on mice and CMR characteristics are suitable to define the toxicity level. Therefore, some test must be carried out in order to recover these by products with appropriate means:
-long duration test on switchgear under electrical field and high temperature in normal conditions for several months
- Internal arc fault tests

Synthesis of gas characteristics and validation tests

Gas characteristics	boiling point at 1 bar
	buffer gas if mixture
	GWP of gas or mixture
	ODP of gas or mixture
	flammability
	toxicity (LC50 on mice and TWA)
Validation tests	dielectric performance for range of operating temperature
	partial discharge level for range of operating temperature
	temperature rise
	long duration test under electrical field (stability during expected life)
	long duration test to determine interactions gas/materials
	internal arc test
	tightness and permeability
	making of disconnector
	homogeneity of gas mixture
Toxic risk during life of product	by-product analysis after long duration test under electrical field
	by-products analysis after internal arc test

Table 2: gas characteristics and validation tests

CONCLUSION

This paper presents characteristics of candidates to replace SF6 and the validation tests to be carried out in order to ensure safety, reliability and expecting life comparable to SF6 equipment. This validation does not concern only electrical performances but many other topics such as toxicity, tightness, gas/materials compatibility and so on. In particular, safety in case of presence of by-product gases must be ensured in all operating conditions. The ideal candidate is not yet found. Some mixtures of gases are not stable, others generate very toxic by-products, are flammable or react very strongly with materials. The new gas should be a compromise between all these parameters which shall be balanced with the GWP reduction.

REFERENCES

[1] Y. Kieffel et al., SF6 alternative development for high voltage switchgears, Cigré Paper D1-305, Paris, 2014