



21, rue d'Artois, F-75008 PARIS CIGRE US National Committee
<http://www.cigre.org> 2022 Grid of the Future Symposium

Reliability of C4-FN Based Mixtures for SF6-free Distribution Switchgear in North America

A. LASO, M. TEFFERI, N. ILIC, F. PYLE, A. DAUKSAS, K. DARKO, N. UZELAC
G&W Electric
USA

SUMMARY

In this work, two parameters of impact on the reliability of C4-FN mixtures are studied: low temperature performance and switching endurance of C4-FN.

Test data shows that C4-FN based mixtures intended for distribution switchgear require design adaptations in order to match previous SF6 performance and size.

The gas mixtures evaluated are stable under the temperature range for which the switchgear is rated, maintaining their dielectric properties. Under the unlikely event of ambient temperatures lower than rated, the gas mixture may partially liquify. However, dielectric properties won't change drastically, keeping the unit functional. After weather conditions improves (temperature increase), the gas mixture will naturally restore its initial gas mixture homogeneity.

Effects of load current interruption in distribution switchgear don't have a limiting effect on the life expectancy of the device. After strenuous load break sequences over the type test requirement per IEEE C37.74, the devices are capable to maintain the dielectric integrity and their current interruption capabilities.

Finally, C4-FN concentration tolerance is evaluated, showing that wide tolerances may be applicable for distribution switchgear depending on the design safety factor.

KEYWORDS

C4F7N, C4-FN, SF6-free, Fluoronitrile, Dielectrics, Reliability, Alternative gas, Distribution, Switching, Decomposition, Lifetime

1. INTRODUCTION

In the most recent years, manufacturers of gas insulated equipment are focusing their efforts to speed-up the development of SF₆-free solutions. As it's common for new technologies, users tend to be sceptic about adopting them and require proof of reliability. One of the main concerns is the dielectric stability of SF₆ gas alternatives through their life. The media must be capable to maintain its dielectric properties over the lifetime of the switch to guarantee voltage surge and lighting endurance. At the same time, switchgear must be capable to interrupt the currents it's rated for.

For the distribution switchgear, numerous requirements as compactness, customization, visual break, visual ground and filling pressure (15psig) reduce the number of options that are technically feasible. With the aim of fulfilling all these requirements, C4-FN based mixtures were selected as the best candidate to replace SF₆.

C4-FN is a fluorinated carbon nitrile with excellent dielectric properties. However, it tends to liquify much more easily when pressurized than SF₆. Because of this, it requires of a carrier gas to avoid partial liquification and to maintain the concentration stable [1].

Carbon dioxide (CO₂), nitrogen (N₂) and oxygen (O₂) have been often used in combination with C4-FN, reducing the liquification temperature of the gas mixture to values lower than the minimum service temperature.

The selection of the carrier gas is driven by its enhancing properties when mixed with C4-FN. For example, CO₂ possesses a higher heat capacitance that helps with current interruption. On the other hand, N₂ has shown slightly better dielectric properties than CO₂ and lower GWP. O₂ is mainly used for being a non-toxic powerful oxidant.

From previous works [2] C4-FN/CO₂ and C4-FN/O₂/CO₂ mixtures were previously analyzed, showing little impact on the load and cable charging interruption performance between the two. However, C4-FN 15%_{mol} and CO₂ 85%_{mol} showed a better overall dielectric performance due to its higher C4-FN concentration [3][4].

Table I: Gas properties

No.	Gas Mixture	Liquification temperature for 9.5psig filling pressure
1	SF ₆	-64°C
2	5%C4-FN + 95% CO ₂	-56°C*
3	15% C4-FN + 85% CO ₂	-38°C*
4	10% C4-FN + 5%O ₂ + 85% CO ₂	-44°C*
5	13% C4-FN + 87% CO ₂	-41°C*

* Based on Peng-Robinson EOS estimation

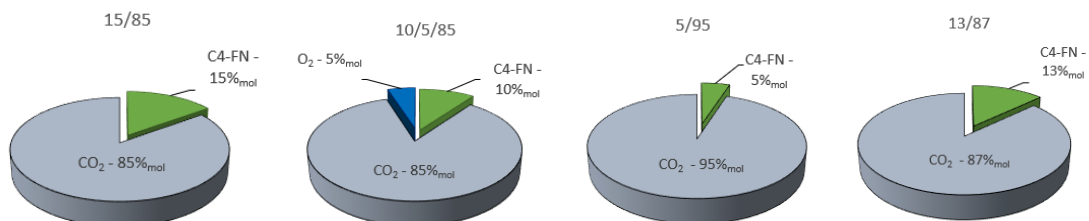


Figure 1: Gas mixtures investigated

2. LOW TEMPERATURE DIELECTRIC PERFORMANCE

2.1 Low temperature gas comparison without partial liquification

Test arrangement

The arrangement consisted of a pressurized compartment with capacity for 3 pairs of electrodes positioned in parallel. These electrodes went through a sliding gas-tight rubber seal. The round electrode was connected to the generator and the flat electrode to ground.

The geometry tested corresponded with a weakly homogeneous field (plane-rod) which is often found in some of the edges in MV switchgear (Figure 2).



Figure 2: Round to plane electrodes (left) and arrangement of electrodes in tank (right)

The compartment was introduced in a temperature-controlled chamber. To reduce the time between series of tests and avoid extended work at low temperatures, the setup allows the connection and disconnection using aerial terminals. A shielded 38kV rated (21.9kV phase-to-ground) cable was used to connect the high voltage signal from the generators located outside the chamber to the inside. A double-elbow connection allows to select between lightning impulse and power frequency without entering the chamber (Figure 3).

Power frequency (60Hz) and lightning impulse (50/1.2 μ s) tests were performed under this configuration for 10mm distance (top and middle electrodes) and 5mm distance (bottom electrodes).

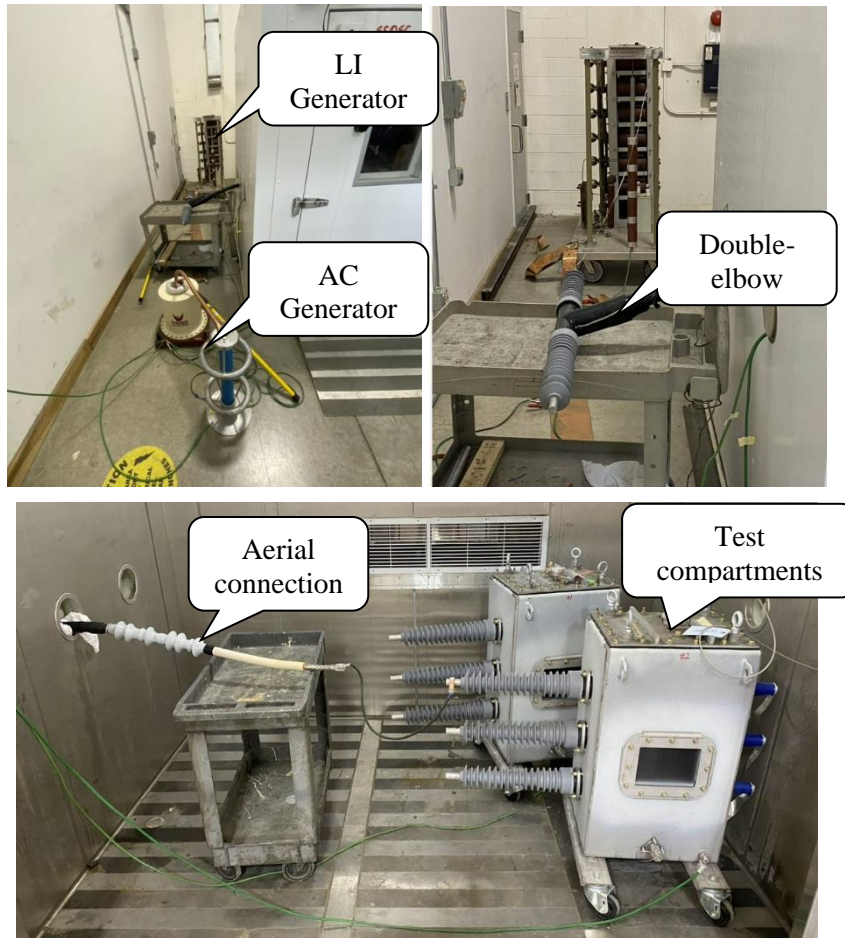


Figure 3: Test arrangement of simple electrodes in temperature chamber

Test results

Results show that all gases maintain their insulation properties at low temperatures (Figure 4). Values of electrical breakdown are shown on the graphs below.

Fluctuations of the electrical breakdown for some of the tests where the breakdown voltage it's lower at high temperatures may be explained by small defects on the electrodes caused by the arc, and shrinkage of the materials that conformed the test arrangement.

All gases maintained their gas composition properties during and after the test sequences.

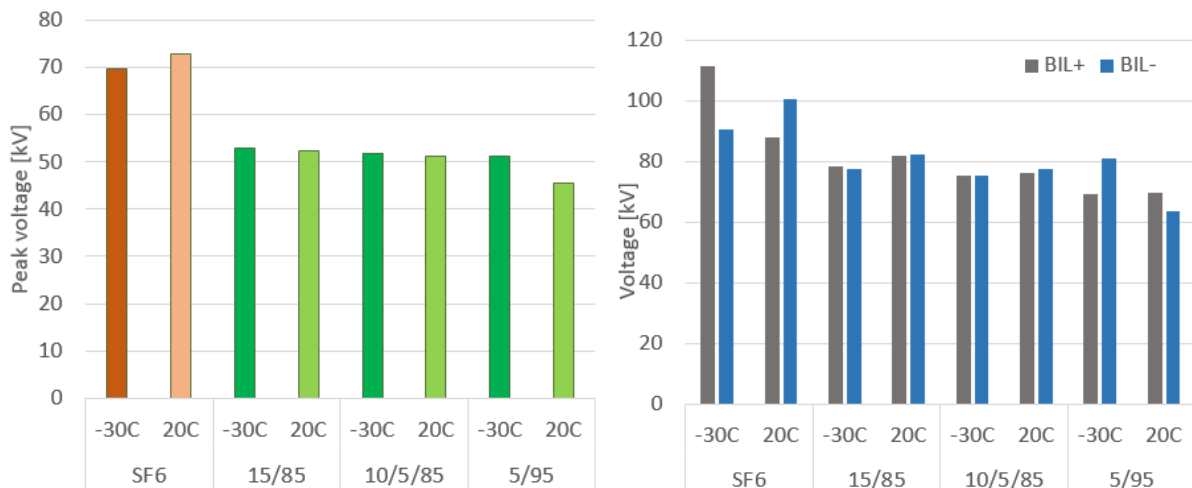


Figure 4: Test results for rod to plane configurations at low temperatures

2.2 Partial liquification of C4-FN at low temperatures

Arrangement

Making use of a 27kV rated (60kV power frequency) rotary switch commonly used for SF6 applications with a volume of 0.1m³, 13%_{mol} C4-FN / 87%_{mol} CO₂ gas mixture was injected, reaching 9.5psig pressure (density ~4.4kg/m³) at 21°C. According to these filling parameters, Peng-Robison model estimates a dew point of -41°C, and NRTL model -45°C. From experimental tests, signs of liquification started at -43°C. Knowing that this temperature is below the minimum rated temperature for this switchgear (-40°C), changes in the sealing materials were implemented to guarantee gas tightness.

The switch was then introduced in a controlled temperature chamber. To measure the gas homogeneity, two gas sampling hoses were connected to an upper and lower port of the gas compartment. These hoses were then externally connected to a manifold to select the gas sampling inlet. A C4-FN gas analyzer based on FT-IR technology was used to measure gas concentration.



Figure 5: Low temperature test arrangement

Test results

C4-FN gas concentration was measured at multiple temperatures. Dwells of 2 hours or more allowed the gas phase to stabilize. The transitions were performed at a rate of 10K/h.

Starting at 22°C, temperature was dropped to -40°C. The concentration didn't change between 20°C and -40°C. For both measurements, the gas composition was practically the same, measuring 13.1-13.4 %_{mol}.

From -40°C, temperature was reduced to -45°C. At this temperature the gas concentration drifted down, registering 11.2-11.4%_{mol}. Concentration was almost the same for the upper and lower side.

By reducing the temperature to -50°C, C4-FN in the gas phase was notably lower, recording 8.8%_{mol} of C4-FN. This has been previously observed on [5].

From here, the temperature was increased to -40°C to allow the liquid phase to gasify. The measurements through the gasification process showed that the concentration increased rapidly at the lower side, reaching a peak after 8hours. From there, the concentration slowly decreases until it reaches the original value. For the upper side, the gas mixture concentration increases slower, reaching the original value after 30hours.

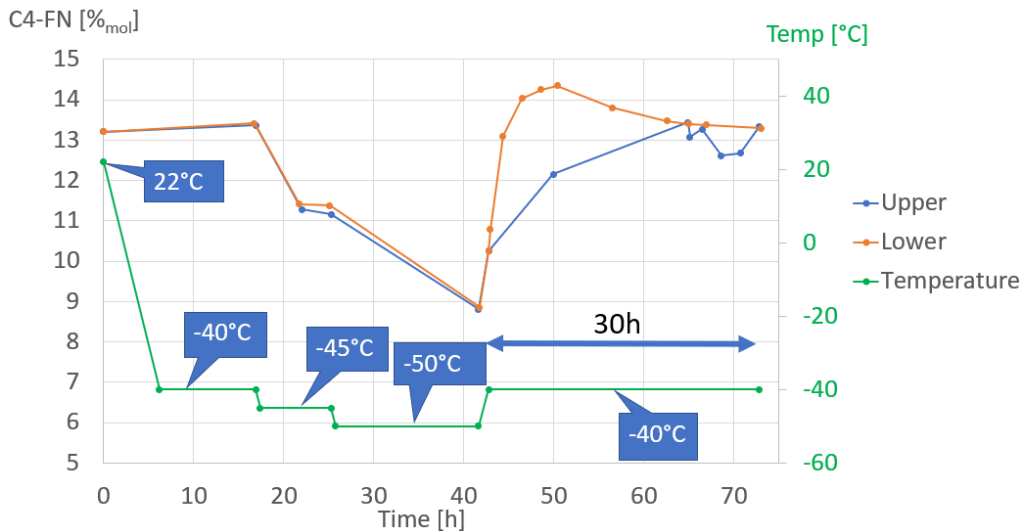


Figure 6: Temperature profile and C4-FN gas composition during partial liquification test

After these measurements, the device was set on temperature cycling, running between -30°C to -50°C , forcing the media to sequentially liquify and gasify for a period of three days with a dwell of 2hours, and a transition rate of 10K/h. After these cycles, the device was brought back to ambient temperature, registering the same gas composition as at the time of filling. However, the device lost 1psi. This may have been caused by the expansion-contraction of the gaskets.

The unit was powered at 80% of the rated power frequency (48kV) for 1 min, with successful results.

As an additional experiment to evaluate effect of temperatures on the homogenization dynamics, the same unit was filled again with 13/87 mixture ratio at 9.5psig, and it was forced to partially liquify at -50°C . After maintaining that temperature for 24h, it was taken out of the chamber and exposed to ambient temperature ($\sim 22^{\circ}\text{C}$). Rapidly after, it was connected to power frequency for 1 min at 80% of the rated value (48kV). After that, the voltage was dropped to 35kV and maintained for 24h. No breakdown was recorded throughout the test. No gas leakage was detected for this experiment.

2 hours after the unit was exposed to ambient temperature the gas media regained its original mixture ratio. Concentration differences between the upper and lower side weren't observed.

3. SWITCHING ENDURANCE

Arcing energy and gas decomposition

As it has been exposed previously, electrical arc events decompose C4-FN molecules during the ionization of plasma, not recombining after. The amount of gas decomposed is calculated based in previous publications [6], using the ratio of C4-FN dissociated per MJ of arcing energy of 0.5mol/MJ.

In the case of distribution switchgear, current interruption it's carried out by the gas media only for load break currents. For fault interruption, fuses and vacuum breakers are commonly used.

The arcing energy it's the best indicator for gas decomposition. It's influenced by current, gas media, arc length and arcing time. The influence of many of these factors it's not linear and it's hard to predict accurately without testing [7].

In the case of arcing time, its influence on arcing energy depends on the arc elongation, heat dissipation and switching technology. By improving the current interruption efficiency of the switch, the required arc length and arcing energy can be effectively reduced.

The gas decomposition has been previously reported for the standard switchgear SF6 design [2]. In this case, load break arcing time using gas alternatives could vary between 17 to 21ms. This variation increased the arcing energy from 2.2kJ to 3.3kJ per shot.

For the new version of rotary switches, changes implemented aimed to increase the efficiency of current interruption and reduce the effects of arc erosion. Material selection and shape of the parts surrounding the arc had a beneficial impact.

The latest tests have shown that arcing time can be reduced to 10ms. This reduction has a large impact on the arcing energy, measuring close to 1.4kJ per shot. This will reduce the arcing energy by nearly half of the value previously reported in [2].

Endurance tests

As part of one of the key aspects of switchgear, endurance test for current interruption was undertaken. Tests were performed over a linear puffer switch, and on the new rotary switch for alternative gas.

The endurance test sequences focused on two aspects: large number of operations at full load, and reduced C4-FN concentration. Arcing time was monitored for all shots. Devices went through power frequency tests per IEEE C37.74 before and after the switching sequences. The test sequence and results are listed on Table II.

Table II: Endurance test sequences

Switch type	Switch ratings	Test sequence	Gas Mixture	Pressure	Avg. Arcing time	Power frequency test
Linear Puffer	27kV/630A	100x 27kV/630A	15% C4-FN + 85% CO2	9.5psig	15ms	60kV - Pass
Rotary Switch	17.5kV/630A	30x 17.5kV/200A	5% C4-FN + 95% CO2	9.5psig	10ms	50kV - Pass
Rotary Switch	17.5kV/630A	75x 17.5kV/200A	15% C4-FN + 85% CO2	9.5psig	13ms	50kV - Pass

The analysis of the results showed that:

- Arcing time increases by reducing the amount of C4-FN in the mixture for the rotary switch.
- Power frequency on the new rotary switch was successful for C4-FN concentrations as low as 5%_{mol}.
- Switching sequence has no observed effect on the power frequency performance of the linear puffer and new rotary switch.
- Devices registered a consistent performance during the load break sequence, even after the long sequences, with arcing times within +/-4ms from the average value for the last pole to clear for the linear puffer, and +/-2ms for the rotary puffer.
- All switch cleared all shots.

4. CONCLUSIONS

SF6-free gas mixtures based on C4-FN/CO₂ mixture have been proven to endure the low temperature and decomposition effects, providing a potential reliable and lasting solution for the power grid.

C4-FN gas mixtures maintain their dielectric properties at low temperatures without partial liquification. For the gas mixture 13%_{mol} C4-FN / 87%_{mol} CO₂ and filling pressure 9.5psig, the gas mixture won't start liquifying until temperature is lower than -43°C. This fulfills the vast majority of the North American low temperature requirements for gas insulated gear applications.

In the event of partial liquification at -50°C, the switch tested is functional and can withstand 80% of its rated power frequency voltage. The gas mixture will homogenize naturally when temperature increases over the dew point. Temperature has an important impact to accelerate the homogenization.

As reported previously, load break gas decomposition of C4-FN has minor effects for MV gear using linear and rotary load breakers. With the redesign of previous SF₆ breakers, the improvement on the arcing energy reduces the gas decomposition even further. Effects on soot formation and CO are also subject to be reduced as well.

Low concentration of C4-FN decreases overall performance mildly. It is likely that the concentration of insulating gas will have a wide tolerance for distribution applications. This will highly depend on the design margins that each manufacturer may apply.

The linear puffer switch and the new SF₆-free rotary switch are capable to endure load break sequences further than the ones required per IEEE C37.74, maintaining their rated power frequency ratings after it.

BIBLIOGRAPHY

- [1] Y. Kieffel, F. Biquez, D. Vigouroux, J. Owens, “*Characteristics of g3 – an alternative to SF6*”, (CIRED, Open Access Proc. J. 2017, p. 1-4)
- [2] A. Laso, M. Tefferi, S. Glomb, N. Uzelac, R. Smeets, “Design considerations for implementing SF₆ alternatives for distribution switchgear applications with focus on toxicity and load break performance” (CIGRE Sessions 2022, A3-136, Paris)
- [1] M. Tefferi, F. Pyle, A. Laso, A. Dauksas, K. Darko, N. Uzelac, A. Scott, W. Xu, “*Streamer Criterion for Desinging Gas-Insulated Medium Voltage Switchgear*”, CEIDP 2022
- [4] B. Zhang, N. Uzelac, Y. Cao “*Fluoronitrile/CO₂ Mixture as an Eco-Friendly Alternative to SF₆ for Medium Voltage Switchgears*”, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 25, No. 4; August 2018
- [5] M. Walter, D. Leguizamon, L. Maksoud, Y. Kieffel, J. Owens, A. Xiao, “*Low temperature behavior and dielectric performance of Fluoronitrile/CO₂/O₂ mixture*”, Cigre Sessions 2020, D1-213, Paris.
- [6] S. Brynda, Y. Park, H. Sohn, T.H. Song, X. Ye, J.D. Mantilla. “*Theoretical and Practical Behaviour of Eco-friendly SF₆ Alternatives in High Voltage Switchgear*”. A3-119, Cigre Session 2020, Paris.
- [7] P. Pietrzak, J. Engelbrecht, Philipp Simka, Henning Janssen, Pascal Devaud, Mahir Muratović and Christian M. Franck. “*Voltage-Current Characteristic of Free Burning Arcs in SF₆ Alternative Gas mixtures*”. ETHZ, Switzerland