doi:10.14311/ppt.2025.3.219
*Plasma Physics and Technology* **12**(3):219–225, 2025 

# AGEING OF $C_4F_7N$ AND $CO_2$-BASED INSULATING GAS MIXTURES BY FREE-BURNING ARCS

A. Subhana[a,*], N. S. Støa-Aanensen[b], F. Mauseth[a]

[a] *Department of Electric Energy, Norwegian University of Science and Technology, Trondheim, 7491, Norway*
[b] *SINTEF Energy Research, Trondheim, 7491, Norway*
[*] arik.subhana@ntnu.no

**Abstract.** This study examines the effects of arc-induced ageing in $CO_2/O_2$ (86.3%/13.7%), $C_4F_7N/CO_2/O_2$ (5%/82%/13%) and $C_4F_7N/CO_2$ (5%/95%) mixtures at 5 bar absolute pressure. The gases were subjected to a series of free-burning arcs with a total energy dissipation relevant to high-voltage circuit breaker applications. The arc voltage remained similar across all mixtures with no significant variation due to ageing or the addition of $C_4F_7N$ and $O_2$. In addition, the influence of the insulating gas on the erosion of the arcing contacts (20% wt. Cu/80% wt. W) was analyzed, and the contact mass loss was found to be relatively higher in the mixtures containing $C_4F_7N$. Decomposition of the gas mixtures was examined through gas chromatography-mass spectrometry analyses. Solid byproducts generated during arcing were analyzed using scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS).

**Keywords:** ageing, arc contact, arc voltage, gas decomposition, $SF_6$-free switchgear.

## 1. Introduction

$SF_6$ gas has been the preferred insulating medium in gas-insulated switchgear (GIS) due to its superior dielectric strength, arc extinguishing capability and thermal properties. However, because of its high global warming potential (GWP) of 24,300 over 100 years [1], research and development in the power sector are now significantly focused on the investigation of eco-friendly substitutes.

Among different alternatives, C4-perfluoronitrile ($C_4F_7N$, CAS number: 42532-60-5, also known as C4-FN) has been identified as a promising candidate for high-voltage applications. It exhibits a dielectric strength more than twice of $SF_6$, while offering a significantly lower GWP (2100 over 100 years). However, its relatively high liquefaction temperature (−4.7 °C) presents challenges for practical applications. To address this, $C_4F_7N$ is commonly used in mixtures with $CO_2$ to achieve reasonable performance at a low liquefaction temperature. $C_4F_7N$ and $CO_2$-based insulating gas mixtures have been commercially deployed in GIS systems rated up to 420 kV [1].

In GIS, the insulating gas gets exposed to electrical discharges such as arcs during breaking operations, which involve very high temperatures that cause decomposition and ionization of the gas. In contrast to $SF_6$, the decomposition products of $C_4F_7N$ and $CO_2$-based mixtures may not readily recombine, potentially causing long-term changes in gas composition. This gradual alteration of the gas may lead to ageing and degradation of its dielectric properties and overall chemical integrity. Understanding the consequences of such ageing is critical to ensure the long-term reliability and resilience of future power systems.

Previous research has explored the dielectric and interruption performance of $C_4F_7N$-$CO_2$ insulating gases, including their arc voltage-current characteristics [2–6]. Investigations have also been conducted into their arc-induced decomposition [6–8]. Several studies have investigated the impact of arcing on contact erosion in $CO_2$ (e.g., [7, 9–11]), while Pietrzak et al. [7] further examined contact erosion in $CO_2/O_2$ and $C_4F_7N/CO_2/O_2$ mixtures. However, analyzing the decomposition products of heavily aged gas mixtures remains a challenge that demands comprehensive laboratory techniques. While some insight into contact erosion in $C_4F_7N$-$CO_2$ based mixtures exists from [7], further research is still needed to develop a more complete understanding. Moreover, the impact of arc-induced ageing on arc voltage–current characteristics has not been extensively investigated, particularly under discharge energy levels representative of real switchgear operations. The amount of byproducts formed during electrical arcing can vary depending on the energy deposition in the arc channel, which is itself a function of both arc voltage and current. While the current is typically governed by the external circuit, the arc voltage depends on intrinsic parameters, e.g., the composition and pressure of the insulating medium, the contact gap, forced cooling, and the materials, geometry, and surroundings of the contacts.

This study examines the effects of arc-induced ageing on arc voltage characteristics, gas decomposition and contact erosion in $CO_2/O_2$ (86.3%/13.7%), $C_4F_7N/CO_2/O_2$ (5%/82%/13%) and $C_4F_7N/CO_2$ (5%/95%) mixtures at 5 bar absolute pressure. The gases were subjected to a series of free-burning arcs with energy levels representative of high-voltage (HV) circuit breaker (CB) applications. The findings can provide a foundation for future advancements in the design of $SF_6$-free GIS.

## 2. Estimation of energy dissipation in an HV CB

In order to achieve a relevant ageing level, the energy dissipation during arc discharges in a 145 kV, 40 kA CB was calculated. IEC Standard 62271-310 specifies electrical endurance testing requirements for circuit breakers rated above 52 kV. These test programs are based on the cumulative electrical stress from current interruptions over a 25-year period, representing a typical maintenance-free service interval. For a rated short-circuit breaking current of 40 kA, the test sequence includes 10 T60 and 9 T10 breaking operations, corresponding to 60% (24 kA) and 10% (4 kA) of the rated short-circuit current, respectively. An average arcing time of 14 ms was assumed based on typical site conditions with average transient recovery voltages. Furthermore, sample arc voltage measurements in a 145 kV, 40 kA circuit breaker filled with a gas mixture of 82% $CO_2$/13% $O_2$/5% $C_4F_7N$ showed average arc voltages of approximately 357 V for T60 and 438 V for T10 test duties. Based on these values, the total energy dissipated throughout the test sequence amounts to approximately 1.4 MJ per phase.

The IEC 62271-310 standard also provides estimates for the number of breaking operations at different interrupted current levels over a 25-year service period. For a rated short-circuit breaking current ($I_r$) of 40 kA, the standard anticipates 21 operations when the interrupted current ($I_{sc}$) is $\leq 0.1\, I_r$, 25 operations for $0.1 < I_{sc}/I_r \leq 0.3$, and 4 operations for $0.3 < I_{sc}/I_r \leq 0.6$. Taking the midpoint values of each current range and estimating the corresponding energy per operation by interpolation between the T10 and T60 values derived earlier, the total energy becomes around 1.7 MJ per phase for an average arcing time of 14 ms.

Based on the two calculation approaches outlined above, a total arc energy of approximately 1.5 MJ per phase can be considered representative of the electrical endurance requirements over 25 years for a 145 kV, 40 kA CB filled with $CO_2/O_2/C_4F_7N$. This corresponds to a total of 4.5 MJ in three phases for a gas volume of 780 L at a filling pressure of 7.5 bar. As described in the next section, the experimental setup used in this study involves a 130 L pressure vessel. With a filling pressure of 5 bar (absolute), the energy dissipation required to achieve a comparable level of ageing would be approximately 500 kJ.

## 3. Experimental methods

### 3.1. Test setup and circuit

The experimental setup is schematically depicted in Figure 1 and more details can be found in [12, 13].

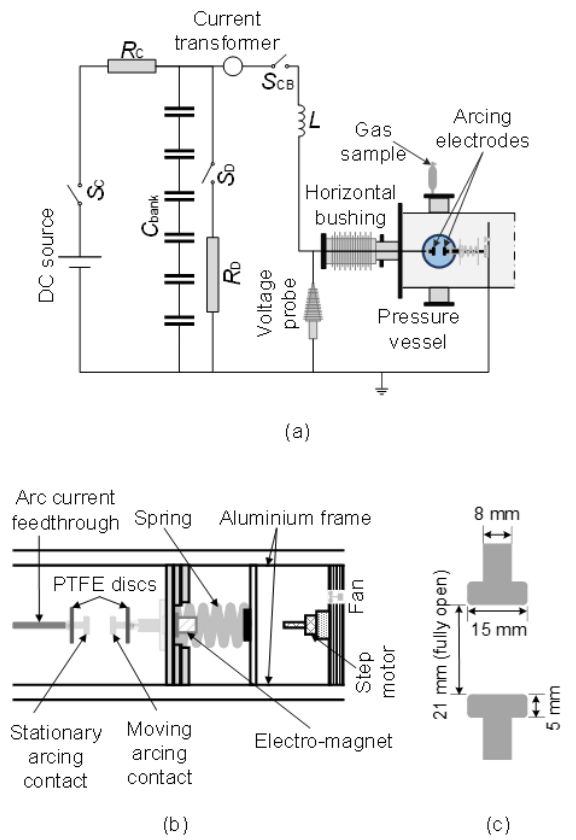


*Figure 1. Schematic depiction of the test setup. (a) The test circuit and pressure vessel. (b) The arcing setup inside the vessel. (c) The arcing contacts.*

The ageing was carried out by discharging a 6-stage capacitor bank ($C_{bank}$, total capacitance 167 µF) across a pair of arcing contacts (20% wt. Cu /80% wt. W) housed in a 130 L cylindrical stainless steel pressure vessel. The arc contacts were cylindrical with slightly rounded edges and had a diameter of approximately 15 mm (Figure 1(c)). The thickness was around 5 mm, with minor variations across different test series. The contacts were initially closed by compressing a spring using a stepper motor and held in position by an electromagnet. The capacitor bank was charged to 20 kV using an HVDC source, resulting in a first peak current of around 1000 A during discharge. A synchronized closing signal for $S_{CB}$ and an opening signal for the arc contacts de-energized the electromagnet, thus releasing the spring and initiating the arc as $C_{bank}$ discharged across the separating contacts. With a 34.7 mH inductor ($L$) in the circuit, the arc current frequency was approximately 60 Hz. The arc contact gap reached approximately 21 mm when fully open. The design produced free-burning arcs, with PTFE back-plates preventing arc commutation to adjacent components. Fans (12 V, 800 mW; 12 V, 720 mW; and 12 V, 7.2 W) were installed in the vessel for effective gas mixing and homogenization after ageing.

| Test series | 1 | 2 | 3 |
|---|---|---|---|
| Gas mixture | $CO_2/O_2$ | $C_4F_7N/CO_2/O_2$ | $C_4F_7N/CO_2$ |
| Ageing (energy deposition), cumulative [kJ] | 530 | 597 | 529 |
| Ageing (charge transfer), cumulative [As] | 2367 | 3082 | 2296 |
| No. of ageing operations | 50 | 62 | 49 |
| Average energy deposition per operation [kJ] | 10.6 | 9.6 | 10.8 |
| Average charge transfer per operation [As] | 47.3 | 49.7 | 46.9 |

*Table 1. Test series overview*

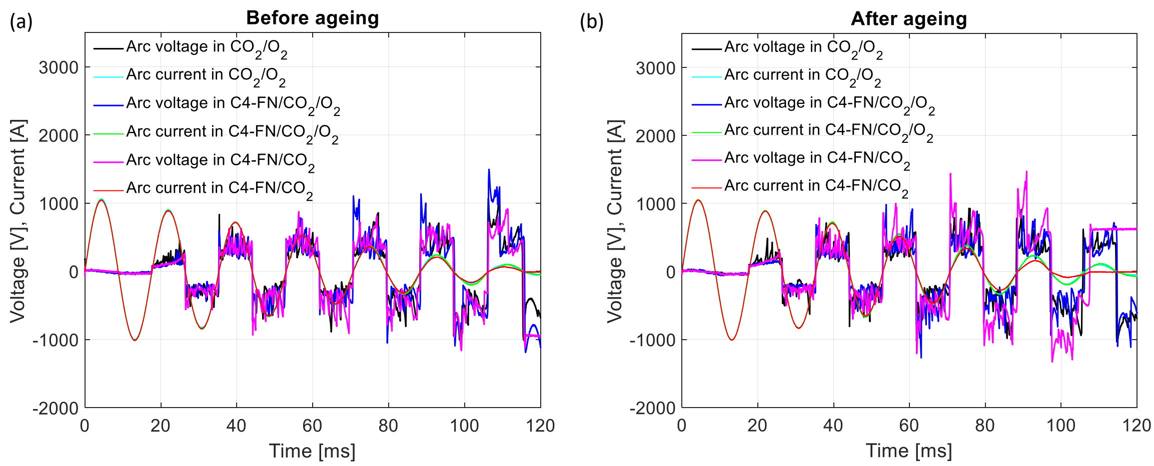


*Figure 2. Arc voltage and current (a) before and (b) after ageing. The "before ageing" plot corresponds to the first arc shot, whereas the "after ageing" plot represents the shot applied after around 530 kJ of cumulative energy deposition.*

### 3.2. Test procedure

After evacuation to below 1 mbar, the pressure vessel was flushed with 1 bar of $CO_2$, re-evacuated, and then filled with the target gas mixture. The 86.3% $CO_2$/13.7% $O_2$ mixture was pre-mixed but the $C_4F_7N$ mixtures were prepared in the vessel by partial pressure filling, i.e., first with $C_4F_7N$ to 0.25 bar, followed by $CO_2$ or the $CO_2/O_2$ mixture until 5 bar, yielding 5% $C_4F_7N$/95% $CO_2$ or 5% $C_4F_7N$/82% $CO_2$/13% $O_2$ mixture, respectively. To make sure the mixture was homogeneous, the fans were operated for more than half an hour. A clean and polished set of arcing contacts was used in each test series, with their mass measured before and after the tests using a precision balance.

To assess the effect of ageing, arc voltage-current characteristics were compared between the newly filled gas mixture and after it was exposed to consecutive arcs with a total energy dissipation relevant to high-voltage circuit breaker applications as described in section 2. The arc energy was derived from the time integral of the product of the recorded arc voltage and current. No compensation was made for stray inductance, connection resistance or electrode voltage drop in the energy calculation; however, voltage readings prior to contact separation were found to be negligible.

To analyze the decomposition characteristics of the gas mixtures, gas samples were collected before and after ageing through a valve from the test vessel to 150 mL vacuumed steel cylinders in case of the $CO_2/O_2$ mixture and to 300 mL steel cylinders with internal PTFE coating for the $C_4F_7N$ mixtures. PTFE is chemically inert, preventing absorption and corrosion from the decomposition byproducts of $C_4F_7N$ during transportation or storage [1, 14]. The byproducts were identified using gas chromatography-mass spectrometry (GC-MS) analysis, performed with an Agilent 7890/5977 GC/MS system equipped with GS-Gaspro 30 m × 0.32 mm GC columns. In case of solid byproduct formation, scanning electron microscope (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS) was employed to examine the composition.

## 4. Results and discussion

This section presents the results from three test series conducted in $CO_2/O_2$ (86.3%/13.7%), $C_4F_7N/CO_2/O_2$ (5%/82%/13%) and $C_4F_7N/CO_2$ (5%/95%) gas mixtures, as summarized in Table 1. The total energy dissipated during the arc operations ranged between 529 – 597 kJ. Table 1 also provides the cumulative charge transfer during ageing, which varied from 2296 As to 3082 As depending on the number of arc operations. On average, each arc operation resulted in an energy dissipation of approximately 10 – 11 kJ and a charge transfer of 47 – 50 As. The accumulated energy and charge transfer were higher in test series 2, as additional arcing operations were carried out for a separate investigation into breakdown performance. This falls outside the scope of this work and will be presented elsewhere.

### 4.1. Arc voltage and current

The arc voltage and current waveforms recorded in the virgin and aged gas mixtures are shown in Figure 2 for the three test series, with "before ageing" referring to the first arc shot (Figure 2(a)) and "after ageing" to the shot applied after approximately 530 kJ of cumulative energy deposition (Figure 2(b)). The arc voltage magnitude and waveshape appeared to be similar across all mixtures with no significant variation due to ageing or the addition of $C_4F_7N$ and $O_2$. Free-burning arcs typically exhibit significant fluctuations, characterized by frequent elongation and then contraction to shorter paths [5]. This leads to noticeable fluctuations in the arc voltage waveshape, as shown in Figure 2.

Figure 3 plots the mean arc voltages for all the studied mixtures, where the arc voltages were averaged over the corresponding current half-cycles. In addition, three arcing shots were taken into consideration in each error bar and the scatter represents the respective maximum and minimum values. As can be seen, the arc voltage increased over time, with the mean value reaching approximately 500 V. This is likely due to arc elongation as the contact gap widened from 0 to 21 mm. While the arc voltage can depend on current, in the studied current range it is expected to remain constant or decrease slightly as the current decreases [15]. Although this may vary with the medium, observations by Pietrzak et al. [5] indicate that in $CO_2/O_2$ and $C_4F_7N/CO_2/O_2$ mixtures the voltage remains fairly constant in the studied current range. Therefore, the observed increase in arc voltage over time, despite the decreasing current, can be attributed primarily to arc elongation. It can also be seen from Figure 3 that, for any given current half-cycle, the arc voltage did not exhibit a systematic dependence on ageing or the presence of $O_2$ or $C_4F_7N$ in the mixture. The observed deviations between the investigated mixtures were within the range of scatter and are therefore considered negligible. Similar observations were reported in previous studies by Pietrzak et al. [5] and Luo et al. [16]. The investigations by Pietrzak et al. showed no significant variation in arc voltage due to the addition of $O_2$ or $C_4F_7N$ to $CO_2$ [5]. Similarly, Luo et al. reported no clear trend in arc voltage as the mixing ratio of $C_4F_7N/CO_2$ mixture was varied [16]. This may explain why the arc voltage in the $C_4F_7N$ mixtures did not vary significantly after ageing in the present study, despite the anticipated reduction in $C_4F_7N$ concentration due to arc-induced decomposition.

Although no systematic differences in arc voltage were observed among the three gas mixtures, the average energy per arcing operation was slightly lower for the $C_4F_7N/CO_2/O_2$ mixture (9.6 kJ) compared to

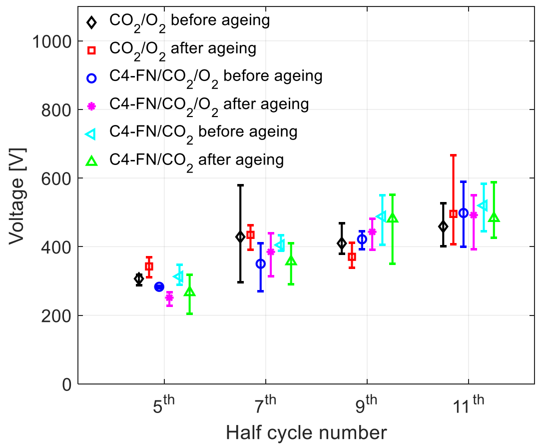


*Figure 3. Average arc voltage across current half-cycles.*

the other two test series (10.6 − 10.8 kJ), as shown in Table 1. This deviation may stem from stochastic variations of the electric arc or some intrinsic difference of the $C_4F_7N/CO_2/O_2$ mixture compared to the other two mixtures. More investigations are needed to draw definitive conclusions regarding the underlying cause.

### 4.2. Arc contact erosion

In this section, the influence of the insulating gas on the erosion of the arcing contacts is analyzed. The contacts exhibited visible ablation traces (Figure 4) and mass loss after the arcing operations (Table 2). Since the arc current was alternating, the mass loss was comparable for both contacts, as expected in real AC switching applications. On average, the mass loss was relatively higher in the mixtures containing $C_4F_7N$. In a previous ageing study by the authors [13], arcs dissipating cumulative energies representative of medium voltage applications led to a lower erosion rate (mass loss per unit energy or charge transfer) of CuW contacts in 1.3 bar technical air (79% $N_2$, 21% $O_2$) and technical air with 7.5% $C_5F_{10}O$ mixture compared to the mixtures examined in the present work. In contrast, Pietrzak et al. reported a higher erosion rate (mass loss per unit charge transfer) in air compared to different $CO_2$ based mixtures, the latter leading to similar erosion irrespective of the addition of $O_2$ or $C_4F_7N$ [7]. That study involved unipolar arc currents, which led to unequal erosion of the anode and cathode. It should be emphasized that only one set of contacts has been used in the present study and in [7, 13]; therefore, further experiments with more samples are necessary to draw definitive conclusions regarding the influence of gas composition on contact erosion.

### 4.3. Gas decomposition

Table 3 provides a list of the decomposition products identified in the aged gas mixtures. Several decomposition byproducts, such as $CF_4$, $C_2F_6$, $C_3F_8$, $C_2F_3N$, $C_3F_6$, $C_4F_{10}$, and $C_2N_2$ were found in the aged $C_4F_7N$ mixtures. These compounds have also

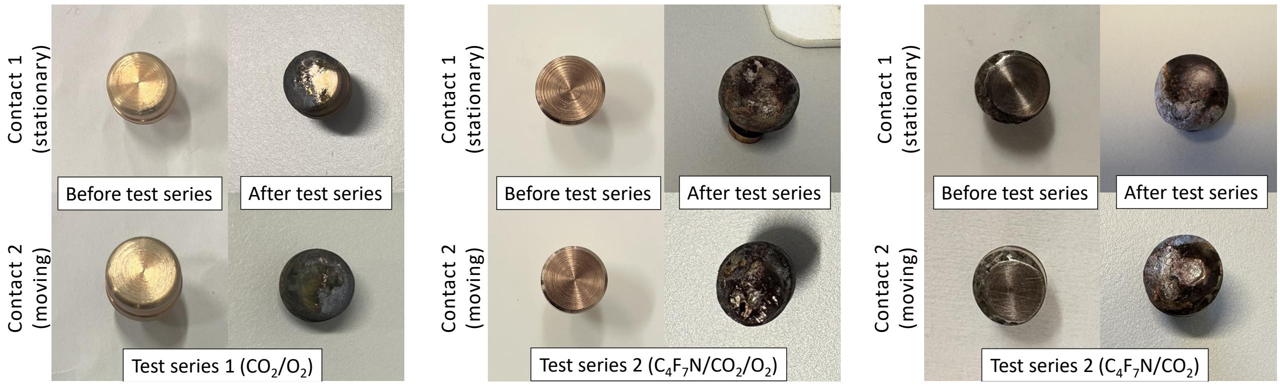


*Figure 4. Arcing contacts before and after the test series in $CO_2/O_2$ mixture (left), $C_4F_7N/CO_2/O_2$ mixture (middle), and $C_4F_7N/CO_2$ mixture (right). For each case, the fresh contacts are shown on the left and the used contacts on the right. The top row shows stationary contacts, while the bottom row shows moving contacts. Colors may appear slightly different due to variations in lighting or printing quality.*

| Gas mixture | $CO_2/O_2$ | $C_4F_7N/CO_2/O_2$ | $C_4F_7N/CO_2$ |
|---|---|---|---|
| Weight, before [g] | 27.90, 25.75 | 19.79, 19.77 | 17.48, 17.51 |
| Weight, after [g] | 27.21, 25.16 | 18.41, 18.31 | 16.59, 16.60 |
| Weight loss [%] | 2.47, 2.28 | 6.98, 7.41 | 5.07, 5.21 |
| Weight loss [mg/kJ] | 1.3, 1.11 | 2.31, 2.45 | 1.67, 1.73 |
| Weight loss [mg/As] | 0.29, 0.25 | 0.45, 0.48 | 0.39, 0.40 |

*Table 2. Weight of both arcing contacts before and after the test series. In each cell, the first value before the comma corresponds to contact 1 (stationary), and the second value to contact 2 (moving).*

| $CO_2/O_2$ | $C_4F_7N/CO_2/O_2$ | $C_4F_7N/CO_2$ |
|---|---|---|
| $CF_4$ | $CF_4$ | $CF_4$ |
| | $C_2F_6$ | $C_2F_6$ |
| | $C_3F_8$ | $C_3F_8$ |
| | $C_2F_3N$ | $C_2F_3N$ |
| | $C_3F_6$ | $C_3F_6$ |
| | $C_4F_{10}$ | $C_4F_{10}$ |
| | $C_2N_2$ | $C_2N_2$ |
| powder | powder | powder |

*Table 3. Decomposition byproducts due to arcing in the studied gas mixtures.*

been detected in previous studies on the decomposition of $C_4F_7N$-based mixtures due to electric discharges [1, 6–8, 14, 17]. As shown in Table 3, gas analysis of the two $C_4F_7N$ mixtures ($C_4F_7N/CO_2/O_2$ and $C_4F_7N/CO_2$) revealed no significant effect of $O_2$ on byproduct formation. This observation is consistent with the findings reported in [17].

As shown in Table 3, the aged sample of the $CO_2/O_2$ mixture contained $CF_4$, which is likely attributable to ablation of the PTFE plates near the arcing contacts. The high arc temperature can degrade PTFE and break its polymer chains, with $CF_4$ being a known pyrolysis byproduct [18].

It should be noted that the list of decomposition byproducts in Table 3 is not exhaustive. For example, CO, commonly reported as a major byproduct [1, 6, 7, 14, 17], was not detected in the GC-MS analysis. The separation was likely insufficient to resolve overlapping or co-eluting peaks in this case, indicating that some species may require different analytical methods for reliable identification.

In addition to gaseous byproducts, solid residues in the form of powdery dust were observed inside the vessel following arcing, as shown in Figure 5. The dust appeared grey to dark grey in color, with slight variations depending on the gas mixture. In the case of the $C_4F_7N/CO_2$ mixture, the particles were predominantly black. The lighter color of the dust observed in the $CO_2/O_2$ and $C_4F_7N/CO_2/O_2$ mixtures suggests that the presence of $O_2$ may inhibit carbon deposition during arc discharges. Similar findings were reported in [19], where lighter colored solid residues were noted in $C_4F_7N/CO_2/O_2$ compared to $C_4F_7N/CO_2$ mixtures. EDS analysis revealed that C, O, F, Cu and W were the main elements present in the solid residues in all gas mixtures. The presence of fluorine in the residue from the $CO_2/O_2$ mixture suggests that the degradation of the PTFE plates may have contributed fluorinated species to the solid byproducts. The presence of significant amounts of Cu and W confirms erosion of the CuW arcing contacts. Notably, higher levels of Cu were detected in the residue from the $C_4F_7N/CO_2$ mixture, which may suggest the formation of copper fluorides as a result of reactions between Cu and the decomposition products of $C_4F_7N$. In contrast, in the two mixtures containing $O_2$, the lower Cu content

*Figure 5. Solid residues observed after arcing. Samples of the solid byproducts collected in a glass container after ageing of the $CO_2/O_2$ mixture (left). Solid byproduct observed inside the vessel after arcing in the $C_4F_7N/CO_2/O_2$ mixture (middle). In the case of the $C_4F_7N/CO_2$ mixture, the solid residues were predominantly black (right). Colors may appear slightly different due to variations in lighting or printing quality.*

could be attributed to the formation of a protective copper oxide layer on the contacts, which may have mitigated further erosion. However, further investigation is required in this regard.

A comparison of the arc voltage before and after ageing (Figure 2 and 3) suggests that the decomposition byproducts have no significant influence on the voltage characteristics of the free-burning arc. However, since many of these byproducts have lower dielectric strength than $C_4F_7N$, they might degrade the overall insulation performance. Due to the presence of different compounds in the aged gas, comprehensive experimental investigation is necessary to conclusively assess their effect. More findings on gas decomposition (including quantitative data) and its impact on insulation performance will be presented in future publications.

## 5. Conclusions

This study examines the effects of arc-induced ageing on the arc voltage characteristics, gas decomposition and arc contact erosion in $CO_2/O_2$ (86.3%/13.7%), $C_4F_7N/CO_2/O_2$ (5%/82%/13%) and $C_4F_7N/CO_2$ (5%/95%) mixtures at 5 bar absolute pressure. The gases were subjected to a series of free-burning arcs with a total energy dissipation relevant to high-voltage circuit breaker applications. The key observations are:

- The arc voltage remained similar across all mixtures with no significant variation due to ageing or the addition of $C_4F_7N$ and $O_2$.
- The contact mass loss was found to be relatively higher in the mixtures containing $C_4F_7N$. However, further experiments with more measurements are necessary to draw definitive conclusions regarding the influence of gas composition on contact erosion.
- Several decomposition byproducts, such as $CF_4$, $C_2F_6$, $C_3F_8$, $C_2F_3N$, $C_3F_6$, $C_4F_{10}$, and $C_2N_2$ were found in the aged $C_4F_7N$ mixtures. In contrast, the aged $CO_2/O_2$ sample contained only $CF_4$, which is likely attributable to the ablation of nearby PTFE plates during arcing.

Powdery solid residues were observed inside the vessel after arcing, with colors ranging from grey to black depending on the gas mixture. The lighter color of the powder in mixtures containing $O_2$ suggests that oxygen may suppress carbonaceous deposits. C, O, F, Cu and W were found to be the main constituents of the solid residues in all gas mixtures.

While arc voltage remained largely unaffected by arc-induced decomposition, the presence of different byproducts may affect the insulation performance. Further analysis of gas decomposition and its effect on dielectric performance will be reported later.

## Acknowledgements

The authors express their gratitude to Cédric Lesaint, Anita Skogholt, Anders Brunsvik and Caterina Rusu for the chemical analyses and to François Biquez for the estimation of the target ageing level. The authors also thank Erik Jonsson Seither and Oddgeir Rokseth for their contributions. This research is financed by the Norwegian Research Council under project number 319930.

## References

[1] W. Wang, X. Yan, H. Wang, and K. Gao. Comparative studies of $C_4F_7N$-based gas mixtures as the eco-friendly alternative to $SF_6$ for interrupting applications. *High Voltage*, 2025. doi:10.1049/hve2.70003.

[2] J. Y. Na, R. Hwang, S. J. Cho, et al. Breakdown characteristics of a fluoronitrile mixture gas according to mixing ratio and oxygen content for high-voltage power equipment application. *IEEE Access*, 12:16117–16126, 2024. doi:10.1109/ACCESS.2024.3359304.

[3] B. Zhang, N. Uzelac, and Y. Cao. Fluoronitrile/$CO_2$ mixture as an eco-friendly alternative to $SF_6$ for medium voltage switchgears. *IEEE Transactions on Dielectrics and Electrical Insulation*, 25(4):1340–1350, 2018. doi:10.1109/TDEI.2018.007146.

[4] B. Zhang, R. Zhou, K. Wang, et al. Arc interruption performance of $C_4F_7N$-$CO_2$ mixture in a 126 kV disconnector. *IEEE Transactions on Power Delivery*, 38(2):1197–1207, 2022. doi:10.1109/TPWRD.2022.3210381.

[5] P. Pietrzak, J. T. Engelbrecht, P. Simka, et al. Voltage–current characteristic of free burning arcs in $SF_6$ alternative gas mixtures. *IEEE Transactions on Plasma Science*, 50(11):4744–4752, 2022. doi:10.1109/TPS.2022.3210995.

[6] W. Wang, K. Gao, X. Yan, et al. Numerical study of the arc-quenching performance of eco-friendly $C_4F_7N/CO_2/O_2$ gas mixtures. *Journal of Physics D: Applied Physics*, 58(18):185207, 2025. doi:10.1088/1361-6463/adc60c.

[7] P. Pietrzak, M. Perret, M. Boening, et al. Wear of the arcing contacts and gas under free burning arc in $SF_6$ alternatives. *IEEE Transactions on Power Delivery*, 38(3):2133–2140, 2023. doi:10.1109/TPWRD.2023.3234364.

[8] G. Qi, F. Yuan, Y. Zheng, et al. Research on the aging judgment method of electrical performance of $C_4F_7N/CO_2$ mixed gases. In *Journal of Physics: Conference Series*, volume 2774, page 012061. IOP Publishing, 2024. doi:10.1088/1742-6596/2774/1/012061.

[9] Y. Zhou, J. E. Humphries, J. W. Spencer, et al. Contact erosion at high currents in high-voltage gas circuit breakers—part I: Experimental research and material testing. *IEEE Transactions on Power Delivery*, 2024. doi:10.1109/TPWRD.2024.3520027.

[10] Y. Zhou, J. E. Humphries, J. W. Spencer, et al. Contact erosion at high currents in high-voltage gas circuit breakers—part II: Assessment of energy balance of arc-electrode. *IEEE Transactions on Power Delivery*, 2024. doi:10.1109/TPWRD.2024.3519952.

[11] Y. Zhou, J. E. Humphries, J. W. Spencer, et al. Contact erosion induced by free-burning arcs in an experimental gas circuit breaker. *IEEE Transactions on Power Delivery*, 2025. doi:10.1109/TPWRD.2025.3543855.

[12] A. Subhana, N. S. Støa-Aanensen, M. Gammelsæter, and F. Mauseth. Laboratory setup for ageing of new environmentally friendly insulation gases. In *Proceedings of the 23rd International Conference on Gas Discharges and their Applications*, pages 358–361, 2023.

[13] A. Subhana, N. S. Støa-Aanensen, M. Gammelsæter, et al. Ageing of technical air and technical air with 7.5% C5-Fluoroketone by free-burning arcs. *Plasma Physics and Technology*, 10(2):89–93, 2023. doi:10.14311/ppt.2023.2.89.

[14] B. Zhang, C. Li, J. Xiong, et al. Decomposition characteristics of $C_4F_7N/CO_2$ mixture under AC discharge breakdown. *AIP Advances*, 9(11), 2019. doi:10.1063/1.5115588.

[15] K. Niayesh and M. Runde. *Power Switching Components: Theory, Applications and Future Trends*. Power Systems. Springer, 2017. ISBN 978-3-319-51460-4. URL: https://link.springer.com/book/10.1007/978-3-319-51460-4.

[16] Y. Luo, W. Wang, R. Zhuo, et al. Current interruption characteristics of $C_4F_7N/CO_2$ mixture in a load switch. In *2020 IEEE International Conference on High Voltage Engineering and Application (ICHVE)*, pages 1–4. IEEE, 2020. doi:10.1109/ICHVE49031.2020.9279898.

[17] P. Pietrzak, J. T. Engelbrecht, D. Kumari, and C. M. Franck. Short-line fault interruption performance comparison of $SF_6$ alternatives. *IEEE Transactions on Power Delivery*, 2024. doi:10.1109/TPWRD.2024.3451178.

[18] W. E. Coleman, L. D. S. Ph.D., R. E. Kupel, and R. L. Larkin. The identification of toxic compounds in the pyrolysis products of polytetrafluoroethylene (PTFE). *American Industrial Hygiene Association Journal*, 29(1):33–40, 1968. doi:10.1080/00028896809342978.

[19] D. Guo, X. Li, W. Wang, and Z. Geng. Effect of the arc extinguishing and insulation properties of $C_4F_7N/CO_2$ mixtures with oxygen addition: Experimental investigations and comparative analysis. *Energies*, 17(17):4202, 2024. doi:10.3390/en17174202.