Application of SF6 Alternatives for Retro-filling Existing Equipment

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— Summary

Sulphur hexafluoride (SF_6) is a gas which has been widely used in gas insulated switchgear (GIS), lines (GIL) and busbars (GIB) as an interruption and insulation medium since the 1960s. The environmental concerns regarding SF_6 usage, the most potent greenhouse gas known, have motivated researchers to find a more environmentally sound alternative as a replacement for SF_6. While most of current research focuses on developing state-of-the-art high voltage (HV) equipment specifically designed for alternative gases, this work investigates the feasibility of retro-filling existing SF_6-designed equipment. This is a more economic and time-saving solution to phase out the usage of SF_6 for the power industry. The first step towards the development of a retro-fill solution is to trial various SF_6 alternatives with the specific aim of identifying a suitable mixture combination for use in existing gas insulated assets.

A reduced-scale coaxial prototype was developed to determine a technically feasible gas mixture that can match the breakdown performance of SF_6 under standard lightning impulse voltage waveform (1.2/50 µs). Breakdown results demonstrate that a 20% C_3F_7CN and 80% CO_2 gas mixture exhibits comparable insulation capability to SF_6 in coaxial geometries with similar field uniformity as found in GIL/GIB. A full-scale SF_6 -designed 420/550 kV rated gas insulated demonstrator was assembled and retro-filled with a 20% C_3F_7CN and 80% CO_2 gas mixture. The demonstrator was type tested under Switching Impulse (SI), Lightning Impulse (LI) and Power Frequency (AC) voltages in accordance with IEC 62271-204. Type test results have shown that the gas mixture can pass the withstand voltage tests at the specified voltage levels for SF_6 gas under similar operating conditions. This work has demonstrated that a mixture of 20% C_3F_7CN and 80% CO_2 could be a viable candidate for replacing SF6 in HV insulation applications without the need for

changing the operating conditions (i.e. rated pressure) of the equipment. This is an encouraging step towards the potential phase out of SF6 in passive components installed across the transmission and distribution networks in the UK.

— 1. Introduction

Greenhouse gas emissions generated by human activities are a key contributing factor towards climate change. There is an increasing emphasis by the power industry to facilitate the transition to Net Zero. One key measure is the continued effort in the search for a more environmentally sound replacement of SF_6, a man-made gas with a global warming potential (GWP) 23,500 times greater than CO2 and a long atmospheric lifetime [1]. It is mainly used in gas insulated equipment across the transmission and distribution networks to provide dielectric insulation and arc interruption. The power industry presently accounts for 80% of the global SF6 inventory [2]. In the UK, it is estimated that the combined SF_6 installed mass in the electricity network is approximately 1,500 t or 35 MtCO2e, with annual SF_6 leak of 0.5 MtCO2e from 2015 to 2018 [3]. For National Grid Electricity Transmission (NGET), the majority of SF_6 is used in passive components which are the focus of this investigation. Without viable alternatives, these figures will increase drastically in the coming decades as the electricity networks continue to phase out ageing air-blast and oil-insulated switchgear with compact SF_6 equipment.

Recent SF_6-free installations use new equipment optimized by manufacturers for Novec™ 4710 and Novec™ 5110 insulating gases [4, 5]. While this is intended to reduce overall SF_6 emissions, it requires considerable investment and replacing all existing SF_6-filled assets worldwide with new-builds is time consuming. An alternative approach and the aim of this study is to investigate the feasibility of retro-filling existing SF_6-filled passive components with alternative gases. This paper provides an overview of the SF_6 replacement research work that has been carried out at The University of Manchester. The paper includes: (a) a review of SF_6 alternatives; (b) insulation characteristics of SF_6 alternatives tested for reduced-scale prototypes; (c) the development and validation of an industrial scaled gas insulated demonstrator designed for SF_6 when the gas is replaced with a chosen gas candidate; and (d) IEC specified standard type test and non-standard type test results using the demonstrator.

— 2. Selection Process of SF6 Alternatives

Any new candidate must have a considerably lower GWP than SF_6, but also satisfy a strict list of technical requirements such as high dielectric strength, good arc-quenching capability, low boiling point as well as being chemically stable, non-flammable, and low in toxicity. The aim of this work is to retro-fill existing SF_6-designed transmission equipment. This means that the candidate must possess similar or better dielectric performance than SF_6, but also be able to remain gaseous at the rated operating pressure of 4.5 bar [6]. Note that all pressures presented in this paper are in absolute value. Based on the literature, four promising fluorinated

gases are shown in Table 1 and their merits are discussed in this section [1, 6-11]. One common limitation for all candidates is the comparatively higher boiling point than SF_6. Therefore, these gases must be used in low proportions mixed with a carrier gas such as CO_2 or N_2 to avoid liquefaction at elevated pressures required for HV applications. Additionally, these fluorinated gases are denser than air. This means that there is a risk of asphyxiation should a substantial level of these gases be released and allowed to settle within an enclosed environment (i.e. indoor GIS).

Gas Name	Dielectric strength relative to SF_6 (pu)	Global Warming Potential	Boiling Temperature (°C)
SF_6 [1]	1.0	23,500	-63.8
CF_3I, Trifluoroiodomethane [7, 8]	1.2	<5	-22.5
$C_3H_2F_4$, HFO-1234ze(E) [9]	0.85	6	-19.4
$C_5F_{10}O$, Novec 5110 [10]	2.1	<1	26.9
C_3F_7CN, Novec 4710 [6, 11]	2.0	2,100	-4.7

Table 1 - Dielectric strength, GWP and boiling point of different insulating gases [1, 6-11]

CF_3I is a gas that is chemically inert, non-flammable and has a dielectric strength that is 1.2 times higher than that of SF_6. The weak chemical bond C-I in CF_3I means that it can be decomposed quickly in the atmosphere via photolysis, and thus has a low GWP [8]. Based on inhalation tests, the US National Research Council's (NRC) committee on toxicology has recommended that CF_3I has a lowest observed adverse level (LOAEL) on cardiac sensitization at 0.4% concentration [12]. The overall toxicity level of CF_3I would drastically reduce when used as a mixture with either CO_2 or N_2. As for $C_3H_2F_4$, commercially known as HFO1234ze(E), there are two key drawbacks: (i) the trade-off of dielectric strength (85% of SF_6) and boiling point (-19 °C) means that its application is limited to medium voltage equipment operated close to atmospheric pressure, and (ii) the soot formation due to high energy discharge. Both CF_3I and $C_3H_2F_4$ gases generate solid precipitations (iodine and soot) that can pose an operational concern if they accumulate on a solid insulator, which could lead to surface flashover at a significantly reduced voltage [8, 9].

A unique "first breakdown" behavior has been reported for $C_3H_2F_4$ [9]. The initial breakdown was subsequently followed by consecutive positive LI breakdowns chopped on the front of the LI waveform (<1 μs) as shown in Figure 1(a). The breakdown characteristic stabilizes after the first withstand is achieved. By using $C_3H_2F_4$ in a mixture, the first breakdown effect is minimized indicating soot formation is the main cause of this behavior, which must be factored into any

potential application of $C_3H_2F_4$. Interestingly, if there is no breakdown occurrence, $C_3H_2F_4$ possesses comparable dielectric performance as SF_6 under non-uniform fields as demonstrated by the partial discharge (PD) characteristics shown in Figure 1(b) [9].
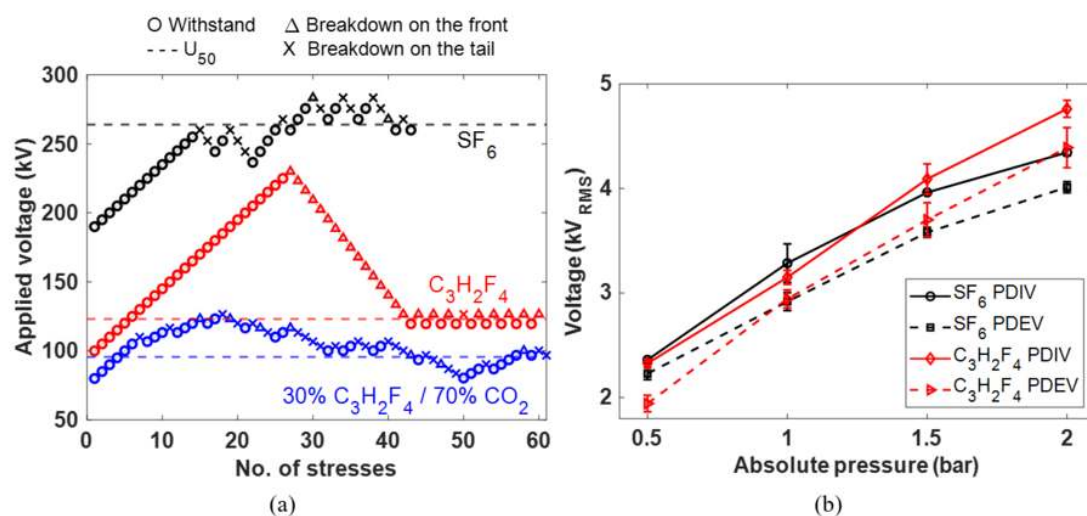

Figure 1 - (a) Test sequences for SF_6, $C_3H_2F_4$ and 30% $C_3H_2F_4$ / 70% CO_2 for LI(+) tested for a stainless steel 25 mm dia. hemisphere-to-plane configuration with a 10 mm gap and at 2 bar pressure, and (b) PDIV/EV characteristics for SF_6 and $C_3H_2F_4$, tested using a hemisphere-to-plane configuration with a 3 μm needle tip radius for pressures ranging from 0.5 to 2 bar [9]

$C_5F_{10}O$ (Novec 5110) is a perfluoroketone gas and to remain gaseous in gas-insulated equipment rated at 4.5 bar, less than 10% of $C_5F_{10}O$ may be used in a mixture. This would provide a $C_5F_{10}O$ mixture that has considerably lower dielectric strength than SF_6 at the same pressure and is unsuitable for retro-fill applications in HV equipment [10].

Novec 4710 is part of the fluoronitrile gas family, the formula C_4F_7N can exist in more than one isometric form: linear and branched. In its branched isometric form, the gas is practically non-toxic, which could be represented by the condensed formula $(CF_3)_2CFCN$. Note that the linear form $CF_3(CF_2)_2CN$ is toxic. Novec 4710 can contain a small amount of the linear isomer with the gas purity being >99.5%. C_3F_7CN is used to make clear that the molecule has a nitrile functionality with "CN" and thus is the preferred formula hereafter. C_3F_7CN has a much shorter atmospheric lifetime of 30 years and a GWP of about a tenth of SF_6. The GWP of this gas is still reasonably high at 2,100 but with only 4 to 10% of C_3F_7CN used in mixtures. This represents a 99% carbon footprint reduction when compared to SF_6 [5]. By adopting a 20% C_3F_7CN and 80% CO_2 mixture, a comparable dielectric strength and a carbon footprint reduction of up to 98% of SF_6 is achieved, while maintaining a low liquefaction temperature of -10 °C [6]. Note that carbon footprint reduction calculation is taking into account the different densities of C_3F_7CN/CO_2 mixture and SF_6 at the same pressure.

A coaxial configuration with a 10 mm outer dia. conductor and a 30 mm inner enclosure dia. that mimic the field uniformity as found in a GIL/GIB was used to compare the different gas candidates. Figure 2 shows that CF_3I/CO_2 mixtures [7, 8, 13] and $C_3H_2F_4$ [9] possess the lowest breakdown performance for both LI polarities. Despite offering an extra liquefaction temperature margin of 5 °C, the use of 16%

C_3F_7CN / 84% CO_2 mixture demonstrates a reduced dielectric strength, particularly under LI(-) which is the critical design voltage for GIL/GIB [11]. It is clear that a 20% C_3F_7CN / 80% CO_2 mixture has similar breakdown strength as SF_6 for coaxial geometries and is the preferred gas candidate in this retro-fill investigation [6].
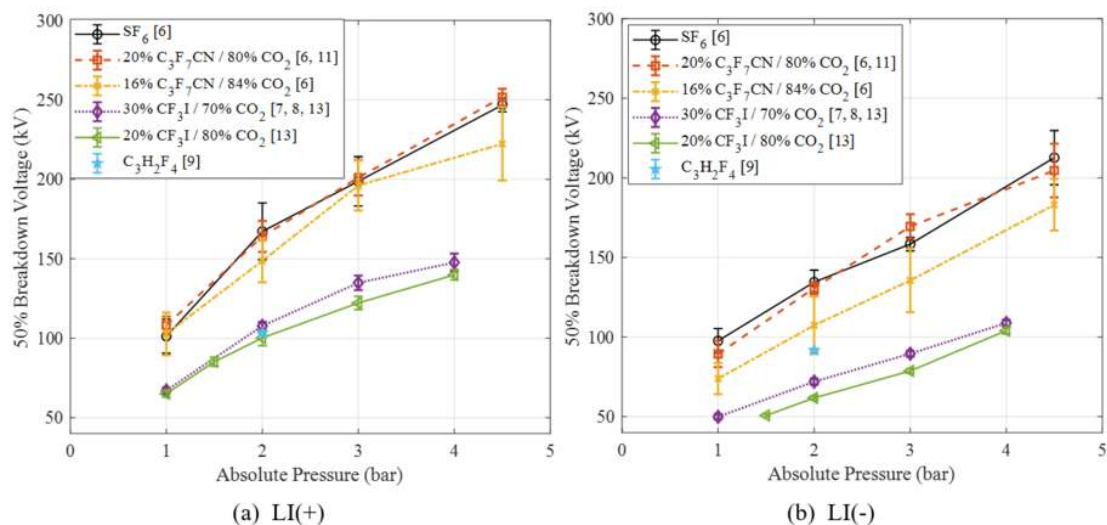

Figure 2 - Breakdown characteristics of SF_6 [6] and $C_3H_2F_4$ [9] gases, and mixtures of 16% C_3F_7CN, 20% C_3F_7CN [6, 11], 20% CF_3I, and 30% CF_3I mixed with CO_2 [7, 8, 13], tested under (a) LI(+) and (b) LI(-) in a 10/30 mm coaxial configuration for pressures of 1 to 4.5 bar

— 3. Experimental Details

This section describes (a) type test procedures in accordance with IEC 62271-204:2011 [14], (b) setup of full-scale demonstrator assembled from transmission rated equipment designed for SF6 and (c) gas handling procedure of binary mixture.

3.1. Experimental Setup

Type tests or withstand voltage tests are performed on equipment to verify whether they can conform to the relevant IEC standard. Equipment undergoes LI, SI, AC and PD type tests prior to commissioning. Although breakdown tests of small-scale prototypes provide useful information on an alternative gas, it cannot be proposed as a viable solution unless it has passed the required type tests on practical scaled equipment. Figures 3(a)–(c) illustrate the individual components including the permeable conical insulator, busbar, and HV bushing. As shown in Figure 3(d), special caution was taken with the assembly of the demonstrator to avoid any potential damage on the conductor surface. All the components were vacuum cleaned and wiped thoroughly with isopropyl alcohol prior to the final assembly to minimize contamination and residual dust.
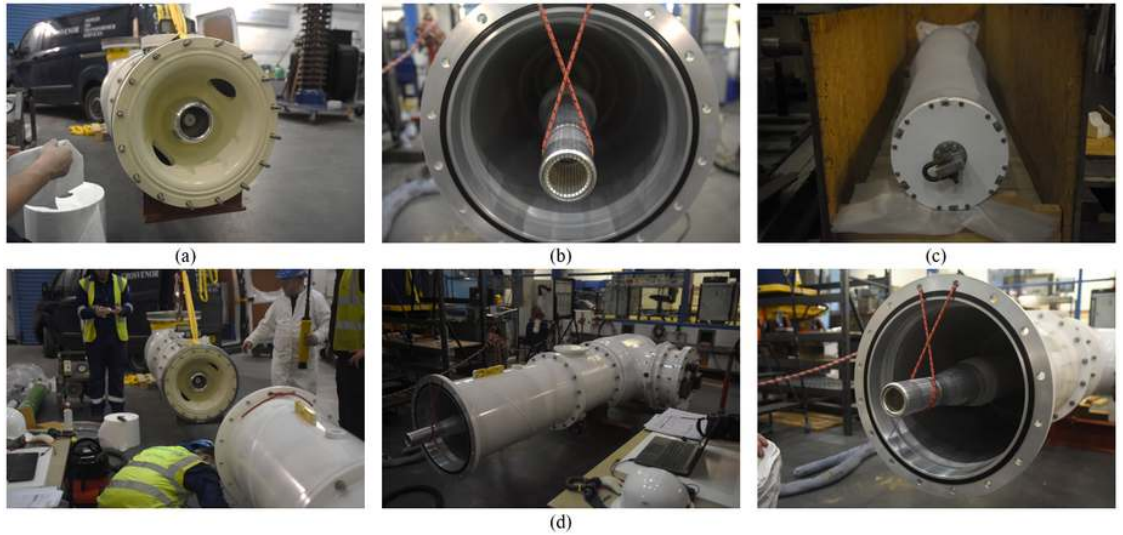
Figure 3 - GIB demonstrator setup: (a) insulating spacer, (b) straight conductor section, (c) HV bushing and (d) illustration of demonstrator assembly process

For the withstand voltage tests, the voltage waveforms and their tolerances are defined in accordance with IEC 60060-1:2010, and listed as follows [15]:

- Standard AC (50 Hz) voltage waveform within ±1% of test voltage;
- Switching Impulse (SI) [250 (±20%) / 2500 (±60%) μs] within ±3% of test voltage;
- Lightning Impulse (LI) [1.2 (±30%) / 50 (±20%) μs] within ±3% of test voltage.

Figure 4 shows the fully assembled GIB demonstrator separated into two zones: the bushing zone and the test zone. Both zones have an operating pressure of 4.5 bar. The bushing zone was always filled with SF6. As for the test zone, it was initially filled with SF6 for a benchmark test to ensure that the setup was correctly assembled before testing with an alternative candidate.
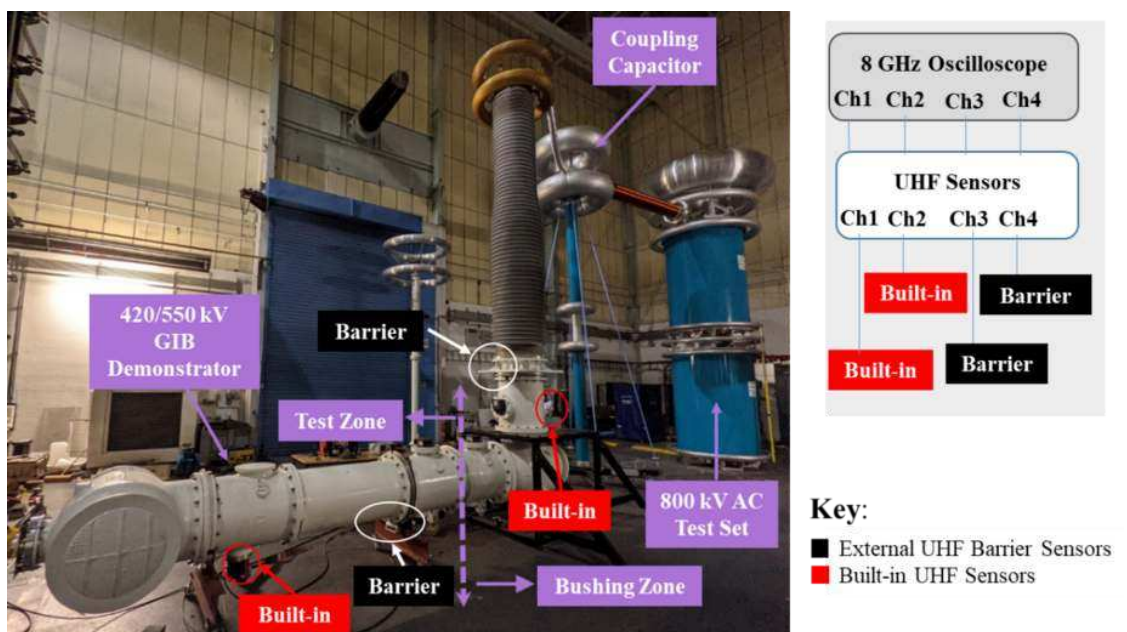

Figure 4 - Photo of the full-scale demonstrator with the location of PD sensors illustrated

Two corona rings were installed to minimize corona activities at the top of the bushing. Two built-in ultra-high frequency (UHF) PD couplers with a bandwidth of 200-1500 MHz were installed for PD measurement. Two additional UHF sensors with a bandwidth of 300-2000 MHz were positioned over viewing slots of the earth continuity bond on top of the conical insulator [6]. The expected frequencies of discharges for PD activity in insulating gases are in the GHz range. A Lecroy ultra-wide band oscilloscope with a bandwidth of 8 GHz was used to measure these signals. Prior to testing, a sensitivity verification procedure was performed using one UHF sensor as a transmitter and the remaining sensors as receivers.

3.2. IEC Type Test Procedure

The full-scale GIB demonstrator is dimensionally designed to withstand up to 550 kV basic insulation level (BIL) but is used by NGET for the 400 kV transmission network in the UK. As the equipment is rated for 420 and 550 kV BIL, both voltage levels were type tested using a 20% C_3F_7CN / 80% CO_2 mixture. Withstand type tests were conducted as per IEC 62271-204:2011 [14]. Type tests of LI, SI, PD and AC were carried out and the test procedures for all voltage waveforms are summarized in Table 2 [6].

Test	Description	Test Conditions and Pass Criteria
AC withstand voltage test	Maintain U_d for 1 minute	U_d = 650 kV (Ur = 420 kV) U_d = 710 kV (Ur = 550 kV) No breakdown
AC + partial discharge (PD) test	$U_{pre-stress}$ = U_d for 1 minute $U_{PD-test}$ = 1.2 Ur / Ö3 for 30 minutes	$U_{PD-test}$ = 291 kV (Ur = 420 kV) $U_{PD-test}$ = 381 kV (Ur = 550 kV) No indication for PD
Lightning impulse (LI) voltage test	15 impulses of both polarities	±1425 kV LI (Ur = 420 kV) ±1550 kV LI (Ur = 550 kV) Breakdowns < 2/15
Switching impulse (SI) voltage test	15 impulses of both polarities	±1050 kV SI (Ur = 420 kV) ±1175 kV SI (Ur = 550 kV) Breakdowns < 2/15

Table 2 - IEC type test procedures for the full-scale GIB demonstrator [6]

3.3. Gas Handling Process

Preparation: Any pressure compartment must always be vacuumed and filled with a dry gas, such as CO_2, slightly above the atmospheric pressure and left for a few hours to absorb any residual moisture. The compartment is again vacuumed below 1 mbar before filling to the desired operating pressure with the test gas or mixture.

Filling: For the initial filling procedure of gas mixtures, the Manometric method based on Dalton's law of partial pressures was adopted. This states that the total pressure of a mixture of non-reacting gases is equal to the sum of the partial pressures of individual gases [16]. This can be expressed mathematically as follows:

$$P_{total} = \sum_{i=1}^{n} p_i \quad or \quad P_{total} = P_1 + P_2 + P_3 + ... + P_n \quad (1)$$

where $P_1..., P_n$ represent the partial pressures of individual gases and P_{total} is the total pressure of the gas mixture.

C_3F_7CN was first filled to the required partial pressure and then topped up with CO_2 to reach the desired total pressure of the gas mixture. The filling of CO_2 must be performed slowly toavoid a possible "forced cooling" effect that results in the liquefaction of some C_3F_7CN due to the cooling effect caused by rapid expansion of CO_2 into the compartment.

Mixing: A re-circulation loop is used after the filling of a mixture. The entire volume of gas inside the pressure compartment is circulated for a minimum of two cycles, which is dependent on the compressor rating in m^3/hour and the compartment volume. This is to ensure that the gas mixture is homogeneously mixed before initiating any test.

Analysis: For SF_6, a purity of >97% is always used as per IEC 60480:2004 [17]. A bespoke alternative gas analysis instrument capable of measuring a 15-30% of C_3F_7CN with a deviation of ±1% was used to determine the gas mixture ratio. SF_6 was recorded to have a 99.8% purity while the gas mixture had a ratio of 20.7% C_3F_7CN / 79.3% CO_2 without any trace of O_2.

Recovery and Re-use: Used gases must be recovered into their respective storage cylinders as part of a close-loop system. Depending on the level of decomposition, these aged gases could be re-used for additional tests. C_3F_7CN tends to liquefy when its partial pressure within a mixture exceeds ≈2.5 bar as result of its boiling point. Liquefaction can be prevented if the storage pressure is well below the saturation vapor pressure of the mixture taking into account the worst-case room temperature. In the event of liquefaction, a heating blanket is used to pre-heat the storage cylinder so that the gas mixture becomes homogeneous prior to filling.

4. Experimental Validation of Full-scale Demonstrator

4.1 IEC Type Test Results

Table 3 shows that 20% C_3F_7CN / 80% CO_2 gas mixture passed the withstand type tests for 420 kV rating as successfully as SF_6 [6]. There was no breakdown occurrence during the SI, LI and power frequency withstand tests at the specified voltage levels in IEC 62271-204:2011 [14]. For the UHF setup, PD discharges emit a signal of at least 16 mV_{pk-pk} and any signal exceeding this value defined as a PD discharge inside the equipment. The equipment was pre-stressed at 650 kV AC_{RMS} for 1 minute and subsequently energized at 291 kV AC_{RMS} voltage for more than 30 minutes. A maximum noise level of 8.01 mV_{pk-pk} was recorded from the UHF sensors during this

period, which indicates no PD activity in the GIB and passed the test. Upon completion of the 420 kV type tests, the retro-filled demonstrator was increased to voltage levels specified for the 550 kV BIL. Similar to 420 kV BIL, Table 3 shows that no breakdown occurrence was recorded even at an elevated voltage level for all voltage waveforms. For the PD test, a maximum signal of 11.42 mV_{pk-pk} was recorded at 381 kV AC_{RMS} voltage after 30 minutes energization tested with a 20% C_3F_7CN / 80% CO_2 gas mixture. This demonstrates that both gas media possess comparable dielectric performance tested in a full-scale industrial equipment. These tests have effectively established that a 20% C_3F_7CN / 80% CO_2 gas mixture could be retro-filled with a significant safety margin for the 400 kV GB transmission network.

Rated Voltage	Test	20% C_3F_7CN / 80% CO2	100% SF_6
420 kV	±1050 kV SI	0/15	0/15
	±1425 kV LI	0/15	0/15
	650 kV AC	No breakdown	No breakdown
	291 kV PD	Signals <16 mV_{pk-pk}	Signals <16 mV_{pk-pk}
550kV	±1175 kV SI	0/15	0/15
	±1550 kV LI	0/15	-
	710 kV AC	No breakdown	No breakdown
	381 kV PD	Signals <16 mV_{pk-pk}	Signals <16 mV_{pk-pk}

Table 3 - IEC type test results for the full-scale GIB demonstrator [6]

4.2. Non-standard Type Test Results

Additional non-standard type tests were carried out using impulse waveforms to push the limit of the chosen gas mixture retro-filled in the demonstrator. The non-standard type tests were carried out at 420 kV BIL and listed as follows:

- **Increasing Impulse Applications:** An increased number of impulse applications from 15, per IEC standards, to 30, which is to investigate the behavior of 20% C_3F_7CN / 80% CO_2 gas mixture under an increased number of overvoltage transient events.
- **Under-pressure:** The operating pressure was reduced to 4 bar to simulate a severe gas leakage event. Type tests at this reduced pressure will determine whether the gas mixture is still able to withstand the required LI and SI voltage levels.

Table 4 shows that the use of a 20% C_3F_7CN / 80% CO_2 gas mixture has successfully passed the LI and SI tests of both polarities with no breakdown occurrence, despite doubling the number of impulse applications for the specified 420 kV BIL. Furthermore, the operating pressure was reduced from 4.5 bar down to 4 bar, representing a pressure drop of >10%. However, the LI and SI type tests of both polarities had no breakdown occurrence recorded at 420 kV BIL. Note that the liquefaction temperature of a 20% C_3F_7CN / 80% CO_2 gas mixture at 4 bar is around -13 °C, which is an extra 3 °C temperature margin for the retro-filled equipment. Standard and non-standard type tests have shown the dielectric performance of a 20% C_3F_7CN / 80% CO_2 gas mixture is comparable to SF6 as a potential replacement solution without having to change the equipment. Note that the differences in the thermal performance of the new gas candidate under high load have not been covered in this study. Similar experimental validation approach could be adopted for other equipment of different make, dimension or voltage rating to examine whether the use of SF_6 in passive components could eventually be phased out.

Rated Voltage	Test	20% C3F7CN / 80% CO2
	(i) Increased Number of Impulse Applications	
420 kV	±1050 kV SI	0/30
	±1425 kV LI	0/30
	(ii) Reduced Operating Pressure to 4 bar	
420 kV	±1050 kV SI	0/15
	±1425 kV LI	0/15

Table 4 - Non-standard type test results for the full-scale GIB demonstrator at 420 kV BIL for (i) 30 impulse applications and (ii) reduced operating pressure at 4 bar

— 5. Potential Retro-fill Locations in the UK

Outdoor equipment retro-filled with a 20% C_3F_7CN / 80% CO_2 mixture can be operated down to -10°C at 4.5 bar. Therefore, it is important to assess the probability of reaching this temperature in potential retro-fill sites in the UK. Table 5 reports NGET substations rated at transmission voltages that possess the largest amounts of installed SF6 (>20 t). These substations represent approximately 40% of NGET's total SF6 inventory. Historic temperature data have been obtained from weather stations close to the locations of substations outlined in Table 5. The weather stations shown in Table 6 have been capturing temperature data that is publicly available on the Met Office website [18]. The majority of the reported substations are located in the South East region of the UK. Five weather stations have been chosen to cover the temperature profiles of regions close to the substations shown in Table 5. The mean daily minimum temperature recorded from 1990 to 2018 shows that the Durham weather station had the lowest mean daily minimum temperature of -3.4 °C recorded in December 2010 [18].

Map Location	Substation Name and Voltage Rating	SF$_6$ Inventory (t)
1	BRAMFORD, 400 kV	53
2	ST JOHNS WOOD, 400 kV	37
3	CONNAHS QUAY, 400 kV	31
4	WEST HAM, 400 kV	28
5	HACKNEY, 400 kV	27
6	SELLINDGE, 400 kV	26
7	NORTON, 400 kV	26
8	LITTLEBROOK, 400 kV	25
9	KILLINGHOLME, 400 kV	24
10	BARKING, 400 kV	22
11	SIZEWELL, 400 kV	22
12	GRAIN, 400 kV	22
13	NEW CROSS, 275 kV	21

Table 5 - NGET substations in the UK with SF$_6$ inventory that exceeds 20 t.

Map Location	Weather Station Location	Mean Daily Minimum Temperature
A	Durham	-3.4 °C
B	Sheffield	-1.9 °C
C	Lowestoft	-1.4 °C
D	Heathrow	-1.5 °C
E	Manston	-1.0 °C

Table 6 - Met Office weather stations located near the substations reported in Table 5 [18]

Temperatures tend to be slightly lower in the North of England than the South East region. The data presented are the mean daily minimum temperatures which means that it is possible to have short periods in a day where the outdoor temperature drops close to the liquefaction temperature of -10 °C for a 20% C_3F_7CN / 80% CO_2 mixture. This could potentially be considered as acceptable for normal operation since the internal conductor carries several thousands of amps during high-load conditions and this will inherently heat up the gas medium. Appropriate temperature control measures are required for scenarios where the current flowing through the conductor is close to the minimum temperature due to light or no-load conditions during a cold winter period.

— 6. Conclusions

This paper presents an investigation into the technical feasibility of adopting a 20% C_3F_7CN / 80% CO_2 gas mixture as a potential retro-fill replacement of existing passive components designed for SF_6. The main conclusions are as follows:

- A comparative analysis was performed on existing literature for coaxial configurations that mimic the field uniformity as found in GIL/GIB equipment. Breakdown results of different alternatives in such prototype demonstrated that a 20% C_3F_7CN / 80% CO_2 gas mixture possesses comparable dielectric performance to SF_6 necessary for a retro-fill solution.
- Type tests with a GIB demonstrator showed that the chosen gas mixture has successfully passed all the required IEC type tests specified for 420/550 kV BIL. Additional non-standard type tests in 420 kV BIL also had no breakdown occurrence even when the operating pressure was reduced to 4 bar. This establishes a greater level of confidence that a retro-fill solution is viable in SF6-designed equipment.

A liquefaction temperature of -10 °C for the chosen gas mixture is a potential limitation for outdoor equipment. However, a review of the minimum temperature profiles from the main SF_6 substations in the UK identified that it is very rare that the mean daily minimum temperature can go below -10 °C.

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