Technical Viability of Retro-Filling C_3F_7CN/CO_2 Gas Mixtures in SF_6-Designed Gas Insulated Lines and Busbars at Transmission Voltages

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***Abstract*—Sulphur hexafluoride (SF_6), the most popular dielectric medium adopted in compressed gas insulated equipment, has been identified as a highly potent greenhouse gas. This has led to increased interest in finding a more environmentally friendly replacement candidate. In this paper, the technical viability of C_3F_7CN/CO_2 gas mixtures was assessed as a potential retro-fill solution for existing SF_6-filled gas insulated lines (GIL) and busbars (GIB). A reduced-scale coaxial prototype was developed to establish the breakdown strength of 20% C_3F_7CN / 80% CO_2 and 16% C_3F_7CN / 84% CO_2 gas mixtures in direct comparison with pure SF_6 under the standard lightning impulse (1.2/50 μs). Breakdown results demonstrate that a mixture of 20% C_3F_7CN / 80% CO_2 exhibits comparable insulation capability to pure SF_6 in coaxial geometries with similar field uniformity to GIL/GIB. This initial finding has led to the construction of a full-scale GIB demonstrator rated for 420/550 kV. Type tests according to IEC 62271–204 showed that the 20% C_3F_7CN / 80% CO_2 gas mixture has passed all the required voltage levels as SF_6. The research findings in this paper are an encouraging step towards a technically viable SF_6-free retro-fill solution for existing GIL/GIB installed for the 400 kV transmission network in the UK.**

***Index Terms*—Heptafluoro-iso-butyronitrile (C_3F_7CN), gas insulation, gas insulated lines and busbars, lightning impulse breakdown, sulphur hexafluoride (SF_6).**

I. Introduction

SULPHUR hexafluoride (SF_6) is a colorless, odorless, non-flammable and chemically inert gas which has been used in gas insulated equipment for decades owing to its exceptional arc quenching and dielectric insulation capabilities. Despite the many benefits of SF_6, it has one major drawback: a global warming potential (GWP) of 23,500 times greater than CO_2 [1]. The long atmospheric lifetime of 3,200 years and the high radiative forcing efficiency are two crucial factors that categorize SF_6 as a significant contributor to greenhouse gas emissions. The power industry, responsible for the annual use of approximately 10,000 tons of SF_6, is the main user, accounting for 80% of the global SF_6 inventory [2].

The SF_6 concentration in the atmosphere has risen over 20% between 2010 to 2015 [2], resulting in an increasing awareness of the need to find an environmentally friendly replacement gas for SF_6. One current strategy, which targets reducing SF_6 emissions from the power industry, is upgrading and replacing SF_6-filled equipment in the network with state-of-the-art equipment specifically designed for suitable SF_6 alternatives [2], [3]. While this is intended to reduce overall SF_6 emissions, it is costly and replacing all existing SF_6-filled assets worldwide with new-builds is time consuming. Most current research focuses on developing new high voltage equipment filled with alternative gases. The aim of the research in this paper, however, is to address the problem from another angle by investigating the feasibility of retro-filling existing SF_6-filled equipment with alternative gases.

There is a general consensus that any alternative candidate should have a considerably lower GWP than SF_6. However, the gas should also satisfy a strict list of requirements such as high dielectric strength, good arc-quenching capability, low boiling point as well as being chemically inert, non-toxic and non-flammable. $(CF_3)_2$-CF-CN or C_3F_7CN, also commonly known as Novec 4710 Insulating Gas, is an emerging candidate which is used in combination with a carrier gas (CO_2, N_2 or dry air) due to its relatively high boiling point. The proposed C_3F_7CN gas mixture can provide most of the aforementioned properties that are required to replace SF_6 in high voltage insulation applications [3].

This paper presents findings from a retro-fill investigation of C_3F_7CN/CO_2 gas mixtures. Key features include a) the selection process of suitable gas candidate; b) development of a reduced-scale coaxial prototype that mimics the electric field found in a full-scale GIL/GIB; c) breakdown characteristics obtained using the coaxial prototype to determine a C_3F_7CN/CO_2 gas mixture with comparable dielectric performance to SF_6; d) assembly of a unique demonstrator made of a gas-insulated bushing and

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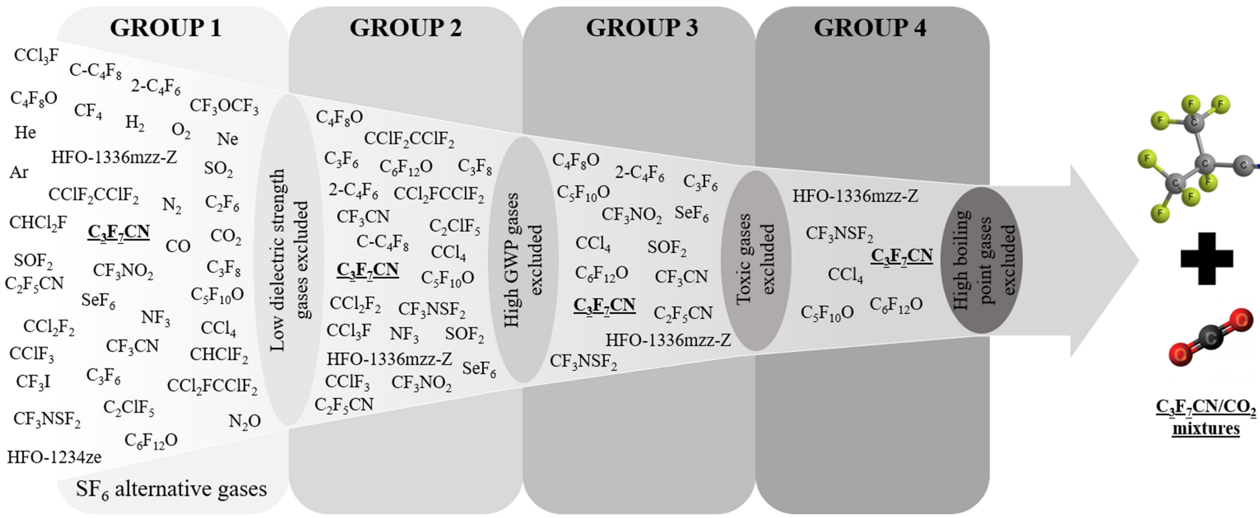

Fig. 1. Elimination of SF_6 alternatives for high voltage insulation applications based on data from [4]–[8].

busbars rated at 420/550 kV for experimental validation; e) type test results of the demonstrator using SF_6 and a pre-determined C_3F_7CN gas mixture; and f) material compatibility investigation of C_3F_7CN with a common gasket material used within the gas-insulated equipment.

II. Selection of Technically Viable Gas Candidate

A. SF_6 Alternatives for Insulation Applications

In the literature, there have been a considerable number of gases that were previously investigated and proposed as potential replacement to SF_6 [4]–[8]. This paper adopts a simple selection method which is based on four key criteria: dielectric strength, global warming potential, toxicity and boiling point. Fig. 1 graphically summarizes the assessment process to narrow down an appropriate gas candidate from a wide range of potential SF_6 alternatives [4]–[8]. From this process, C_3F_7CN has emerged as a gas medium that can be considered technically viable for the retro-fill research investigation carried out in this paper.

Group 1 illustrates a wide selection of potential SF_6 alternatives studied to date [4]–[8]. Group 2 excludes the gases that have low dielectric strength relative to SF_6. Naturally occurring gases are an example of this elimination since they possess dielectric strength of about a third of SF_6 [6], [7]. This would inherently require a higher operating pressure or an increased internal electrical clearance, which not only goes against the efforts to reduce equipment footprint but would also lead to additional complexities in replacing existing SF_6-designed equipment. Group 3 eliminates the undesirable gases that have a relatively high GWP in the range of 4,000 to 12,000. An example being the perfluorocarbon gases which have demonstrated that they can reach or even exceed the dielectric strength of SF_6 because of the presence of multiple fluorine atoms in their molecular structure. However, due to their extremely long atmospheric lifetime (>2600 years), these gases are also categorized as greenhouse gases [7]. High toxicity gases are eliminated in Group 4 since any alternative to SF_6 gas should not pose a risk to the personnel handling it [9]. Finally, gases with an extremely high boiling point are eliminated in the last stage after Group 4 because they can only be used at low pressures under room temperature (20 °C) to prevent liquefaction. Therefore, they are not suitable for high voltage equipment where higher pressures of over 4 bar (abs) are used. The fluoroketone gases family is an example of this group of gases [6], [7]. Following this process of elimination, C_3F_7CN is selected as a potential candidate for further investigation.

B. C_3F_7CN/CO_2 as a Gas Mixture

1) Environmental Impact and Toxicity: Fig. 1 illustrates that no pure gas was able to combine all four key properties: high dielectric strength, low GWP, low toxicity and low boiling point. Taking all the candidates in Fig. 1 into consideration, C_3F_7CN used with a carrier gas appears to be the most technically viable alternative. In its pure form, it has a significantly lower environmental impact compared to SF_6 since it has an atmospheric lifetime of 100 times shorter (30 years) and a GWP of about a tenth (2,090) that of SF_6. The overall GWP will reduce further when C_3F_7CN is used as mixtures. In [3], 4%, 6% and 10% C_3F_7CN concentrations were reported to have a GWP of 327, 462 and 690 respectively. According to the CLP regulation 1272/2008, with a LC_{50} (lethal concentration at 50% mortality) well above 20,000 ppm, C_3F_7CN is classified as a practically non-toxic gas. Similar to the GWP, the overall toxicity reduces when C_3F_7CN is used as part of a mixture with CO_2, which indicate that an acceptable personnel safety margin can be achieved in typical gas release scenarios within substations [3], [10].

2) Dielectric Strength: C_3F_7CN is an electronegative gas which implies that the more concentration used in a mixture, the higher the dielectric strength of the overall gas mixture. While C_3F_7CN has almost double the dielectric strength of SF_6, its relatively high boiling point means that it has to be used as a mixture with a carrier gas such as CO_2, N_2 and dry air [11]. As the aim of this research is retro-filling SF_6-designed equipment, one must first determine a mixture ratio that has a comparable dielectric performance as SF_6. For a parallel disk electrodes with

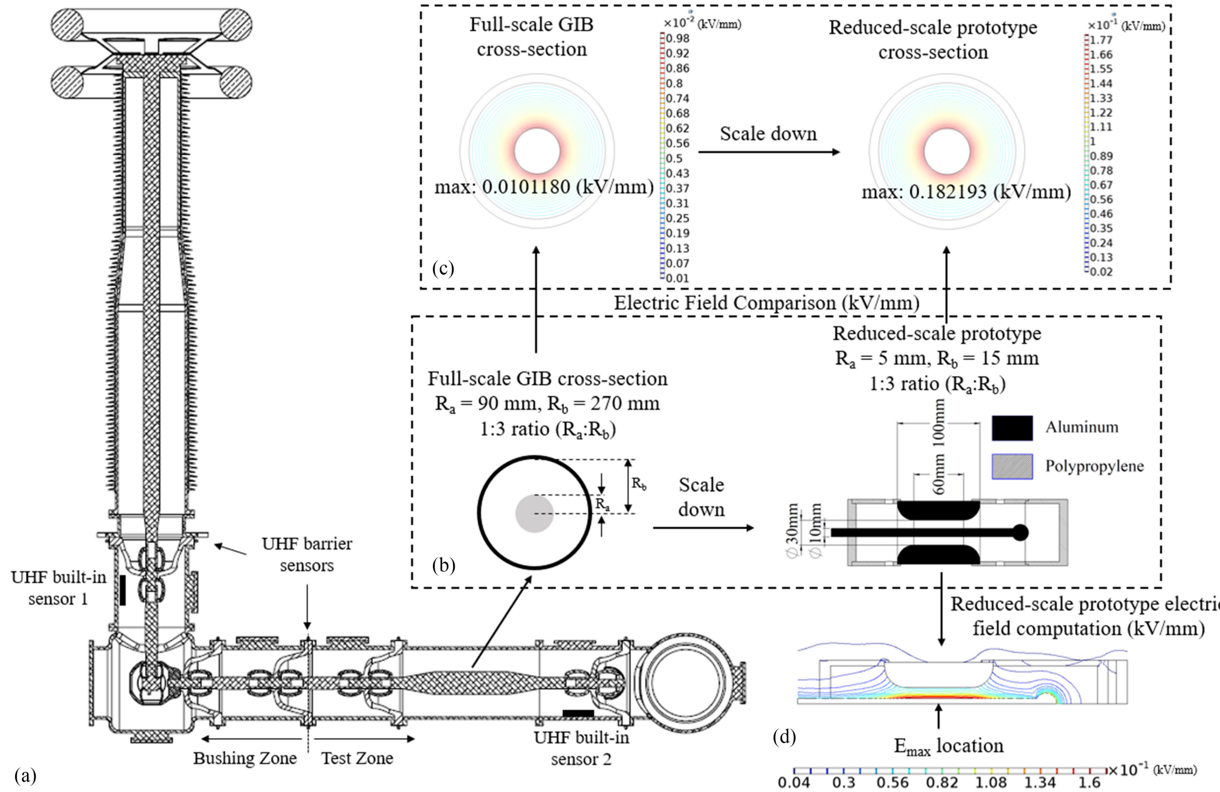

Fig. 2. (a) 420/550 kV GIB demonstrator, (b) Development of reduced-scale coaxial configuration based on the GIB demonstrator, (c) Electric field comparison of full-scale and reduced-scale prototype straight sections (kV/mm) and, (d) Reduced-scale prototype E_{max} (kV/mm) location.

TABLE I
LIQUEFACTION POINT OF 16% AND 20% C_3F_7CN GAS MIXTURES AND SF_6 [13] FOR 1–4.5 BAR (ABS)

Gas / Gas Mixture	Boiling Point (°C)			
	1 bar	2 bar	3 bar	4.5 bar
20% C_3F_7CN / 80% CO_2	-42.0	-28.6	-19.8	-10.1
16% C_3F_7CN / 84% CO_2	-45.9	-33.2	-24.8	-15.6
SF_6 [13]	-63.8	-49.4	-40.8	-32.2

a gap of 2.54 mm, it was reported that a mixture of 20% C_3F_7CN and 80% CO_2 exhibits comparable dielectric performance to SF_6 and higher than 20% C_3F_7CN mixtures with N_2 or dry air [11]. As a result, CO_2 has been chosen as the carrier gas in this study. However, the use of 20% C_3F_7CN concentration must be further experimentally validated using a representative test configuration like a coaxial geometry, prior to retro-fill such a mixture ratio in the GIB demonstrator for type tests.

3) Boiling Point: The key difference between SF_6 and C_3F_7CN is the higher boiling point of -4.7 °C. For the breakdown tests, the main focus is on two mixtures: 16% C_3F_7CN / 84% CO_2 and 20% C_3F_7CN / 80% CO_2. As mentioned earlier, a 20/80% mixture was chosen because it was reported to have the equivalent dielectric strength as SF_6. The 16/84% mixture was chosen since the reduction in C_3F_7CN ratio can lower the liquefaction temperature by approximately 5 °C. As the operating pressure of the GIB demonstrator is 4.5 bar (abs), the liquefaction temperatures for both C_3F_7CN mixtures at pressures of 1–4.5 bar (abs) were calculated using the Peng-Robinson Equation of State method and shown in Table I [12].

III. DEVELOPMENT OF REDUCED-SCALE COAXIAL PROTOTYPE

As it is costly and time-consuming to assemble an industrial-scale demonstrator, using a full-scale test rig would not be practical for the optimization of C_3F_7CN gas mixtures through breakdown tests. Therefore, a reduced-scale coaxial prototype was developed and fabricated to experimentally determine the breakdown characteristics of the pre-selected C_3F_7CN/CO_2 mixtures and with the SF_6 test data used as the reference. The geometrical design of the prototype is scaled down based on the dimensions of the GIB demonstrator.

A. Dimensions of the Reduced-Scale Prototype

Fig. 2(a) illustrates the internal structure of the GIB demonstrator and Fig. 2(b) shows the reduced-scale prototype. The GIB is essentially a coaxial cylindrical electrode. The design is based on a trade-off between the gap spacing and field uniformity, which are determined by two design parameters: outer conductor radius (R_a) and inner enclosure radius (R_b). There is an optimal ratio between these two parameters which controls the maximum electric stress $[(E_b)_{\max}]$ the gas can withstand. The optimal ratio is derived based on equations (1) and (2) [14], [15]:

$$E_b = \frac{U_b}{R_a \cdot \ln\left(\frac{R_b}{R_a}\right)} \; (kV/mm) \qquad (1)$$

TABLE II
COMPARISON OF PARAMETERS FOR THE FULL-SCALE GIB DEMONSTRATOR AND THE REDUCED-SCALE PROTOTYPE

Parameter	Full-scale GIB demonstrator	Reduced-scale prototype
Conductor Radius (mm) [R_a]	90	5
Inner Enclosure Radius (mm) [R_b]	270	15
Field Utilization Factor	0.549	0.549

In the case of the breakdown field strength, E_b, (1) can be re-written with the breakdown voltage, U_b, as a subject. Then by differentiating it with respect to R_a, assuming E_b and R_b are constants, maximum U_b is given when [16]:

$$\ln\left(\frac{R_b}{R_a}\right) = 1 \text{ where } \left(\frac{R_b}{R_a}\right)_{optimal} = e \approx 2.72 \quad (2)$$

Fig. 2(b) shows the cross-sectional view of the busbar in the demonstrator, where the ratio of R_b/R_a is equal to 3 and close to the optimal ratio. As shown in Fig. 2(b), the coaxial prototype was developed to have the same field uniformity by having the same enclosure-to-conductor ratio. Using the field utilization factor equation for coaxial configurations, Table II shows that this factor is identical for both the GIB demonstrator and the reduced-scale prototype. Therefore, the developed coaxial prototype is expected to replicate the quasi-uniform field as found in the GIB demonstrator. Table II also shows a full comparison of dimensions between the full-scale GIB and reduced-scale prototype. Fig. 2(c) compares the electric field distribution of the GIB demonstrator and prototype simulated using COMSOL Multiphysics 5.3. As shown in the figure, using a constant voltage of 1 kV, E_{max} of the full-scale is roughly 18 times smaller than the reduced-scale prototype which is due to larger equipment dimensions. The E_{max} value can also be calculated using equation (1).

Having a much higher E_{max}, while keeping the same field utilization factor, enabled the design of the reduced-scale prototype for destructive breakdown testing.

B. FEA Simulation for Reduced-Scale Prototype

Following the dimensioning of the conductor and inner enclosure radius, the internal space-constrained dimensions of the pressure vessel, such as height and diameter, had to be taken into consideration. This was done with the help of finite element analysis (FEA) simulations and with the software of COMSOL Multiphysics 5.3. Mesh refinement study was first carried out to ensure that the subsequent simulation results are mesh independent.

When fabricating coaxial configurations for breakdown tests, it is important to identify the region of the highest field intensity (E_{max}) where a breakdown will most likely to occur. It is important for the breakdown to occur within the central region of the inner conductor as depicted in Fig. 2(d). To do so, the clearance from the grounded pressure vessel, the conductor termination as well as the rim edge of the coaxial enclosure are factors that must be considered.

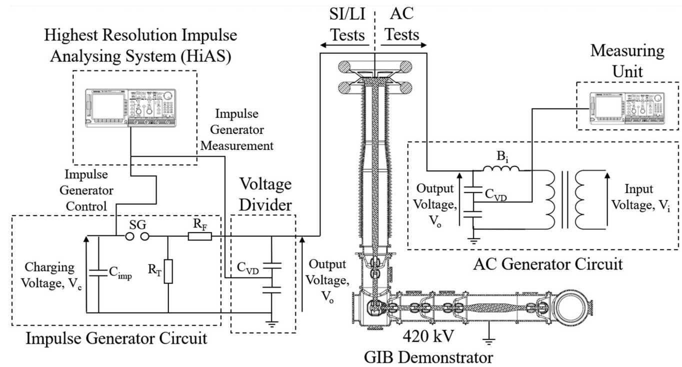

Fig. 3. Withstand voltage tests circuit diagram.

Fig. 2(d) shows the electric field distribution, using a constant voltage, for the coaxial model developed. As shown in Fig. 2(d), all of the aforementioned parameters were carefully considered to have the E_{max} in the central region of the conductor. The conductor tip is terminated with a large spherical electrode to minimize the high field region. A sufficient clearance of more than double the gap distance between the conductor and the inner enclosure is kept from the bottom of the pressure vessel. These precautions are to ensure that a breakdown will not take place from the tip of the conductor to the grounded test cell. The enclosure edges were also chamfered to avoid any breakdown occurrence along the edge of the enclosure. In summary, by introducing smoother edges to the design, such as sphere conductor termination or rounding the enclosure edges, there is a more uniform field at the critical design regions which ensure that coaxial breakdowns occur at the location of interest.

IV. EXPERIMENTAL SETUP, TEST TECHNIQUES, AND GAS HANDLING PROCEDURES

A. AC and Lightning Impulse Generators Test Setup

Fig. 3 shows the test circuit diagram including the AC and impulse generators. The same circuit diagram was used for both the breakdown and the withstand voltage tests. Both setups involved a high-pressure test rig (full-scale GIB or reduced-scale prototype), a voltage divider and a measuring and control unit. For all the experiments, standard AC (50 Hz), switching impulse (SI) [250/2500 μs] and lightning impulse (LI) [1.2/50 μs] voltage waveforms were used. A 10-stage Haefely Marx impulse generator that can go up to 2 MV was used to generate the switching and lightning impulse waveforms. The voltage measurement was taken through a voltage divider with a conversion ratio of 1.107 kV/1 V which is connected to the HiAS (Highest Resolution Impulse Analysing System) 744 system. A High Volt 2-stage cascade transformer AC generator that can go up to 800 kV was used to generate the AC waveform. The measurement was again taken through a voltage divider as shown in Fig. 3.

B. Reduced-Scale Setup for Breakdown Characterization

A stainless-steel pressure vessel with a 170 kV rated SF_6 bushing was fabricated for the breakdown tests conducted in this work. The pressure vessel can withstand up to 10 bar (abs) pressure and the bushing can withstand up to 325 kV AC and 750 kV lightning impulse voltages.

The coaxial electrodes were made of aluminum and polypropylene insulators were used as support structures to center the HV and earth electrodes within the pressure vessel. The support structure was also used to represent a similar function to the conical insulators as found in practical equipment. Electrodes were polished to a mirror finish with a mean surface roughness of 0.2 μm and cleaned thoroughly with propanol prior to testing.

C. Up-and-Down Procedure for Lightning Impulse Breakdown Tests

The up-and-down method was used to determine the 50% lightning impulse breakdown voltage (U_{50}) in accordance to the IEC 60060–1:2010 [17]. A set of 30 LI impulses with a two-minute time interval between each impulse was applied. Note that 10–15 initial impulses were used to condition the electrode and establish the step voltage level (ΔU) after every new setup. The statistical analysis to acquire U_{50} and the standard deviation (σ) was done with the guidance of [18].

D. Full-Scale Demonstrator for Withstand Type Tests

After establishing the margin between pure SF_6 and C_3F_7CN mixtures in terms of breakdown performance, the most technically viable C_3F_7CN mixture was then retro-filled in the full-scale GIB demonstrator for type tests. The full-scale GIB demonstrator is dimensionally designed to withstand up to 550 kV equipment rating but is widely used for the 400 kV transmission network in the UK. As shown in Fig. 2, the GIB demonstrator is separated into two zones: the bushing zone and the test zone. The bushing zone was always filled with SF_6 gas. The test zone was initially filled with SF_6 in order to be tested as a benchmark and ensure that the setup was fully functioning prior to testing with the C_3F_7CN/CO_2 gas mixture. The operating pressure of the GIB demonstrator is 4.5 bar (abs) in both zones. Two corona rings were used to minimize corona activities at the top of the bushing. Fig. 4 shows the AC generator setup connected to the GIB demonstrator for testing. Areva ultra-high frequency (UHF) partial discharge (PD) couplers with a bandwidth of 200–1500 MHz were built-in the GIB demonstrator for measuring PD activities. Two additional UHF sensors with a bandwidth of 300–2000 MHz were attached on the external enclosure of the GIB insulators [19]. The positions of the built-in and the barrier UHF sensors are shown in Fig. 2(a). The expected frequencies of discharges for PD activities in insulating gases are in the GHz range. To measure these signals, a Lecroy ultra-wide band oscilloscope with a bandwidth of 8 GHz was used. Prior to testing, a sensitivity verification procedure was performed using one UHF sensor as a transmitter and the remaining sensors as receivers.

E. IEC 62271-204:2011 Type Tests Procedures

Withstand type tests were conducted with the guidance of IEC 62271-204:2011 [20]. Lightning impulse, switching impulse, partial discharge and power frequency type tests were carried out. As the equipment is rated for 420 and 550 kV, both voltage levels were type tested for the C_3F_7CN/CO_2 mixture. The test procedures for each of the voltage waveforms are shown in Table III.

Fig. 4. AC Generator test setup.

TABLE III
TYPE TESTS PROCEDURES FOR FULL-SCALE GAS INSULATED BUSBARS

Test	Description	Test Conditions and Pass Criteria
AC withstand voltage test	Maintain U_d for 1 min	U_d = 650 kV (U_r = 420 kV) U_d = 710 kV (U_r = 550 kV) No breakdown
AC + partial discharge test	$U_{pre\text{-}stress}$ = U_d for 1 min $U_{pd\text{-}test}$ = 1.2 U_r / √3 for > 1 min	$U_{pd\text{-}test}$ = 291 kV (U_r = 420 kV) $U_{pd\text{-}test}$ = 381 kV (U_r = 550 kV) No indication for PD
Lightning impulse (LI) voltage test	15 impulses of both polarities	±1425 kV LI (U_r = 420 kV) ±1550 kV LI (U_r = 550 kV) Breakdowns < 2/15
Switching impulse (SI) voltage test	15 impulses of both polarities	±1050 kV SI (U_r = 420 kV) ±1175 kV SI (U_r = 550 kV) Breakdowns < 2/15
U_r:	*rated voltage for equipment*	
U_d:	*AC withstand test voltage*	
$U_{pre\text{-}stress}$:	*pre-stress voltage*	
$U_{pd\text{-}test}$:	*test voltage for PD measurement*	

F. Gas Handling Procedures

The first step of the gas handling process was to vacuum down the pressure compartment (GIB demonstrator or pressure vessel) down to 1 mbar and then fill it with CO_2 to absorb moisture and minimize air impurities. The pressure compartment was then vacuumed down to 0.5 mbar, before filling the test gas or mixture up to the desired pressure. A DILO SF_6 purity analyzer was used to measure the SF_6 gas purity after the filling. SF_6 of >97% purity was always used as per regulation set by the IEC 60480:2004 standard [21]. For C_3F_7CN/CO_2 gas mixtures, filling was carried out using the Manometric method. C_3F_7CN was first filled up to the required partial pressure and then topped

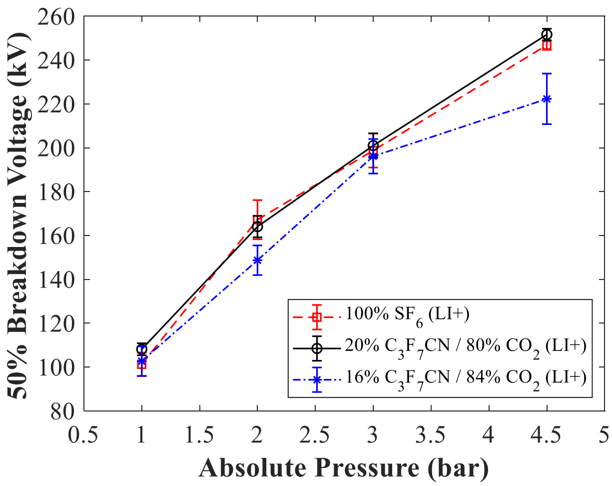

Fig. 5. U_{50} as a function of absolute pressure in the reduced-scale GIB prototype for SF_6 and C_3F_7CN/CO_2 mixtures with 20% and 16% C_3F_7CN concentration under positive lightning impulse (LI+).

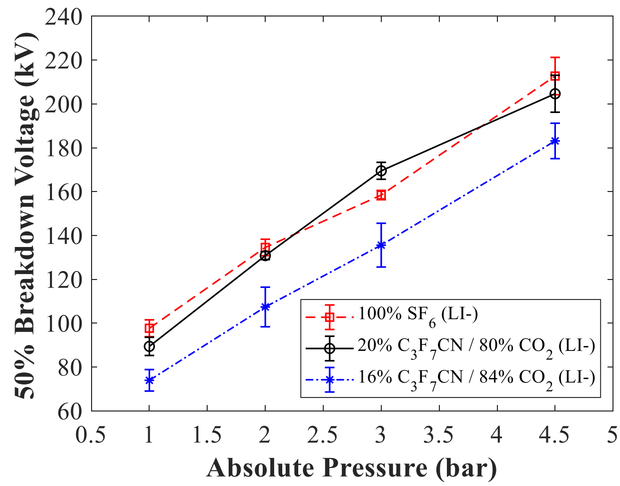

Fig. 6. U_{50} as a function of absolute pressure in the reduced-scale GIB prototype for SF_6 and C_3F_7CN/CO_2 mixtures with 20% and 16% C_3F_7CN concentration under negative lightning impulse (LI-).

up with CO_2 to reach the required 4.5 bar (abs) test pressure. Following the gas mixture filling procedure, a recirculation loop was connected using the two gas filling points on the gas compartment with the DILO alternative gas Piccolo cart series. The loop was used to circulate the entire volume of gas inside the gas compartment for a minimum of two cycles (depending on the Piccolo gas cart compressor rating in m^3/h) in order to ensure that the C_3F_7CN and CO_2 are homogeneously mixed. A bespoke WIKA GA11 alternative gases analysis instrument capable of measuring a 15–30% concentration of C_3F_7CN with a deviation of $\pm 1\%$ was used to measure the gas mixture ratio.

V. Comparison of Breakdown Characteristics Between SF_6 and C_3F_7CN Mixtures

This section shows the 50% breakdown voltage, U_{50}, and the standard deviations as error bars, against pressure for a direct comparison between the two C_3F_7CN/CO_2 gas mixtures and 100% SF_6. Fig. 5 compares the breakdown performance of SF_6 to the gas mixtures with 16% and 20% C_3F_7CN concentration under positive lightning impulse. The breakdown voltage of 100% SF_6 and the 20% C_3F_7CN / 80% CO_2 mixture increases almost linearly with pressure in the investigated range. The breakdown voltage of the 16% C_3F_7CN / 84% CO_2 gas mixture increases linearly up to 3 bar (abs) and then slightly saturates as the pressure is increased to 4.5 bar (abs). The non-linear increase of breakdown voltage at higher pressures has been observed in previous studies on gaseous dielectric mediums [22]. This trend could be due to the increased density of the gas at higher pressures, where density will not make as much difference to ionization and attachment processes as it did at lower pressures since the gas molecules are more densely populated. In Fig. 5, the breakdown characteristics of 100% SF_6 and the 20% C_3F_7CN / 80% CO_2 gas mixture are almost identical to each other with the two curves overlapping. The 16% C_3F_7CN / 84% CO_2 has a slightly lower breakdown voltage than the other two gases and saturates at a lower pressure. This is in good agreement with previous studies [2], [11] where it was stated that a C_3F_7CN/CO_2 gas mixture with a 18-20% C_3F_7CN concentration can have an equivalent dielectric strength to pure SF_6.

Fig. 6 shows the breakdown characteristics of the same gases under negative lightning impulse. Once again, the breakdown characteristics of 100% SF_6 and the 20% C_3F_7CN / 80% CO_2 gas mixture are comparable under negative polarity. The mixture with 16% C_3F_7CN concentration has a slightly weaker breakdown performance than SF_6 and the mixture with 20% C_3F_7CN concentration. As shown in Figs. 5 and 6, the negative polarity lightning impulse breakdown voltages tend to be lower than the positive polarity in coaxial configurations. This agrees with the previous study [22], as the conductor is negatively charged, it can be considered as an additional source of electrons which result in an electron avalanche initiated at a lower electric field. In the case of a positively charged conductor, an electron is initiated from detachment from a negative ion or ionizing a neutral molecule which may require a higher electric field. This is an indication that gas insulated busbars have a higher failure probability under a negative lightning impulse as opposed to a positive lightning impulse. This highlights the importance of the 20% C_3F_7CN / 80% CO_2 gas mixture having the same breakdown performance with 100% SF_6 under negative lightning impulse as shown in Fig. 6.

Fig. 7 compares the breakdown voltage of the three candidates at 4.5 bar (abs) which is the operating pressure for the GIB demonstrator. It demonstrates that the 20% C_3F_7CN / 80% CO_2 gas mixture slightly outperforms SF_6 under positive polarity but SF_6 has a higher negative lightning impulse breakdown voltage. The 16% C_3F_7CN gas mixture demonstrates a comparative lower breakdown performance than the other two gases at this pressure under both polarities.

VI. 420 kV Gas Insulated Busbar Demonstrator

A. *Type Test Results*

The results from the breakdown characteristics in Section V have shown that the mixture of 20% C_3F_7CN / 80% CO_2 is

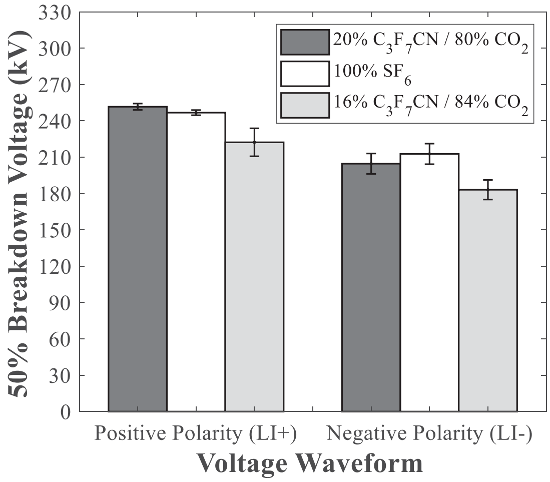

Fig. 7. U_{50} for 100% SF_6, 20% C_3F_7CN / 80% CO_2 and 16% C_3F_7CN / 84% CO_2 in the reduced-scale GIB prototype at 4.5 bar (abs).

TABLE IV
TYPE TESTS RESULTS FOR FULL-SCALE GAS INSULATED BUSBAR

Rated Voltage	Test	20% C_3F_7CN / 80% CO_2	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}

a more technically viable alternative to SF_6 for high voltage insulation applications in terms of breakdown characteristics. This specific mixture was later retro-filled in the full-scale GIB demonstrator in order to carry out the type tests described in Table III. As new gases were used for filling SF_6 and the C_3F_7CN/CO_2 mixture in the GIB demonstrator, it was important to make sure that SF_6 had a satisfactory gas purity and the 20% C_3F_7CN / 80% CO_2 mixture ratio was successfully achieved prior to testing. Using the equipment described in Section IV, 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 traces of O_2. Table IV shows that the 20% C_3F_7CN / 80% CO_2 gas mixture has passed the type tests for 420 kV rating as successfully as SF_6. There was no breakdown occurrence during the SI, LI and power frequency withstand tests at the specified IEC voltage levels. For the UHF sensor setup, PD discharges emit a signal of at least 16 mV_{pk-pk} and a signal exceeding this value was defined as a PD discharge in the equipment. Following the pre-stress procedure at 650 kV AC_{RMS} for 1 minute, the GIB was energized at 291 kV AC_{RMS} voltage for more than 30 minutes for the PD type test. The maximum noise level recorded from the UHF sensors during this period was 8.01 mV_{pk-pk}

Fig. 8. EPDM elastomer sample tested for compatibility with C_3F_7CN gas.

TABLE V
C_3F_7CN PURITY WHEN AGED AT 105 °C IN CONTACT WITH EPDM ELASTOMER SAMPLE

Time (days)	C_3F_7CN GC area (%)
0	99.99
15	99.84
28	99.85
55	99.9
90	99.86
112	99.86

which indicates no PD activity in the GIB at the IEC voltage level.

Following the completion of the 420 kV type tests, the 20% C_3F_7CN / 80% CO_2 gas mixture was pushed up to the voltage levels specified for the 550 kV equipment rating in accordance to the IEC 62271-204:2011 [20]. Table IV shows that no breakdown occurrence was recorded, even at an elevated voltage level for all voltage waveforms. No PD pulses were detected from the UHF sensors since the maximum signal recorded was 11.42 mV_{pk-pk} at 381 kV AC_{RMS} voltage (energized for 30 minutes) for SF_6 and the 20% C_3F_7CN / 80% CO_2 gas mixture, indicating a comparable dielectric performance for both dielectrics in full-scale industrial equipment. These tests have effectively established that the 20% C_3F_7CN / 80% CO_2 gas mixture can be retro-filled with a significant safety margin for the 400 kV transmission network.

B. Material Compatibility of Gaskets

C_3F_7CN gas compatibility with the O-ring material was evaluated using a sample of an EPDM elastomer used in the existing GIL / GIB. A small sample of the EPDM elastomer was placed into a dried 50 mL glass vial and sealed with a PTFE-lined septum cap as shown in Fig. 8. An approximate 27% C_3F_7CN mixture in air was created by adding 0.1122 g of C_3F_7CN to this vial. The test sample was placed in an oven for more than 3 months. The oven was operating at 105 °C which according to [23], [24] is the maximum operating temperature SF_6 can be exposed to within a GIL / GIB configuration.

The purity of the gas mixture was assessed by extracting 100 μL samples from the vial using a gas-tight syringe. The samples were analyzed using gas chromatography (GC). The purity results of the gas corresponding to the time interval taken after the placement of the sample in the oven are shown in Table V.

TABLE VI
SF_6 YEARLY LOSSES AS REPORTED FROM NATIONAL GRID [26]

Year	SF_6 losses (tons)
2014/2015	12.4
2015/2016	12.0
2016/2017	14.7
2017/2018	14.0
2018/2019	14.4

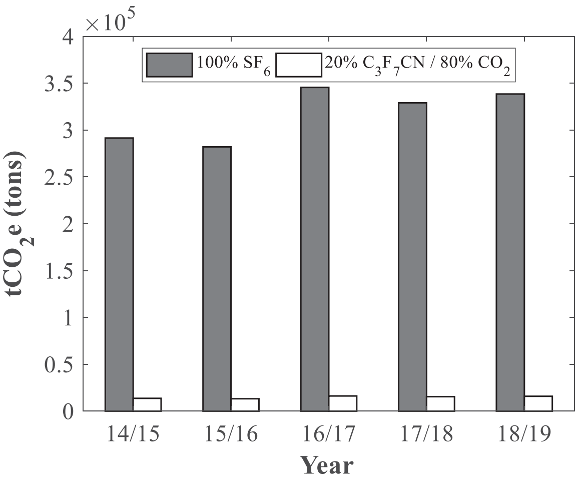

Fig. 9. Comparison of SF_6 and 20% C_3F_7CN / 80% CO_2 gases equivalent CO_2 emissions (tCO2e) using leakages from 2014 to 2019 from Table VI.

Table V illustrates that the purity of the gas is not affected by the elastomer material even when exposed to elevated temperatures. The purity of C_3F_7CN is reduced by less than 0.2% after 112 days exposure at 105 °C. The test results highlight that there should not be any degradation to the EPDM elastomer gasket or to the C_3F_7CN when they are exposed to elevated temperatures over an extended period of time. This shows that the C_3F_7CN/CO_2 mixture does not have any risk of losing its insulation capability through degradation or gas leakage because of damaged EPDM elastomer gaskets when retro-filled in SF_6-designed equipment.

VII. Impact of Retro-Fill Solution for UK Transmission Network

The purpose of a retro-fill solution is to extract all the SF_6 gas currently being used in UK network assets and replace it with an environmentally friendly gas mixture. Ofgem reports the total SF_6 volume used in the network is still increasing with new assets being regularly installed [25]. Table VI shows the recorded SF_6 leakages from the past 5 years as documented from National Grid in the UK [26]. As SF_6 has a GWP of 23,500, it can be seen from Fig. 9 that the CO_2 equivalent emissions (tCO_2e) of SF_6 leakages can go up to 350,000 tons. This value is calculated using (3) [27].

$$tCO_2e = \left(\frac{Mass\ of\ F\ gas\ (kg)}{1000}\right) \cdot F\ gas\ GWP \qquad (3)$$

The 20% C_3F_7CN / 80% CO_2 gas mixture was calculated to have a GWP of approximately 1,100 which represents a 95% reduction of SF_6. Outdoor equipment retro-filled with 20% C_3F_7CN / 80% CO_2 can be operated down to −10 °C (liquefaction point for the mixture at 4.5 bar abs). This can be considered as acceptable since the internal conductor carries several thousands of amps and will inherently heat up the insulating medium. Fig. 9 shows the impact of replacing the SF_6 inventory in National Grid with the C_3F_7CN/CO_2 gas mixture. As shown in Fig. 9, assuming the leakage rates continue as indicated in Table VI, by adopting a 20% C_3F_7CN / 80% CO_2 mixture instead of SF_6 will significantly reduce the CO_2 equivalent emissions.

VIII. Conclusion

This paper presents results of retro-fill research on C_3F_7CN/CO_2 mixtures as potential alternatives to SF_6 for high voltage insulation applications in GIL and GIB. The type test results demonstrate strong potential for replacing SF_6-filled network assets with a more environmentally friendly medium of 20% C_3F_7CN / 80% CO_2 gas mixture. The main conclusions are as follows:

1. Breakdown tests conducted on a reduced-scale coaxial configuration showed that a 20% C_3F_7CN / 80% CO_2 gas mixture has breakdown performance comparable to SF_6. A mixture with 16% C_3F_7CN concentration can provide a lower liquefaction temperature of 5 °C than 20% C_3F_7CN but has a noticeably lower breakdown strength.
2. Type tests with the demonstrator showed that the 20% C_3F_7CN / 80% CO_2 gas mixture passed all the required type tests as SF_6, indicating that the two gases have the same electrical performance for 420/550 kV equipment.
3. A material compatibility test showed no clear sign of degradation using C_3F_7CN with a common gasket material EPDM elastomer when subjected to the maximum operating temperature in a GIL / GIB.
4. The retro-fill recommendation is that the use of a 20% C_3F_7CN / 80% CO_2 mixture at 4.5 bar (abs) with a −10 °C liquefaction temperature can reduce the CO_2 equivalent emissions up to 95% when compared to SF_6.

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