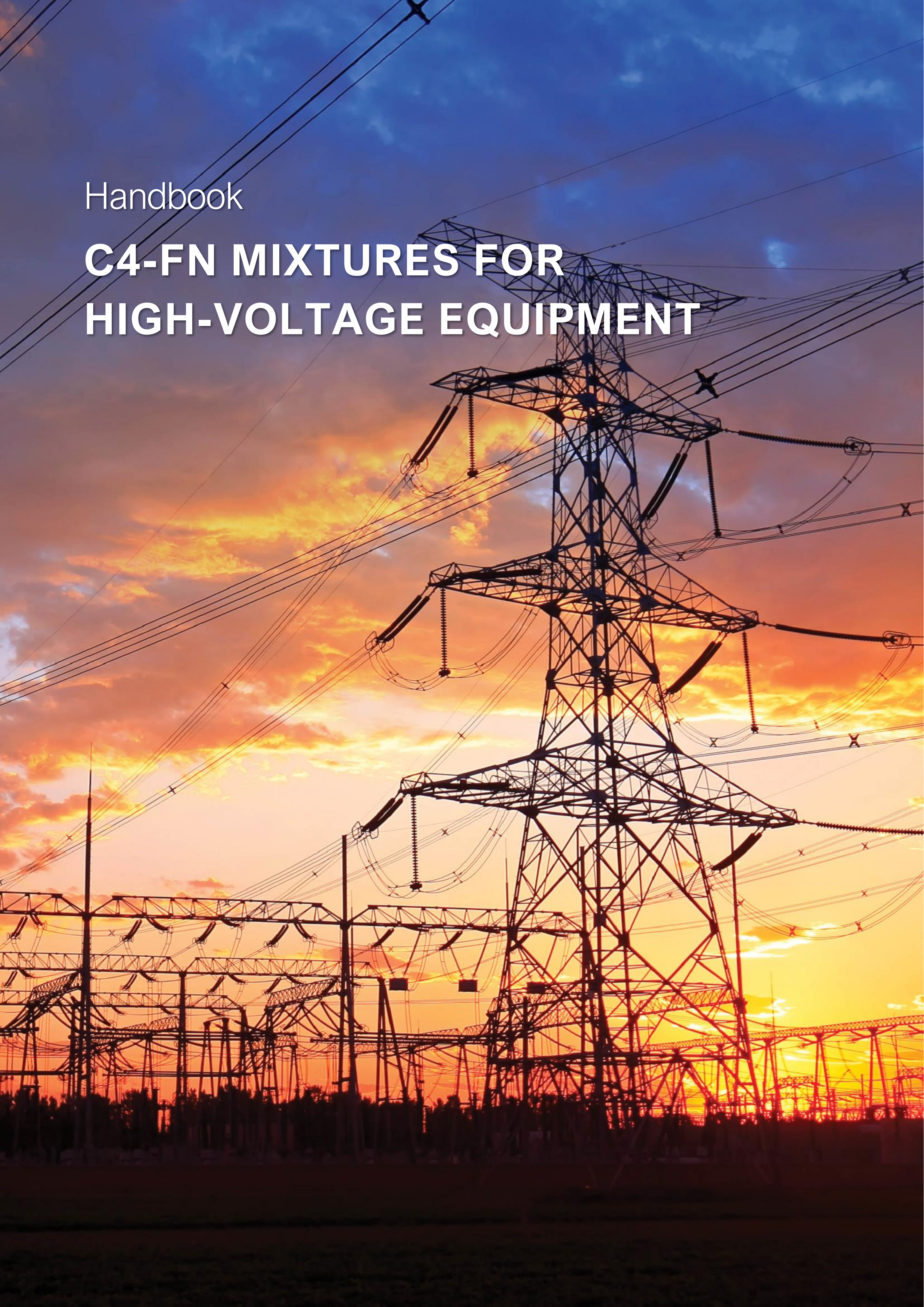
Handbook

C4-FN MIXTURES FOR HIGH-VOLTAGE EQUIPMENT



Handbook

C4-FN MIXTURES FOR HIGH-VOLTAGE EQUIPMENT

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Executive summary

For more than five decades, high-voltage equipment relied on sulfur hexafluoride (SF_6) gas with excellent properties for insulation and arc interruption, but with a very high global warming potential (GWP). To significantly reduce the carbon footprint of high-voltage equipment during its complete life cycle, users and manufacturers are implementing SF_6 alternatives.

One such alternative is C4-FN (fluoronitrile), a synthetic molecule, which when mixed with oxygen (O_2) and carbon dioxide (CO_2) or nitrogen (N_2) performs similarly to SF_6. C4-FN mixtures allow us to build state-of-the-art high-voltage equipment on the same principles as for SF_6 technology (circuit-breaker included), occupational health and safety standards, and gas handling procedures.

The CO_2-equivalent of the insulating gas is practically eliminated with this solution. The reduction for typical applications in high-voltage equipment is indeed 99 %. With the removal of SF_6, the manufacturing phase and Joule losses are the biggest remaining contributors to the total carbon footprint of SF_6-free equipment. Because of the high dielectric performance of C4-FN, the equipment maintains low material use and minimizes the greenhouse gas (GHG) emissions of the manufacturing phase, ensuring a low carbon footprint on the entire life cycle.

This handbook will cover the key points of the technology using C4-FN mixtures, independent of specific equipment design, in a compact and user-focused format. The topics include:

- Technical characteristics of C4-FN mixtures
- Health, safety, and environmental aspects
- User guide including gas handling

Independently of each other, two major equipment manufacturers, GE Vernova and Hitachi Energy, have gained more than a decade of experience with C4-FN mixtures for high-voltage applications through research, technology development, product development, and testing, as well as with several full-scale installations.

Both manufacturers are committed to each independently continue their efforts to extend the technology to a full range of high-voltage equipment.

The objective of this handbook is to serve as a common reference for the high-voltage community when working with C4-FN mixtures, and to support the urgent transition away from SF_6.

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1 Introduction

1.1 High-voltage equipment and SF_6

Reliable electricity supply is essential for a modern society. In the transmission and distribution system, substations are the nodes that control and protect the power grid. Over the past decades, SF_6 has been the dominant technology for reliable, scalable, and compact high-voltage equipment, like gas-insulated switchgear (GIS), gas circuit-breakers (GCB), live tank breakers (LTB), dead tank breakers (DTB), gas-insulated lines (GIL), and gas instrument transformers [1].

SF_6 is a synthetic gas with unparalleled insulating and arc quenching properties. SF_6 technology was initially introduced in the 1960s and SF_6 gas circuit-breakers displaced bulk oil, minimum-oil, and air blast circuit-breakers for newly installed equipment during the 1970s and 1980s. The advantages of SF_6 technology in performance, size, and reliability were considerable [1] [2].

The high GWP is the significant downside of SF_6, resulting from a high radiative efficiency and long atmospheric lifetime. Even for high-voltage equipment with state-of-the-art sealing systems and mastered gas-handling procedures, SF_6 emissions are the dominant contribution to the equipment's carbon footprint (see section 3.1.3). The concentration of SF_6 in the Earth's atmosphere is increasing annually [3]. Worldwide, SF_6 emissions make up several tenths of percent of all CO_2-equivalent emissions [4], which corresponds to the yearly CO_2 emissions produced by approximatively 100 million cars.

Since the 2010s and with even more intensity in the 2020s, it is a priority for manufacturers to develop and for users to deploy high-voltage equipment using SF_6 alternatives, which significantly reduce the products' carbon footprint while at the same time retaining the advantages of SF_6 technology: reliability, scalability, and compactness [4] [5] [6] [7].

1.2 Climate change: a global challenge

Climate change is the 21st century's biggest, most global challenge. We have seen an unprecedented level of progress, life quality, and dominance over our environment. But because our world relies on energy, fossil-fuel energy sources have significantly affected Earth's climate by emitting various GHGs. With the current and future surface temperature increase, global biodiversity is endangered, and we must use as many levers as possible to minimize the effects of global warming.

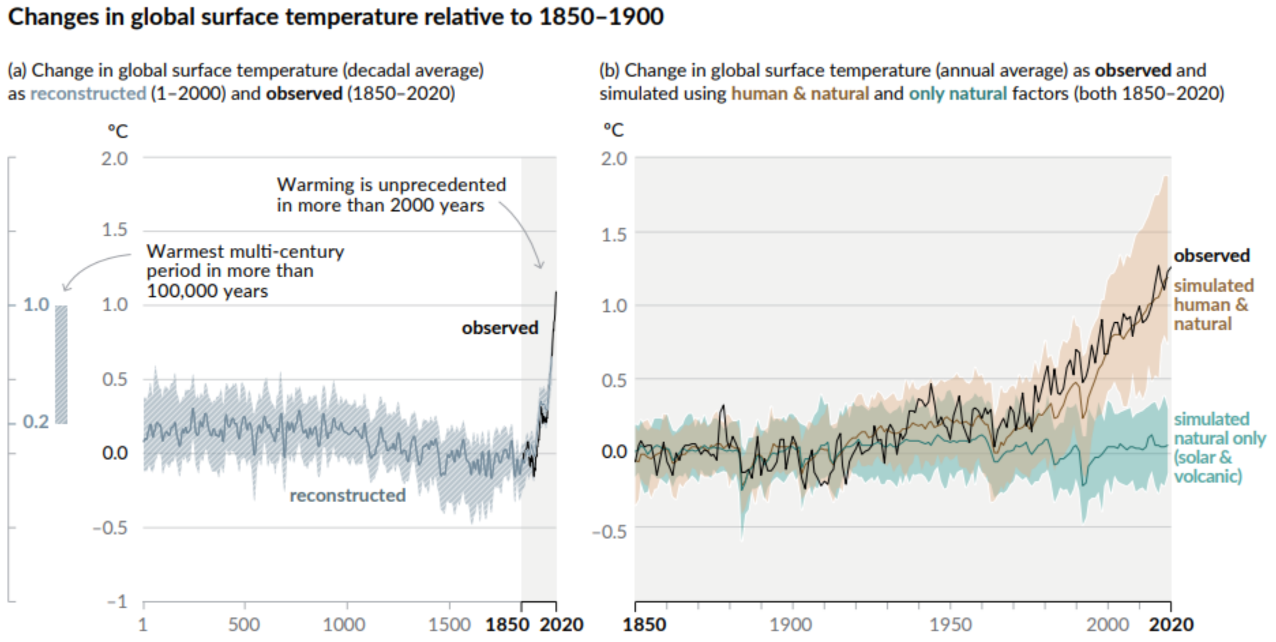
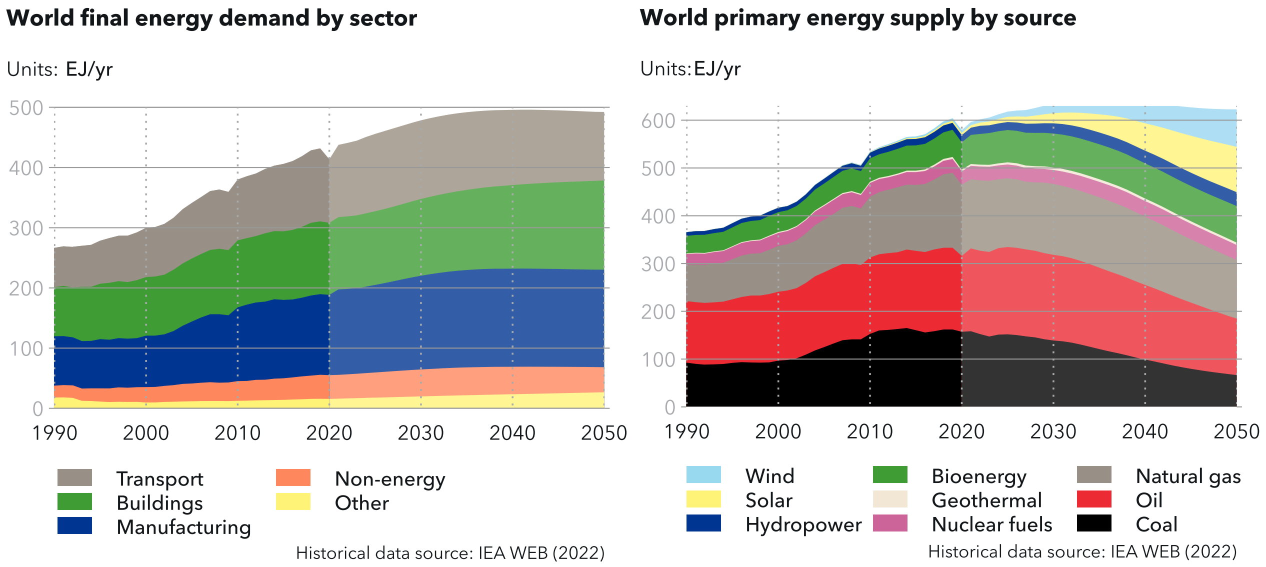


Figure 1: Evolution of Earth's surface temperature due to the GHG emissions [8]

Transitioning out of fossil energy relies mostly on three factors [9] [10]:

- Sufficiency: using energy when and where we need it, reducing non-essential uses and rationalizing the equipment (capabilities in relation with the needs, re-use, repairability, etc.).
- Efficiency: improving equipment and processes so that less raw energy or material is required for the same result.
- Carbon-neutral energies: developing renewable energy sources (hydro, wind, solar, etc.) is necessary to compensate for the reduction of fossil fuel sources. However, low-carbon/non-renewable energies like nuclear electricity production are also necessary for the transition.

As per a DNV study [11], the global energy demand should peak around 2036 and the low-carbon energy share is estimated to reach 51 % of the total energy supply by 2050.


World final energy demand by sector

Units: EJ/yr

Historical data source: IEA WEB (2022)

World primary energy supply by source

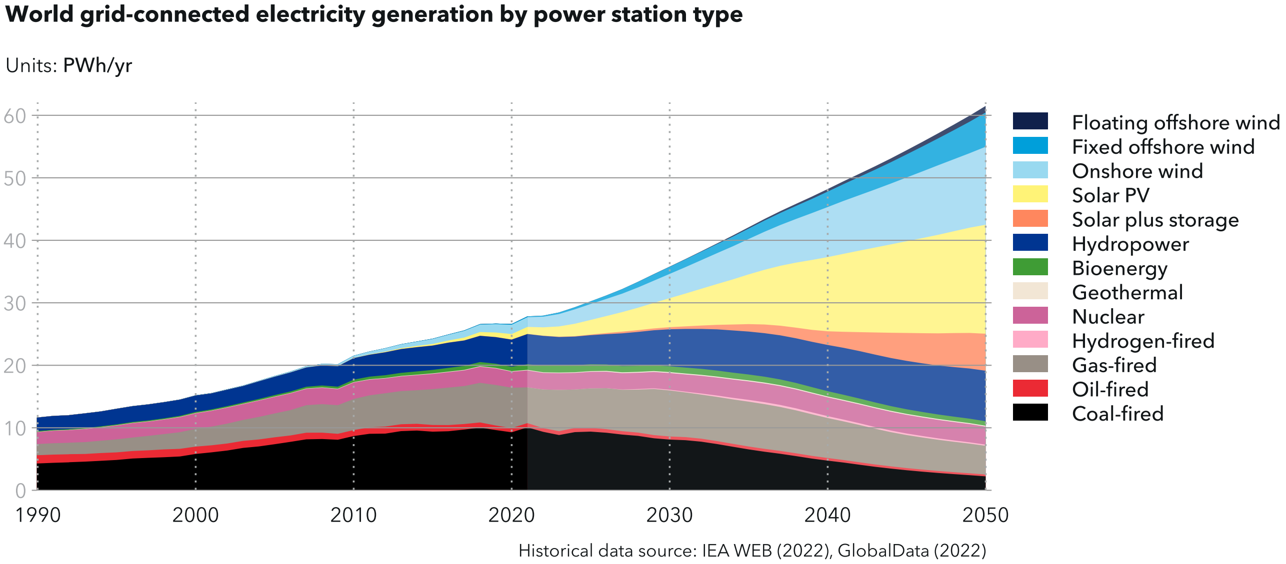
Units: EJ/yr

Historical data source: IEA WEB (2022)

Figure 2: Historical and forecasted global energy demand and supply from 1990 to 2050 [11]

Electricity from renewable sources (hydropower, solar and wind) is leading the transition out of fossil fuels, standing as the fastest-evolving sector (Figure 3).

Based on [11], between 2022 and 2050, the fossil fuels share in the electricity mix should drop from 59 % to 12 %. The change is mostly led by the fast increase of solar PV and wind, which will almost reach 70 % of worldwide electricity production. Hydro power is seeing a slower increase as potential for new major installations are limited. Produced nuclear energy is relatively stable due to the phase-out of some installations and a limited number of forecasted new projects.


World grid-connected electricity generation by power station type

Units: PWh/yr

Historical data source: IEA WEB (2022), GlobalData (2022)

Figure 3: Historical and forecasted grid-connected electricity generation [11]

The changes in the electricity mix create major challenges for the complete sector. These necessary evolutions directly impact the transmission and distribution networks with a continuous increase of the total power and energy supply via a more distributed network and higher energy supply volatility.

For the transmission system operators (TSOs) and distribution system operators (DSOs), the underlying challenges of reducing climate change impact include:

- Adapting to the changes in energy supply and demand described above (increase of average and maximum transmitted power, higher energy volatility, meshed networks).
- Reducing the losses in the network. In the EU in 2009, there were power losses of 28.4 % in the electricity network, including 1.4% from electricity transmission and distribution, 5.0 % due to the energy sector's own consumption, and 22.0 % due to the power transformation [12].
- Reducing the carbon footprint of the equipment used in the grid by removing potent gases like SF_6, selecting new installations based on their life cycle assessment (LCA), extending service lifetime of existing material, and improving recycle rate at the end-of-life.

This handbook focuses on a small part of the global effort necessary to mitigate global warming. However, at the TSO and DSO scale, the replacement of SF_6 is one of the key ways to reduce the GHG emissions quickly and definitively.

1.3 Our mission: minimize the carbon footprint of high-voltage equipment

SF_6 is the most potent GHG. As per the latest IPCC report (AR6) [13], 1 kg of SF_6 is equivalent to 24 300 kg of CO_2. The excellent dielectric, arc quenching, and thermal properties of SF_6 make it, environmental impacts aside, the best technical solution as an insulation and interruption medium in high-voltage equipment. However, despite the constant effort of manufacturers and users to reduce SF_6 leakage, SF_6 leakage is not completely removed. Small SF_6 emissions occur during gas handling in production, maintenance, and at the end-of-life. Additionally, even the most advanced sealing systems will have a certain leakage rate during the long use phase of the equipment [14]. Additionally, the total number of installed high-voltage pieces of equipment and the total quantity of banked SF_6 worldwide is constantly increasing.

The estimated SF_6 emissions of 22 countries or areas in 2020 was collected by the United Nations Framework Convention on Climate Change (UNFCCC) [15]. They can be related to the electric power consumption of 2020 [16] (Figure 4). The more electricity is consumed in a country, the more SF_6 is emitted.

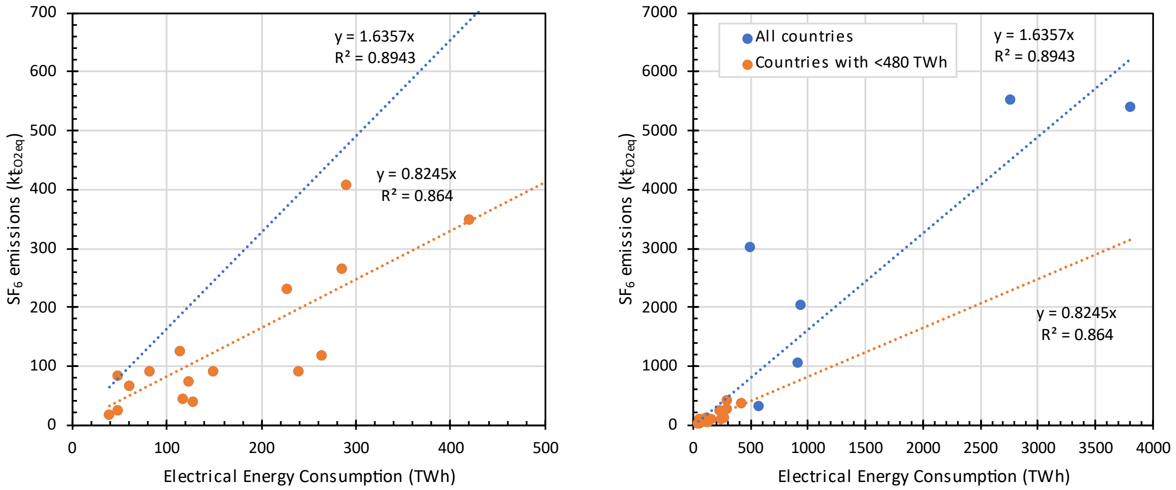


Figure 4: Relation between the electricity consumption and SF_6 emissions in 2020 for 22 countries (same dataset on both figures, left as a zoomed view) [15] [16]

Similarly, it is pointed in [17] that the rapid increase of SF_6 electrical equipment installation due to the rise of power demand and renewable energy sources, can be directly linked to the increase of SF_6 emissions in the atmosphere. Without action, the additional increase of electricity demand (Figure 3) resulting in the need of more electrical equipment, more SF_6 emissions can be expected. The availability of SF_6-free electrical equipment has the potential of mitigating these effects, although newly banked SF_6 will cause emissions for the next 30-40 years due to the long lifetime of the equipment.

The transition from SF_6 requires specific developments by equipment manufacturers and the speed of developments is linked to market demand and strongly influenced by regulations and public opinion.

The real uptake of developing SF_6-free high-voltage equipment started around 2015, when the first SF_6-free high-voltage equipment with rated voltages of 145 kV and above were installed. These new technologies use C4-FN (C_4F_7N, fluoronitrile) mixtures, C5-FK ($C_5F_{10}O$, fluoroketones) mixtures, natural-origin gases, or vacuum interrupters insulated in synthetic air.

Over the last few years, many TSOs and DSOs have started testing and adopting these technologies. Today, this trend is accelerating as the demand rises and manufacturers are increasing their SF_6-free product portfolio.

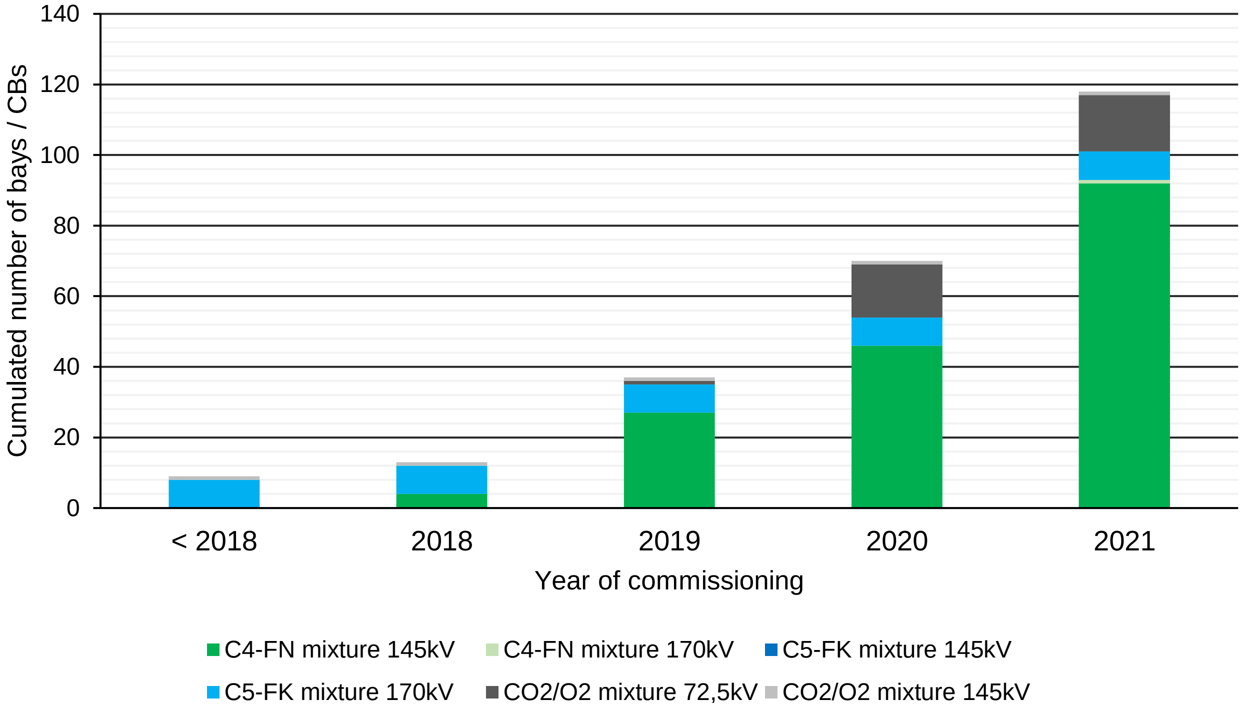


Figure 5: Cumulated number of high-voltage SF_6-free gas-filled switchgear in service [4]

More recently, the focus has not only been the replacement of SF_6, but also the reduction of the total carbon footprint of the entire product. To evaluate the carbon footprint of the product, proper LCAs must be performed. While all newly developed SF_6-free technologies show a decrease of the carbon footprint, the replacement of the SF_6 cannot be the only factor to be explored, as all parts and materials of the complete system contribute to the carbon footprint.

It is not expected that C4-FN mixtures will become the only SF_6 alternative in the coming years. Multiple solutions are likely to coexist, each with its strengths and weaknesses. The major strengths of the C4-FN technology are its high dielectric withstand voltage and that it allows users to utilize the reliable and time-tested gas circuit-breaker technology. This enables it to quickly cover the complete range of existing SF_6 applications with similar compactness. SF_6 alternatives using vacuum interrupters face technical limits at 245 kV and above and for high continuous currents.

The figure below summarizes the roadmaps from several manufacturers, allowing a quick replacement of SF_6 within high-voltage switchgear on the complete range of applications.

	72.5 kV	145 kV	170 kV	245 kV	362/420 kV	550 kV
GIS	✅	✅	✅	✓	✅	✓
DTB	✓	✓		✓	✅	✓
LTB	✓	✅		✓	✓	✓

Figure 6: Ratings of high-voltage switchgear using C4-FN mixtures, either available (✅) or announced (✓) until 2026 [18], [19], [20]

This handbook's objective is to support the quick transition to SF_6 alternatives by strengthening the knowledge base on C4-FN technology. Multiple manufacturers are already offering and developing products using C4-FN mixtures and many system operators are selecting C4-FN technology for their networks [21].

Standardization will require years to fully adapt to the SF_6 alternatives, although the standard IEC 62271-4 shows that things are moving quickly. So far, most of the work was coordinated through CIGRE and its working groups, with the development of three high-quality technical brochures [22], [5], [4], many workshops and tutorials, and an incredible number of papers and discussions with GE and Hitachi Energy being important contributors.

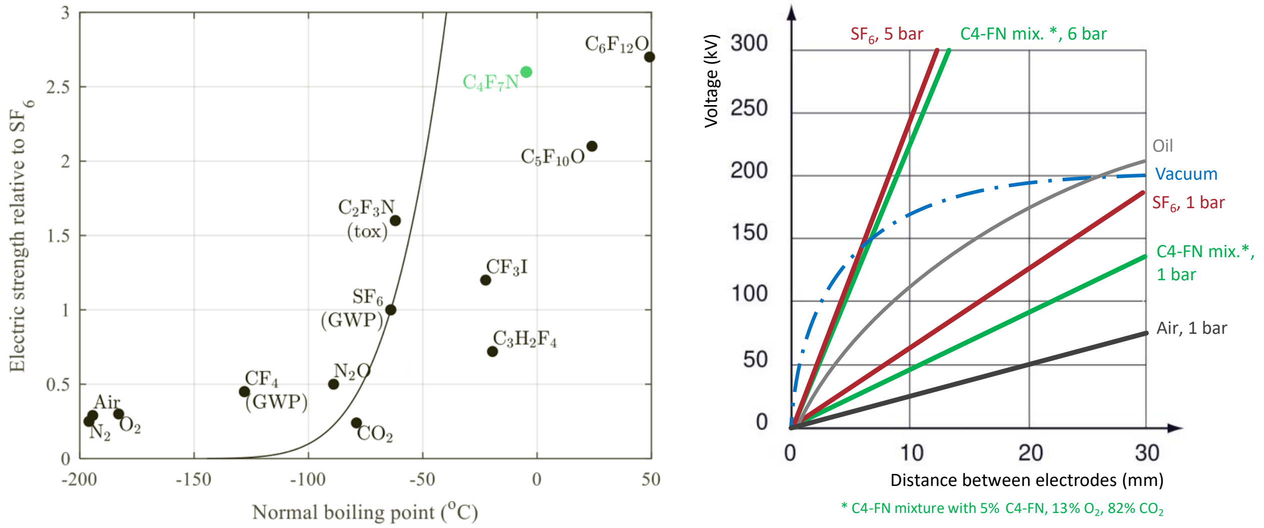
It is the purpose of this handbook to deliver fundamental knowledge about C4-FN mixtures, allowing readers to accelerate this transition. The handbook should help with the interoperability of equipment (e.g., same temperature compensation of a pressure measurement) and simplify processes for users (e.g., clear rules regarding PPEs).

This handbook also briefly describes some fundamentals but will not present sophisticated scientific details that are better addressed in specialized literature and conferences. General concepts are discussed, and relevant data extracts presented. It is dedicated to high-voltage experts as well as engineers and technicians engaged in C4-FN technology.

1.4 C4-FN mixtures for high-voltage equipment

C4-FN mixtures are gas mixtures having C4-FN mixed with O_2, CO_2, or N_2. These gas mixtures are versatile because they offer flexibility to adapt the gas mixture to its need.

- **C4-FN** is a key additive that boosts the dielectric performance of the gas mixture. C4-FN is mixed with a carrier gas, either CO_2 or N_2, to lower the boiling temperature of the gas mixture and to allow its use in typical application temperatures at a high total pressure.
- **CO_2** is the main carrier gas of C4-FN mixtures used for insulation and interruption, because it provides the highest arc quenching capabilities among the three possible carrier gases (CO_2, N_2 and O_2).
- **N_2** can be used as carrier gas if no interruption is necessary. N_2-based C4-FN mixtures have a slightly better dielectric performance and a low permeation rate when used with legacy sealing materials, which makes them interesting for retrofill.
- **O_2** is an optional additive to C4-FN mixtures. O_2 is mostly used to mitigate the appearance of free carbon as solid by-product, and O_2 also reduces the content of the toxic by-product CO of arced gas. O_2 also has a positive effect on the switching performance of circuit-breakers, allowing higher performance without oversizing the product [23].



* C4-FN mixture with 5% C4-FN, 13% O_2, 82% CO_2

Figure 7: Left: Various possible SF_6 alternatives (C_4F_7N = C4-FN; $C_5F_{10}O$ = C5-FK) [24]; Right: Comparison of the dielectric withstand voltage of various insulating media, based on [25] amended with data for C4-FN mixture

No SF_6 alternative matches the SF_6 properties in terms of insulation and interruption performance. But using C4-FN mixtures leads to the following advantages:

- C4-FN mixtures combine a low GWP_{100} in the range of 350-700, and a low gas density in the range of 30 %-60 % compared to SF_6, which leads to a reduction of about 99 % of the CO_2equivalent of the installed gas, compared to an equivalent SF_6 solution (see section 2.2).
- High dielectric performance, keeping the equipment footprint identical to SF_6 solutions and avoiding higher use of materials which impacts the cost and the total carbon footprint of the equipment.
- Good arc quenching capabilities that allow users to use the same self-blast or puffer technology, as developed over the last few decades for SF_6.

The first developments in C4-FN technology focused on voltage levels between 145 kV and 170 kV, but it quickly demonstrated its fast scalability (first commercially-available C4-FN product was a 420 kV GIL). There are now several 420 kV products, including circuit-breakers (see Figure 6), and it is expected to be able to cover typical application up to 550 kV, 800 kV, and beyond. The same scalability applies with short-circuit and nominal currents, with up to 63 kA and 5 000 A already available.

A key focus for European TSOs is focusing on the development of C4-FN for 420 kV GIS. In Europe, the 420 kV level contains the largest share of SF_6 inventory and a lot of new equipment will need to be installed within the next decade [26].

The high dielectric performance and flexibility of using C4-FN technology enables the following two additional applications that are not available for other SF_6-free technologies:

- **Dual-gas equipment**
  Dual-gas equipment is equipment that can be used with either SF_6 or a C4-FN mixture for identical or very similar ratings, allowing a smoother transition away from SF_6 for the manufacturer (supply chain) and user (architecture, training, spare parts, etc.). C4-FN circuit-breakers are similar to SF_6 circuit-breakers, using the same self-blast and puffer principles, but minor designs changes (e.g., inside the arcing chamber, at the exhaust volume, or at the operating mechanism) are needed. For early adoption of the C4-FN technology, or for critical applications where SF_6 cannot be replaced yet, dual-gas architecture allows users to have a compact C4-FN GIS with a SF_6 circuit-breaker.
- **Retrofill**
  Retrofill is a relatively easy retrofit concept where SF_6 is replaced on-site with a C4-FN mixture, while the key parts of the high-voltage equipment like enclosures, conductors, and insulators stay in place. Retrofill with C4-FN mixtures is available for gas-insulated lines (GIL) and has the potential to remove large amounts of SF_6 from the grid with low on-site effort [27].

1.5 Abbreviations and definitions

Below lists of abbreviations and definitions that are frequently used in the handbook are given. Common terms related to high-voltage equipment can be found in IEC and ISO platforms and documents.

1.5.1 Abbreviations

AIS	Air-insulated switchgear
ATE	Acute toxicity point estimate
C4-FN	Synthetic fluid having the molecular formula C_4F_7N (for details see section 2.1).
C5-FK	Synthetic fluid having the molecular formula $C_5F_{10}O$
CAPEX	Capital expenditures
CB	Circuit-breaker
CLP	The CLP Regulation is a European Union regulation from 2008, which aligns the European Union system of classification, labelling and packaging of chemical substances and mixtures to the Globally Harmonised System (GHS).
CT	Current transformer
DES	Combined disconnector and earthing switch
DS	Disconnector
DSO	Distribution system operator, also called grid operator or utility
DT	Dead-tank, type of AIS with an earthed enclosure
EPDM	Ethylene propylene diene monomer rubber
ES	Earthing switch, also grounding switch (US)
FES	Fast earthing switch, or earthing switch with short-circuit making capability, also called make-proof earthing switch
GHG	Greenhouse gas This type of gas contributes to the global warming by trapping the heat when released in the atmosphere.
GIL	Gas-insulated line
GIS	Gas-insulated substations
GWP	Global warming potential Characterization factor for climate change impact, providing a CO_2-equivalent value of a substance or product. In the high-voltage sector, the GWP is mostly used to refer to the characterization factor of the gas itself (e.g., GWP_{100} = 24 300 for SF_6). GWP values can be computed for different durations, usually 100 years. Values can be found in the IPCC AR6 report 7SM [3].
HSE	Health, safety, and environment. Equivalent of EHS.
HV	High-voltage
LC50	“Lethal Concentration” which causes the death of 50 % (one half) of a group of test animals

LCA	Life cycle assessment LCAs are studies to assess the impact of a product or system on the environment. It includes the climate change indicators but also many others like material depletion or acidification potential. LCA is recognized by the EU as the right methodology to evaluate the environmental impacts of a product [28].
LCC	Local control cubicle
OEM	Original equipment manufacturer The company supplying the equipment, typically the high-voltage switchgear.
OPEX	Operational expenditures
PR-EoS	Equation of state formulated by Ding-Yu Peng and Donald Robinson
SDS	Safety datasheet
SRK-EoS	Equation of state formulated by Giorgio Soave, Otto Redlich, and J.N.S. Kwong
TSO	Transmission system operator, also called grid operator or utility
VdW-EoS	Equation of state formulated by Johannes Van der Waals
VLE	Vapor liquid equilibrium
VT	Voltage transformer
(X)IIR	Isobutylene isoprene rubber or simpliefied butyl rubber

1.5.2 Definitions

Gas	Matter characterized by identical or different molecules and/or atoms being arranged without structure so that they are collectively fluid and have neither a definite shape nor a definite volume. A gas might contain contaminants.
Single gas	Gas made up of identical atoms or molecules. A single gas might contain contaminants.
Gas mixture	Gas made up of a minimum of two single gases. A gas mixture might contain contaminants.
Pressure	Pressure of a gas or a component of a gas mixture, expressed in bar or mbar. If not otherwise stated in this document “pressure” stands for “absolute pressure” and the pressure values “bar”, resp. “mbar”, stand for “bar absolute”, resp. “mbar absolute”.
Composition (of a gas mixture or a liquid)	Percentage (or ratio or concentration) of a single gas or liquid being a component of a gas mixture or a liquid. Compositions are preferably defined in mole fraction (%mol). Using mass fraction is also meaningful (%wt), while volume fraction (%vol) is to be avoided as it is not constant with pressure and temperature in non-ideal conditions due to the non-linear compressibility.

Mole fraction (%mol)	The ratio of the moles n_i of one component or contaminant of interest to the total moles n_{tot} of the gas or liquid, generally expressed in %mol for components and contaminants. $$\%mol_i = x_i = \frac{n_i}{n_{tot}}$$ The mole fraction has no pressure or temperature dependence. It can be used to quantify the components in a mixture. For contaminants it can also be expressed in parts per million by mole, ppm. Throughout this document mole fraction (%mol) is the preffered unit for concentrations. Therefore the unit % referes to %mol if not otherwise indicated.
Mass fraction (%wt)	The ratio of the mass m_i of one component or contaminant of interest to the total mass m_{tot} of the gas or liquid, generally expressed in %wt for components and contaminants. $$\%wt_i = \frac{m_i}{m_{tot}}$$ The mass fraction has no pressure or temperature dependence. It can be used to quantify the components in a mixture. For contaminants it can also be expressed in parts per million by mass, ppmw or its numerically equivalent and preferred unit µg/g.
Volume fraction (%vol)	The ratio of the volume V_i of one component or contaminant of interest to the total volume V_{tot} of the gas or liquid, generally expressed in %vol for components and contaminants. $$\%vol_i(T,p) = \phi_i = \frac{V_i(T,p)}{V_{tot}(T,p)}$$ The volume fraction of a component is pressure and temperature dependent. Normal conditions are often considered but their definitions can vary depending on usage. Defining a mixture using its molar fraction is preferred. For contaminants it can also be expressed in parts per million by volume, ppmv.
C4-FN technology	Any activity or equipment within the framework of using C4-FN or C4-FN mixtures.
Technical grade C4-FN	C4-FN having a low level of contaminants as per 2.6.2.
Natural-origin gases	Natural-origin gases are N_2, O_2 and CO_2, and their mixtures in any combination [29].
Technical grade natural-origin gases	Technical grade natural-origin gases are technical grade N_2, technical grade O_2 and technical grade CO_2, and their mixtures in any combination.
Technical grade N_2	N_2 having a low level of contaminants as per 2.6.2.
Technical grade O_2	O_2 having a low level of contaminants as per 2.6.2.
Technical grade CO_2	CO_2 having a low level of contaminants as per 2.6.2.
C4-FN mixture	Mixture of C4-FN with one or more natural-origin gases [29].
Technical grade C4-FN mixture	Mixture of technical grade C4-FN with one or more technical grade natural-origin gases.
Used C4-FN mixture	C4-FN mixture which has been introduced into electric power equipment [29].

Non-arced C4-FN mixture	Used C4-FN mixture that never experienced arcing and contains no relevant gas decomposition and no relevant solid by-products, but where small quantities of by-products can be present. Small quantities of by-products can be present for example when partial discharges have occurred in the gas. Non-arced C4-FN mixture is often suitable for reuse.
Normally arced C4-FN mixtures	C4-FN mixture that experienced arcing during load current or fault current switching operations and which has never failed to interrupt.
Heavily arced C4-FN mixtures	C4-FN mixture that contains large amounts of by-products after experiencing an internal arc fault or an excessive number of fault current swithing operations. Heavily arced C4-FN mixtures also contain large amounts of solid by-products.
By-products	Contaminant(s) which is/are formed by the degradation of the gas by electrical arcs, corona effect or sparks, or formed by chemical reaction with other substances or materials [29].
Contaminants	Foreign substance or material in an insulating liquid, gas, or solid [29].
Retrofill	Replacement of SF_6 with an SF_6 alternative in an existing installation while keeping most of the high-voltage parts of the equipment in place.
Retrofit	Replacement of SF_6 with an SF_6 alternative in an existing installation with significant changes on the equipment in place.

1.6 Standardization activities

Table 1, Table 2, and Table 3 give a brief overview of ongoing and finalized IEC, IEEE, and CIGRE activities about characteristics, specifications, and handling procedures of gases alternative to SF_6 used in electrical equipment.

1.6.1 IEC standards

Table 1: IEC standards covering specifications and requirements for C4-FN mixtures used in high-voltage equipment

Document name	Title	Status
TC17/AHG5	Report on the impact of new gases and their impact on switchgear standards	Report TC17/AHG517/1030/INF
IEC 62271-4	High-voltage switchgear and controlgear Part 4: Handling procedures for gases for insulation and/or switching	Edition 2.0 Issued 2022-07
IEC 63360	Fluids for electrotechnical application: specification of gases alternative to SF_6 to be used in electrical power equipment.	Future edition 1.0 (10/1166/CD) CDV stage 2023-05
IEC 63359	Fluids for electrotechnical application: specifications for re-use of gases alternative to SF_6 to be used in electrical power equipment.	Future edition 1.0 CD stage 2023-12

1.6.2 IEEE guides and standards

Table 2: IEEE standards and guides covering specifications and requirements for C4-FN mixtures used in high-voltage equipment

Document name	Title	Status
PES-TR64	Impact of alternative gases on existing IEEE standards	Technical report May 2018
IEEE C37.100.7	Guide for the evaluation of performance characteristics of non-sulphur hexafluoride insulation and arc quenching media for switchgear rated above 1 000 V	Draft version D4.1, 2022-10
IEEE C37.122.10	Guide for handling non-sulphur hexafluoride (SF_6) gas mixtures for high-voltage equipment	Draft in progress (IEEE WG K19)

1.6.3 CIGRE brochures and working groups

Table 3: CIGRE working groups covering topics related to C4-FN mixtures used in high-voltage equipment

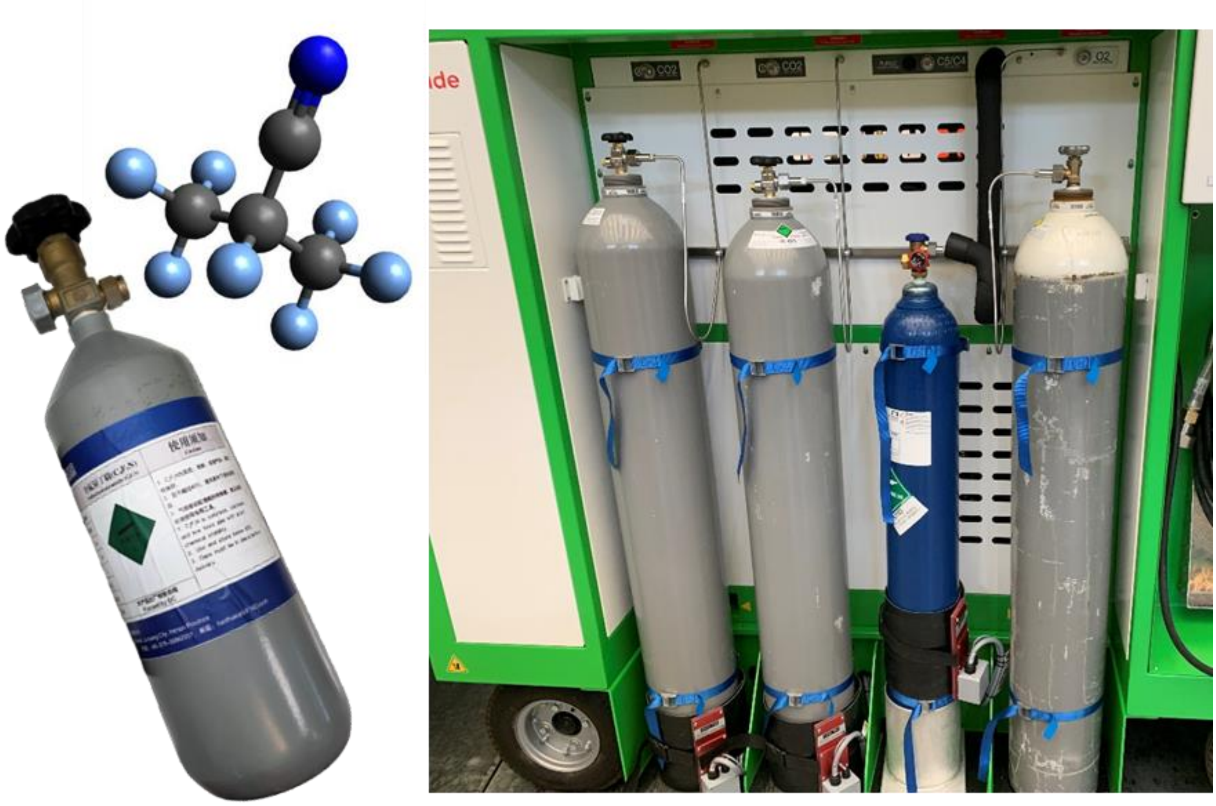
CIGRE WG	Main task	Technical brochure
B3.45	Application of non-SF_6 gases or gas-mixtures in medium and high-voltage gas-insulated switchgear	TB 802 (2020)
D1.67	Electric performance of new non-SF_6 gases and gas mixtures for gas-insulated systems	TB 849 (2021)
A3.41	Current Interruption in SF_6-free switchgear	TB 871 (2022)
B3/A3.60	User guide for non-SF_6 gases and gas mixtures in substations	Not yet released

2 Technical characteristics of C4-FN mixtures

This chapter contains key technical information for the application of C4-FN mixtures in high-voltage equipment. Starting from the properties of the C4-FN molecule itself, the main characteristics of mixtures are treated: environmental footprint, dielectric properties, thermodynamic properties, quality, and purity requirements, as well as long-term behavior. From the user point of view, especially thermodynamic properties and quality requirements are of high importance, here quantitative models and limits are given.

2.1 Designation of C4-FN

In the high-voltage community, C4-FN is the commonly used designation for the molecule having the molecular formula C_4F_7N (see Figure 8).



Structure of C4-FN (C_4F_7N) molecule and C4-FN cylinder containing partially liquefied C4-FN.

Blue C4-FN cylinder in a filling cart, together with CO_2 and O_2 cylinders to prepare a C4-FN/O_2/CO_2 mixture.

Figure 8: C4-FN molecule, C4-FN cylinder, and C4-FN mixing cart

In scientific literature, regulations, standards, or patents, the following equivalent designations can be found: fluoronitrile; *i*-C_3F_7CN; *i*-C_4F_7N; $(CF_3)_2$-CF-CN; 2,3,3,3-tetrafluoro-2-(trifluoromethyl)-propanenitrile; and perfluoroisobutyronitrile. The CAS number is 42532-60-5.

2.2 Environmental footprint of C4-FN and its mixtures

C4-FN has a lower environmental footprint than SF_6 as the result of two factors:

- Its atmospheric lifetime is 34.5 years, much less than the 1 000 years of SF_6.
- Its radiative efficiency is divided by more than two compared to SF_6 (0.248 $W.m^{-2}.ppb^{-1}$ instead of 0.567 $W.m^{-2}.ppb^{-1}$).

Should C4-FN leak, it will stay in the atmosphere for a much shorter time and will have a significantly reduced greenhouse effect compared to SF_6. This is visible through the characterization factors (GWP) as provided by the IPCC [3] and given in Table 4 below.

Table 4: Material properties of SF_6 compared to C4-FN [8]

Category	**Unit**	**SF_6**	**C4-FN**
Atmospheric lifetime	years	1 000	34.5
GWP	GWP_{500} GWP_{100} GWP_{20}	29 000 24 300 18 200	835 2 750 4 580
Ozone depletion potential	ODP	0	0
Molecular mass	g/mol	146	195
Boiling point	°C (at 1 bar)	-64 °C	-4.7 °C

Because of its considerably higher boiling point (see Table 4), C4-FN is always used in mixtures with other gases to allow a high filling pressure of the gas mixture without liquefaction of any of its components.

The application of the C4-FN in diluted form enhances the environmental benefits compared to SF_6 even more. Instead of 100% SF_6, a low C4-FN concentration is used to fill typical high-voltage equipment (see Table 5). This leads to a reduction of the CO_2 equivalence of the gas inside the high-voltage equipment of about 99%.

Table 5: CO_2-equivalent of a 100 m three-phase GIL when filled with SF_6 or with a C4-FN mixture [8] [30]

Category	**Unit**	**SF_6**	**Exemplary C4-FN mixture** (3.5 % C4-FN / 10 % O_2 / 86.5 % CO_2)
GWP	GWP_{100}	24 300	391
Gas pressure	bar at 20 °C	5.3	9.1
Gas density	kg/m^3	34	18.8
Gas volume	m^3	32	
Gas mass	kg	1 090	602
Total banked CO_2-equivalent	t_{CO2eq}	26 400	236
CO_2-equivalent and reduction	-	100 % (reference)	**0.9 %** **-99.1 %**

2.3 Dielectric properties of C4-FN mixtures

2.3.1 Dielectric withstand compared to SF_6

C4-FN has been selected for its excellent dielectric properties, which – when used as single gas – are higher than for SF_6. In practical applications, C4-FN is mixed with other gases to reduce the dew temperature. A full dielectric performance assessment of an insulating medium in high-voltage equipment is complex and needs to cover various parameters like gas mixture composition, pressure, sensitivity to surface roughness, contaminations, or utilization factor [31] [32].

There are elaborate literature reviews [33] and experimental studies [5] [34] publicly available that allow for assessing the basic dielectric properties of C4-FN mixtures and compare their performance with SF_6.

Basic experimental investigations

The CIGRE Technical Brochure TB 849 [5] provides some key experimental results on the dielectric performance of SF_6 alternatives. In a uniform arrangement, a 20 % C4-FN / 80 % CO_2 mixture has approximatively the same AC withstand voltage as SF_6 (see Figure 9).

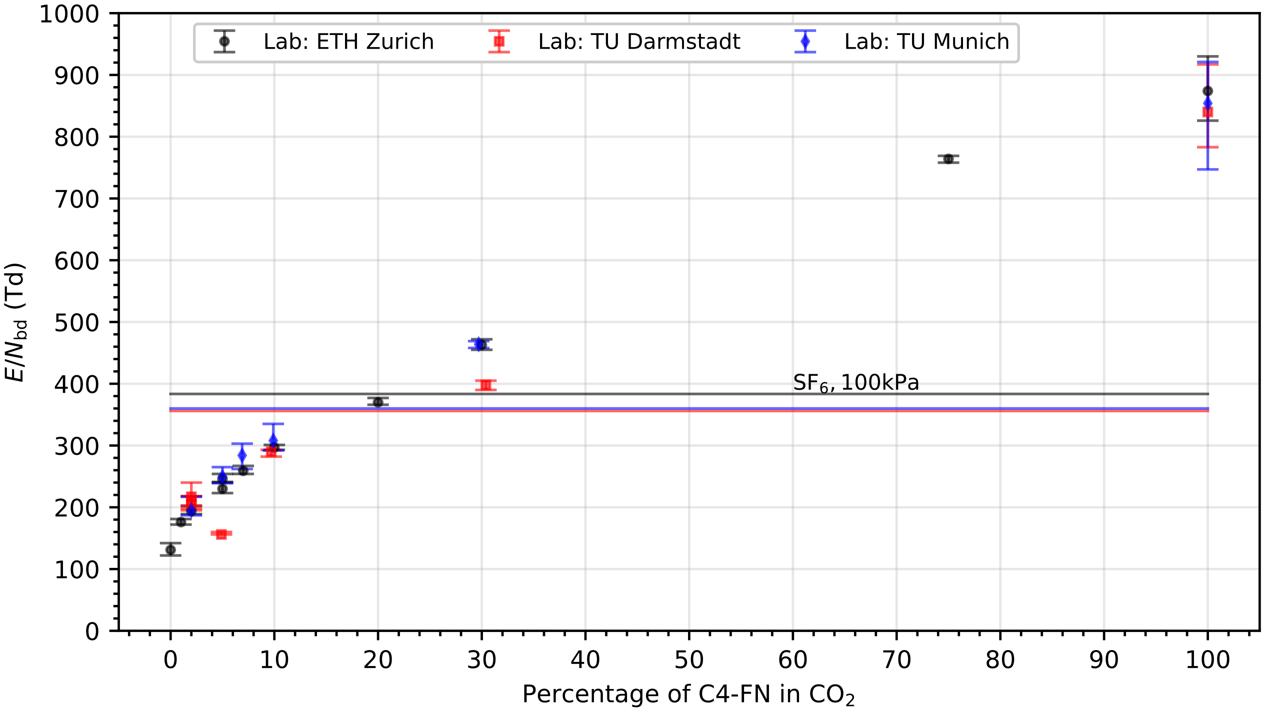


Figure 9: Dielectric breakdown voltage of 1 bar C4-FN/CO_2 mixture, compared with SF_6, derived from [5]

A concentration of 20 % of C4-FN is too high to reach temperature ratings of -25 °C or -30 °C at typical filling pressures needed in high-voltage equipment (see section 2.4). Therefore, C4-FN concentrations below 10 % are used in high-voltage equipment. A 5 % C4-FN / 5 % O_2 / 90 % CO_2 mixture at 6 bar has between 70 % and 80 % of the SF_6 performance at identical pressures (see Figure 10). This lower performance can be compensated by a moderate filling pressure increase.

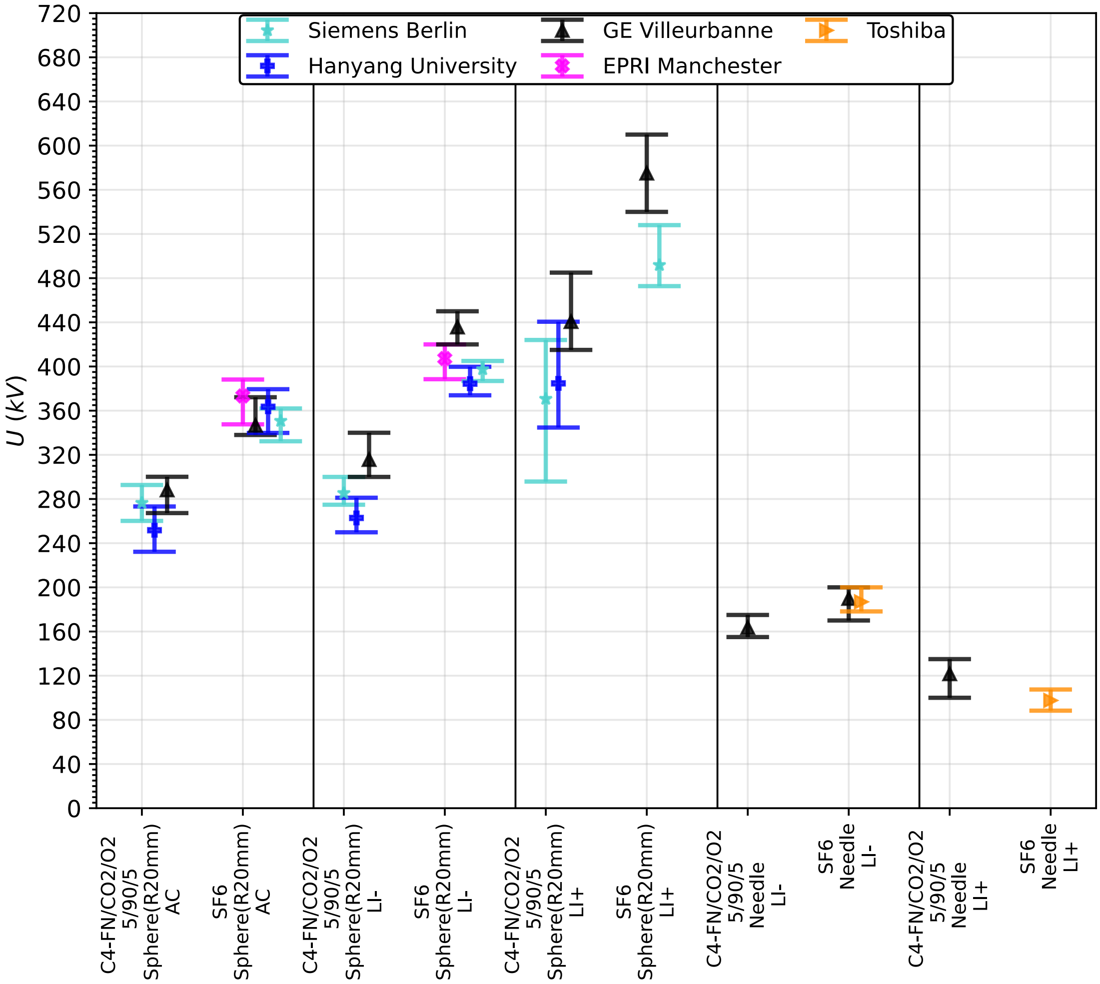


Figure 10: Dielectric breakdown voltage of 6 bar 5 % C4-FN / 5 % O_2 / 90 % CO_2 mixture and SF_6 for different arrangements, derived from [5]

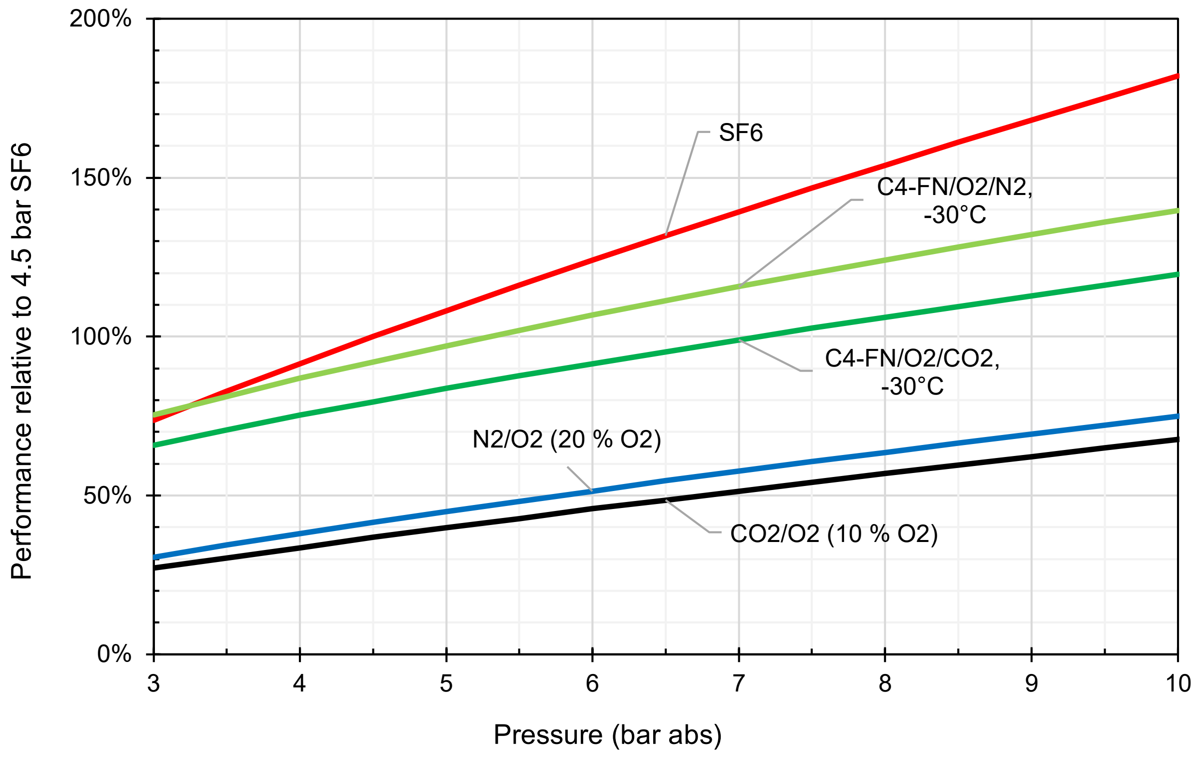
SF_6 equivalency and other SF_6 alternatives

The concept of SF_6 equivalency can be used to compare the dielectric strength of SF_6 with SF_6 alternatives like CO_2/O_2 and N_2/O_2 (technical air) and their mixtures with C4-FN [27]. The dielectric performance of surfaces that are clean and have typical roughness for electrodes in high-voltage equipment is limited by streamer inception. Under this condition, it was found that gases and gas mixtures with similar critical electrical field E_{crit} show similar behavior [27]. E_{crit} denotes the field where the net ionization coefficient becomes zero and becomes positive with a further increase of the electric field. E_{crit} for the gases and gas mixtures can be calculated from literature data for the net ionization coefficients [35]. Scaling of performance (e.g., withstand field strength E_w) with pressure p, is done using power law Eq. (1) where exponents $k < 1$ have been established. In the following $k = 0.75$ will be used.

$$E_{\mathrm{w}}(p) = E_{\mathrm{w}}(p_0)\left(\frac{p}{p_0}\right)^k \qquad (1)$$

with E_{w} withstand field strength.
p pressure of insulation gas
p_0…reference pressure with known withstand field strength
k exponent, 0.75 is used here

A comparison of SF_6 and SF_6 alternatives is shown in Figure 11, normalized to performance of 4.5 bar SF_6, a typical minimum functional pressure used for SF_6 insulated equipment.



Withstand voltage of SF_6 and SF_6 alternatives in a clean insulation system with typical surface roughness for gas-insulated high-voltage equipment [36]. This comparison is based on the concept of SF_6 equivalency. The pressure-dependence of the SF_6 performance is provided by the power law Eq. (1). The E_{crit}-values needed to establish the SF_6 equivalency of typical SF_6 alternatives are taken by fitting the experimental data from [35]. The C4-FN based gas mixtures are defined to have a dew temperature of -30 °C (see section 2.4).

Figure 11: Comparison of dielectric performance of SF_6 and SF_6 alternatives in clean insulation systems

The addition of the strong electron-attaching C4-FN to N_2/O_2 or CO_2/O_2 yields a considerable increase of E_{crit}. For a technical reference application with 4.5 bar SF_6 insulation (100 % performance in Figure 11), an SF_6 alternative with equivalent dielectric performance can be found based on C4-FN/O_2/CO_2 or C4-FN/O_2/N_2 if the pressure is reasonably increased. This also means that SF_6-insulated and C4-FN/O_2/CO_2- or C4-FN/O_2/N_2-insulated equipment can have similar dimensions.

Using an SF_6 alternative with lower performance, such as N_2/O_2 (air), results in the need to increase the size of the equipment to insulate the electrode system properly. A way to somewhat limit the equipment’s size increase is by a significant increase of the gas pressure. However, the less-than-linear performance increase with pressure visible in Eq. (1) and the increasing material consumption to build a stable enough pressure vessel must be considered.

2.3.2 Scalability

High-voltage equipment using C4-FN mixtures for insulation and interruption is scalable towards all voltage levels. This is assessed based on the following perspectives:

- Insulation: C4-FN/O_2/CO_2 and C4-FN/O_2/N_2 mixtures both showed excellent dielectric performance that make it possible to work at moderate pressures and keep overall SF_6 dimensions.
- Interruption: C4-FN/O_2/CO_2 shows good performance using the same gas circuit-breaker technology as used for the last few decades in SF_6. With the appropriate design, it can be scaled towards all relevant ratings.

Insulation

In pressurized gaseous insulation, inception of discharges is decided locally, typically at the scale of millimeters or even smaller (streamer inception, see section 2.3.1). To prevent such inception of discharges and have compact equipment, the high-voltage gas-insulated systems are typically designed to yield only slightly inhomogeneous fields. Often, coaxial cylinders (inner cylinder = active part, outer cylinder = enclosure) define the base design. Larger inhomogeneity typically occurs exclusively at defects and imperfections, such as mobile particles, scratches of surfaces, and surface roughness. In many cases, the field distortions resulting from such defects can be described as follows:

- In case of larger defects, the field distortions are so far ranging that discharges incept at relatively low background fields in the form of partial discharges, which do not cross the entire insulating gap. Partial discharge or breakdown can happen at relatively low voltage value.
- In case of smaller defects (e.g., surface roughness), at inception, the voltage and background field are so high that a discharge will propagate across the entire insulating gap.

Overall, local discharge inception and the background field are decisive for breakdown. Therefore, excessively high electric field strengths must be prevented from occurring in high-voltage equipment, independent of the actual voltage rating. The corresponding design limits remain practically the same for equipment of all voltage ranges, provided that the production environment and the quality of the manufactured equipment are similar. Specifically, this means that designing equipment for higher voltage levels, like IEC 420 kV, 550 kV or 800 kV rating, requires the same design rules as the ones for lower voltages, like 72.5 kV or 145 kV. Therefore, high-voltage equipment using C4-FN mixtures is scalable towards all voltage levels. Additionally, C4-FN mixtures that can reach similar dielectric performance as SF_6 (see section 2.3.1) and are therefore an ideal base for the full range of compact SF_6-free high-voltage equipment.

Switching

The gas circuit-breaker technology using SF_6 has been in operation in the grid for more than five decades and has proven reliability. It has been successfully scaled up to 1 200 kV [37]. By taking advantage of the reliable, long-known SF_6 gas circuit-breaker technology and adapting it to the properties of C4-FN/O_2/CO_2 mixtures, circuit-breakers, fast earthing switches, and disconnector-earthing switches can be designed to address the full range of voltage and current ratings for the power sub-transmission and transmission networks.

SF_6 alternatives with drastically reduced arc quenching properties like N_2/O_2 need to apply alternatives to gas circuit-breaker technology, like vacuum interrupters, for fault current interruption. This technology has limited experience at 145 kV and its scalability is more challenging due to saturation effects (see Figure 12) and not yet proven beyond 145 kV.

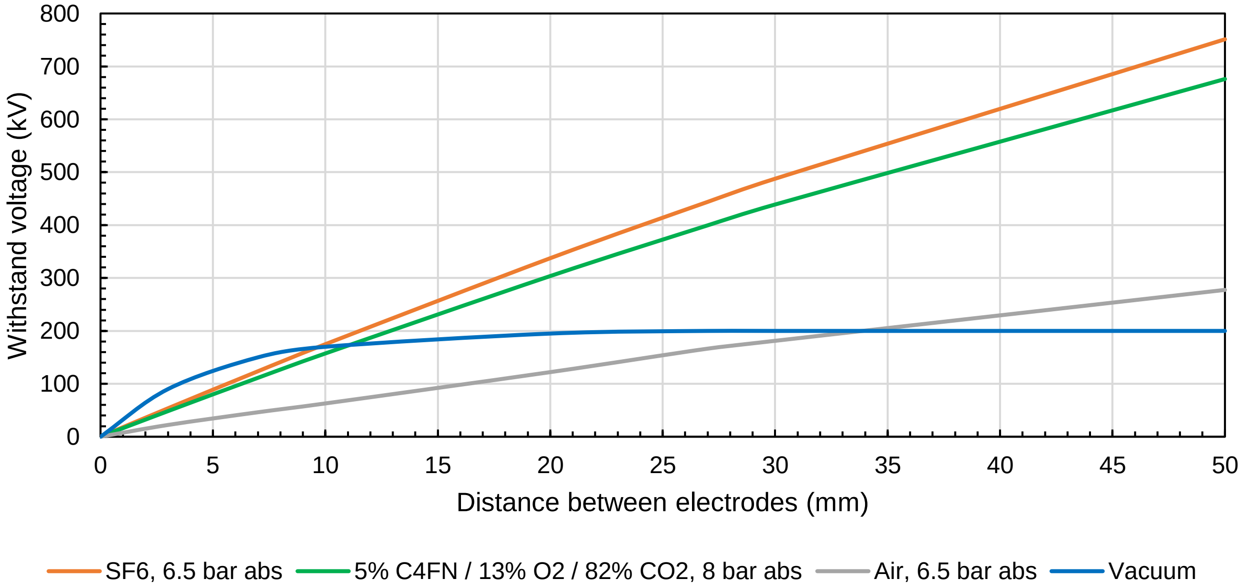


Figure 12: LI- withstand voltage vs. electrodes gap distance for various insulation media: SF_6, 5 % C4-FN / 13 % O_2 / 82 % CO_2 mixture, technical air (79 % N_2 / 21 % O_2), typical vacuum interrupter behavior – in slightly heterogeneous field, reproduced from [38]

2.4 Thermodynamic properties

2.4.1 Importance of thermodynamic model

As for SF_6, C4-FN mixtures will, depending on temperature and pressure, occur in different states:

- Gaseous state
- Liquid state
- Vapor Liquid Equilibrium (VLE) state
- Supercritical or superheated state

The solid form is irrelevant for high-voltage applications (occurs at too low temperatures to be of relevance).

A thermodynamic model for C4-FN mixtures (see section 2.4.2) is important for full-scale application of the technology as for the operation of high-voltage equipment and gas handling, it is necessary to know the boundaries between the fluid states as well as properties like density of the C4-FN mixture.

A typical phase diagram of a relevant C4-FN/O_2/CO_2 mixture is given in Figure 13.

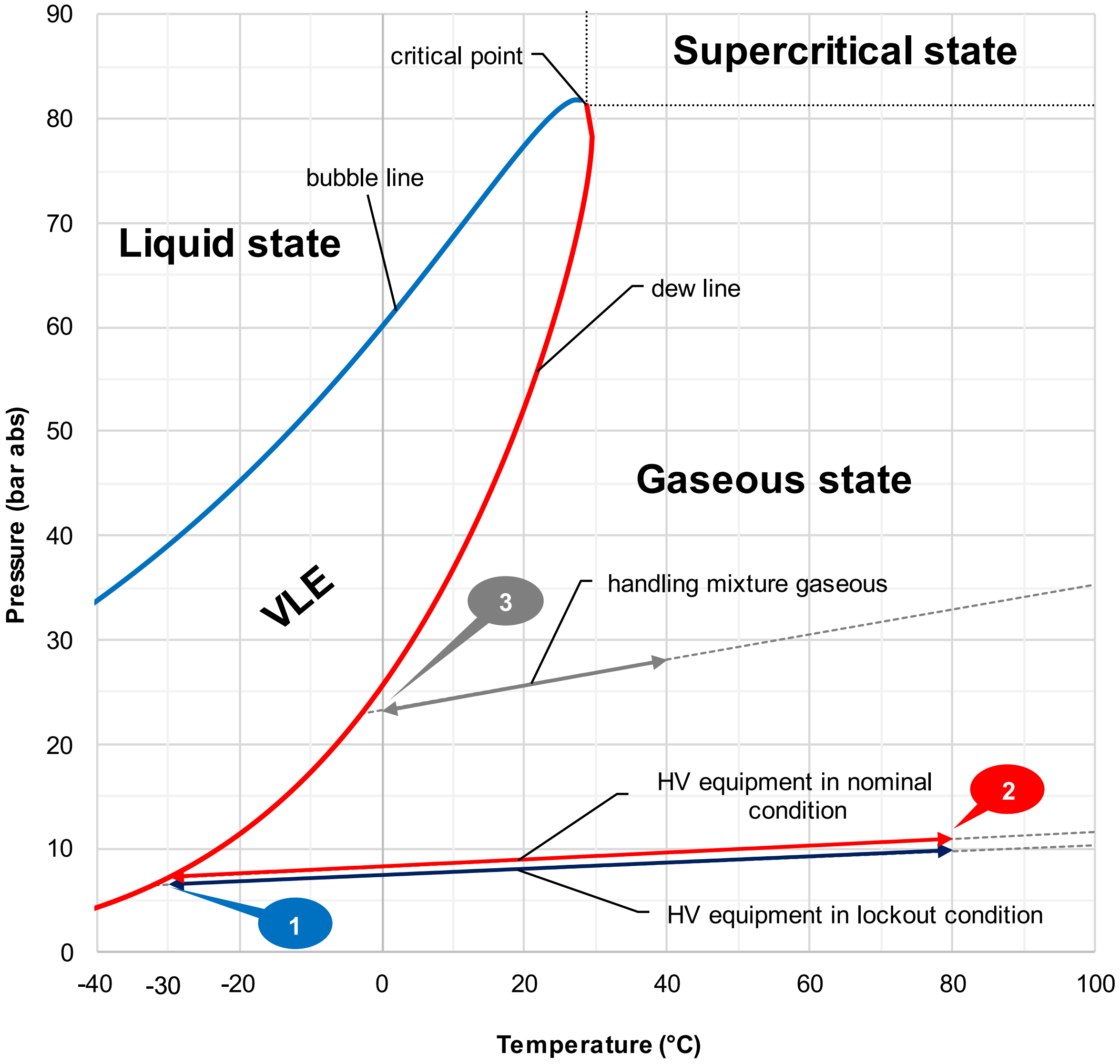


Figure 13: Phase diagram of 3.5 % C4-FN / 10 % O_2 / 86.5 % CO_2 mixture with examples of gas mixture conditions in high-voltage equipment, as well as in gas handling scenarios. Bubbles 1-3 are described in the text below.

For high-voltage applications, there are two main areas of interest described below. Additionally, the case of supercritical and superheated gas, mostly relevant for the filling operations with high density premixed gas is separately addressed in the section 2.4.7.

High-voltage equipment operation

- The mixture fulfills its function as gaseous insulation and arc quenching medium in the gaseous state.
- To define the lock-out condition of the equipment, characterized by a minimum functional pressure, it is necessary to consider the dew line (border between gaseous and VLE phase) of the C4-FN mixture (bubble 1 in Figure 13).
    - Section 2.4.3 describes a method how to calculate dew curves for typical C4-FN mixtures.
- In gaseous state, pressure varies with temperature. Pressure inside the closed compartments gets higher with increasing temperature (isochoric state change, constant density).
    - Pressures at ambient temperatures around +20 °C are important for filling operations and ratings (filling pressures are usually given for a standardized temperature of +20 °C).
    - Pressures at higher temperatures in the range of +70 °C to +100 °C are relevant to define the design pressure of the pressure vessel of the equipment (bubble 2 in Figure 13).
    - Section 2.4.4 describes a method how to calculate pressure variations (Isochores) for typical C4-FN mixtures.
- For equipment in **nominal condition**, it may be that at the lowest operational temperatures, the mixture just crosses the dew line and goes into VLE region.
    - Partial condensation may occur (see section 2.4.6).
    - This is uncritical to equipment function (same as for SF_6).

Gas handling: Store, fill, reclaim

For gas handling, it is desirable to store the gas in a denser form. There are three basics options:

- **Handling mixture gaseous:** Increasing the pressure and avoiding any condensation by keeping the gas at temperature above dew temperature, e.g., by keeping the storage tank indoor (≥0 °C, bubble 3 in Figure 13).
- **Handling mixture partially liquefied:** Increase the pressure even further and accept the mixture going into VLE region, then use appropriate gas handling equipment to heat-up the mixture to go to supercritical phase and obtain a homogeneous gas mixture for filling operations (see section 2.4.7).
- **Handling single gases (partially liquefied)**: Using of gas equipment directly mixing the single gases into a homogeneous gas mixture.

2.4.2 Gas models and equations of state

The study and description of gases started in the 17th century. The relation between pressure, temperature, and volume of one gas is called an equation of state.

In 1873, Johannes Van der Waals formulated a new cubic equation of state (VdW-EoS) that applies to both gases and liquids. His work introduced the notion of attraction and repulsion of real gas molecules, which corrected the non-validity of the ideal gas law for gases at high pressures.

This work has been continuously improved and completed by various scientists, who worked on universal laws or specific gas mixtures and applications, introducing different approaches to calculate the attracting and repulsing parameters. Modern, frequently applied successors of the cubic VdW-EoS are, for example, the Peng-Robinson or the Soave-Redlich-Kwong – type (PR-EoS, SRK-EoS). For single gases, those modern EoS need the critical point, the molecular weight and the so-called acentric factor as input parameters, which have to be determined experimentally [39]. When those EoS are applied to gas mixtures, interactions between the species usually require additional parameters (so-called binary interaction parameters) in the gas models. Several formulations exist for mixing and combining rules. It requires interaction parameters for each molecule pairing inside the mixture and the complexity of the system quickly increases with the number of species in the gas mixture.

Generally, very accurate single gas models are available in the literature for common fluids. For mixture of gases, the available data varies significantly and is typically constrained to frequently applied systems. Best studied gas mixtures are air, some mixtures of natural-origin gases and natural gas mixtures in oil and gas applications.

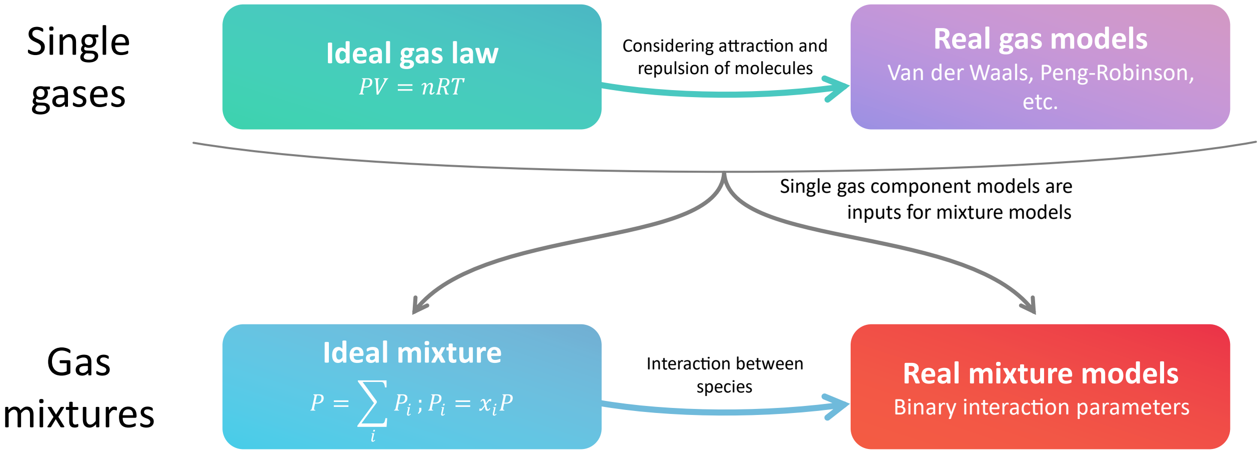


Figure 14: Various approaches of gas models for single gases and gas mixtures (simplified)

As per the literature [39], for noble gases or small molecules the ideal gas law is a valid approach for pressures up to 3…5 bar but shows a growing deviation for higher pressures. Additionally, the borderline between gaseous and liquid state (or in case of mixtures, the VLE) cannot be calculated. Regarding the gas mixtures, this is very dependent on the species and usually, interactions between species cannot be ignored especially in presence of complex molecules.

In the case of C4-FN/O_2/CO_2 and C4-FN/O_2/N_2 gas mixtures, studies were required because:

- C4-FN is a synthetic gas with a complex molecular structure, which was not applied before its introduction in high-voltage equipment. Despite its low concentration in the gas mixture, its properties lead to a pronounced real gas behavior and application of ideal gas rules will lead to significant deviations.
- Ternary mixtures with C4-FN, O_2 and CO_2 or N_2 combine very different molecules whose interaction parameters were not investigated before.
- Typical high-voltage equipment filling pressures are in the range of 5 to 11 bar, which require accurate real gas models, as for SF_6. Additionally, gas cylinders or gas handling equipment can operate at higher pressures, where the use of appropriate models is necessary.

To build a reliable gas model applicable to various C4-FN mixtures, applications and use scenarios, multiple experiments have been conducted and include:

- Vapor-Liquid Equilibrium (VLE) at various temperatures for binary and ternary mixtures to define saturated vapor curves (dew lines) with varying composition.
- Solubility experiments at various temperatures with varying compositions for binary mixtures, to evaluate the composition of the saturated liquid (bubble lines).
- Pressure-temperature curves with a defined composition and density to confirm dewpoints and general isochore behavior.

Based on these results, an appropriate gas model based on the Peng-Robinson equation of state has been defined and calibrated using RefProp [40]. The performed VLE, isochoric and solubility experiments showed good agreement with the calculations. Comparisons are presented in sections 2.4.3 and 2.4.4. The model has inherent limitations for gas mixtures close to the critical point due to the use of Peng-Robinson models. Further work is required to obtain a full-range equation of state, for example based on Helmholtz equations. Regarding the partial liquefaction occurring at very low temperatures, the experiments permitted to consolidate the data regarding the dew curve equation and the composition of the forming liquid phase. This provides a clear view of the behavior of the gas at low temperatures.

The complete models cover a 4-dimensional scope defined by the C4-FN and O_2 concentrations, temperature, and pressure. In the scope of a product however, the mixture composition is known, and the model returns to usual equations like the ones used to describe SF_6, SF_6 mixtures, or air. The application of this PR-EoS demands for specialized equation solvers, especially the derivation of dew and bubble lines demands for an iterative algorithm, which is a complex task due to convergence problems during iterating the equilibrium conditions of liquid and vapor fugacity coefficients. Therefore, in chapter 2.4.3 a method describes how to calculate dew lines with “straight forward” equation systems, which does not demand for any iterative routines. Although appearing complex, these equations can be integrated quite easily in spreadsheet-based programs, e.g., Excel or similar.

A complete phase diagram of a C4-FN mixture including dew lines and selected isochores in gaseous state is visible in Figure 13.

2.4.3 Dew curves

The model and formulas described in this section can be used to calculate the dew curves for C4-FN/O_2/**CO_2** mixtures. For C4-FN/O_2/**N_2** a similar description is in preparation and will be included in a future revision of the handbook.

Calculation of dew curves

From the high-voltage equipment perspective, knowing the dew line of a given C4-FN mixture is essential to calculate the dew pressure corresponding to a dew temperature (e.g., -25 °C, -30 °C). Generally, dew curves are given in the following form:

$$p_{\mathrm{dew}} = f(\vartheta_{\mathrm{dew}}, x_{\mathrm{C4\text{-}FN}}, x_{\mathrm{O2}}) \qquad (2)$$

The dew pressure p_{dew} is calculated as function of dew temperature ϑ_{dew}, concentration $x_{\mathrm{C4\text{-}FN}}$ of C4-FN and concentration x_{O2} of O_2. The function is valid for a given ternary system e.g., C4-FN/O_2/CO_2 and within certain ranges of concentrations and dew temperatures. For high-voltage applications, it is important to know that the calculated dew pressure p_{dew} is the pressure at ϑ_{dew} (e.g., -30 °C, -25 °C). The important equipment ratings, like filling pressure and minimal functional pressure, however, are given as pressures at +20 °C as per the IEC 62271-1 [41], because this is the typical temperature at which the equipment is initially filled. Thus, the calculated p_{dew} needs to be corrected to +20 °C, as shown in the next section 2.4.4.

Based on the gas model developed for C4-FN/O_2/CO_2 (see section 2.4.2), a Wagner-type equation was derived for calculation of the dew curves in the relevant range for operation of high-voltage equipment. This type of equation is the modern successor of the so-called Antoine equation and is widely used to reproduce dew lines of single gases from the triple-point up to the critical point. The exponents inside the exponential term in this equation may vary, for single gases quite frequently the combinations [1/1.5/2.5/5] or [1/1.5/3/6] can be found. In this investigation and for the considered validity range, the best results were obtained with the exponents [1/1.5/3/4]. The applied Wagner-type equation for C4-FN mixtures has the form:

$$p_{\mathrm{dew}} = p_{\mathrm{pc}} \cdot \exp\left(\frac{n_1 \cdot \tau + n_2 \cdot \tau^{1.5} + n_3 \cdot \tau^3 + n_4 \cdot \tau^4}{T_r}\right) \qquad (3)$$

with

$$T_r = \frac{\vartheta_{dew} + 273.15\ K}{T_{pc}}$$

$$\tau = 1 - T_r$$

and

$$T_{pc} = 300\ \mathrm{K}$$
$$p_{pc} = 98.5\ \mathrm{bar}$$
$$n_1, n_2, n_3, n_4 = f(x_{\text{C4-FN}}, x_{\text{O2}}) \rightarrow \text{see Table 6 or Annex 6.1}$$

valid with high accuracy in the range

$$x_{\text{C4-FN}} = 0 \ldots 8\ \%\text{mol}$$
$$x_{\text{O2}} = 0 \ldots 20\ \%\text{mol}$$
$$\vartheta_{\text{dew}} = -50 \ldots \pm 0\ ^\circ\mathrm{C}$$

The subscript “pc” denotes a pseudocritical pressure and temperature. When used for mixture calculations as in equation (3), these parameters can be regarded as mathematical fitting parameters, in contrary to the single gas equation versions, where the real critical temperature and pressure has to be applied. To apply equation (3), the coefficients n_1, n_2, n_3, n_4 need to be known. They are constants for a given mixture. As an example, for typical mixtures used in high-voltage equipment, the coefficients in Table 6 apply.

Table 6: Coefficients n_1, n_2, n_3, n_4 for Wagner equation (3) for typical gas mixtures

	5 % C4-FN / 13 % O_2 / 82 % CO_2	3.5 % C4-FN / 13 % O_2 / 83.5 % CO_2	3.5 % C4-FN / 10 % O_2 / 86.5 % CO_2
n_1	-37.008	-28.583	-30.968
n_2	79.532	56.414	64.331
n_3	-420.53	-300.92	-349.31
n_4	760.78	540.44	631.22

More generally, the coefficients $n_1 \ldots n_4$ for Eq. (3) can be calculated for any given mixture using the procedure in Annex 6.1

Example

See section 2.4.5 for an example how dew curves for typical mixtures can be calculated.

Verification testing

For verification, the calculated dew curves are compared with measurements. Three principal methods were applied.

- VLE tests
- Isochoric scans
- Dew point measurements

Verification approach 1 – VLE

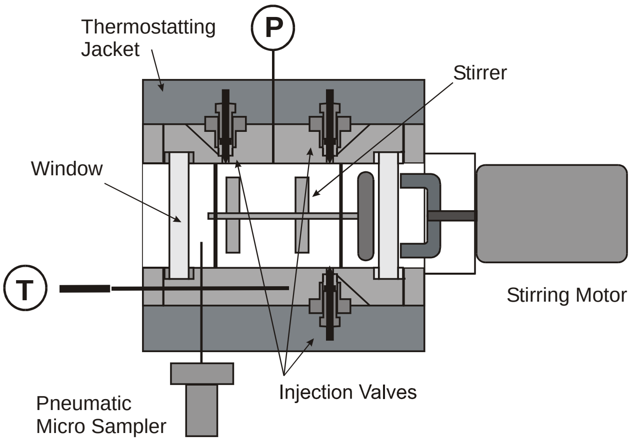


Figure 15: Equilibrium cell for VLE tests (Picture from LTP [42])

To measure the dew pressure for specific temperatures, vapor liquid equilibrium tests were performed at Laboratory for Thermophysical Properties and Thermodynamic Research (LTP) in Oldenburg, Germany [42]. For this Vapor-Liquid Equilibrium (VLE) tests, a cell (see Figure 15) containing a small pressure vessel, is filled with a C4-FN/O_2/CO_2 mixture. The vessel is cooled down to a defined temperature (-40 °C, -30 °C, and -25 °C for these tests). The vessel contains enough C4-FN to ensure that there is always a gaseous and a liquid phase. Gas samples are taken from the gas phase and analyzed with gas chromatography. In this way, the C4-FN concentration in the gas phase for the given temperature and the given pressure is determined for the saturated state (dew point). The test is repeated for different pressures and a dew curve results as an isotherm in dependance on the C4-FN mole fraction (see Figure 16). This method is suitable to yield dew points for a relatively wide range of C4-FN concentrations and is thus well suited for gas model calibration and verification (see section 2.4.2). The advantage of this method is that temperature and pressure can be well controlled. Decisive is that the gas analysis is well calibrated. For the results shown in Figure 16, the gas chromatography was calibrated using nine different C4-FN/O_2/CO_2 mixtures from three gas mixture suppliers with C4-FN concentrations between 0 and 10 %mol and O_2 concentration between 0 and 13 %mol.

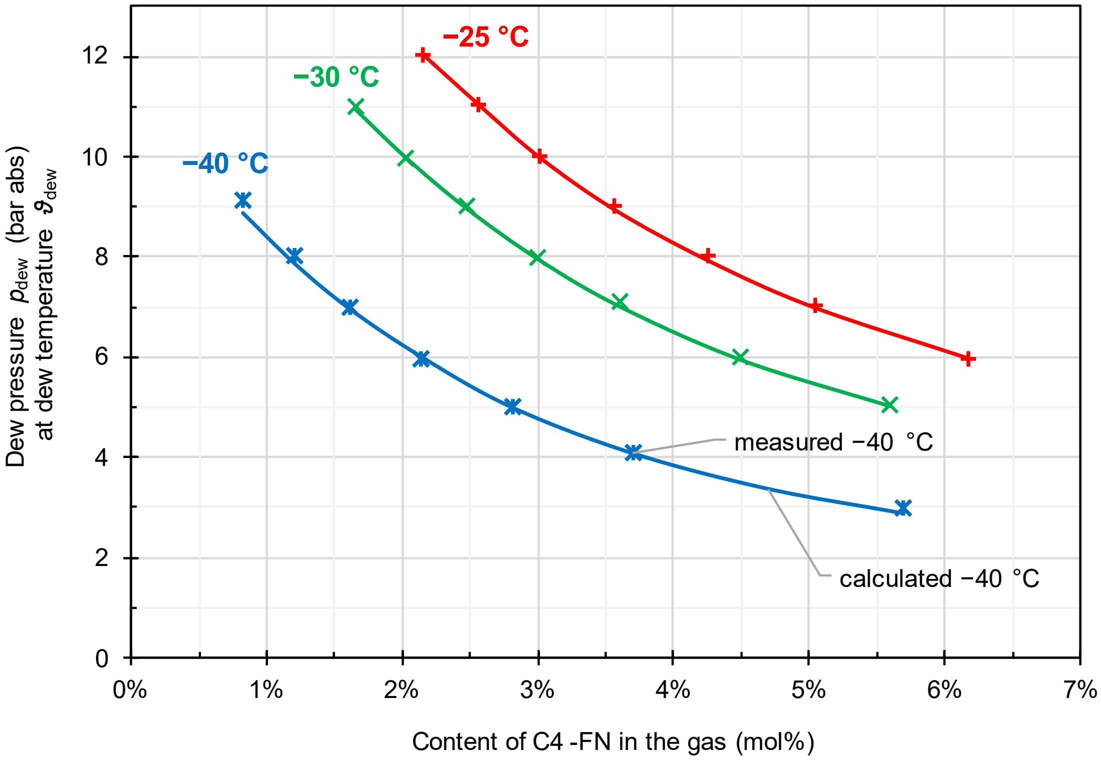


Figure 16: Measured vs. calculated (Eq. (3)) dew curves of C4-FN at -25 °C, -30 °C, and -40 °C, with a O_2 content in the gas phase of 10 % and the rest being CO_2.

A good fit between measured and calculated data is visible in the figure above. Please note: the Wagner equation (3) parameters have not been optimized for best overall fit, but for ensuring that the calculated dew pressure is either exactly at the measured value or slightly below. This is important when the Wagner equation is used to calculate the limits of the vapor phase (see Figure 13).

Verification approach 2 – isochoric scans

In this method, a given gas mixture is filled into a small compartment at defined ambient temperatures and pressure (e.g., 8 bar at 20 °C). The compartment is then cooled down to a temperature clearly below the expected dew temperature for this mixture and pressure. The pressure is recorded and the transition from vapor into VLE phase is visible by a change in the pressure temperature curve's incline ("kink" in Figure 17). This method is in some way comparable to high-voltage equipment experiencing a temperature drop. It should be noted however, that due to experimental effort it is only suitable for comparisons of a few points (gas mixture and pressure combinations) and not for calibration of a complete gas model. Additionally, especially with gas mixtures with low C4-FN content, it can be challenging to identify the "kink" in the pressure curve reproducibly (compare with section 2.4.4). In execution of isochoric tests, placement of temperature sensors and temperature gradient is important to ensure reproduceable results.

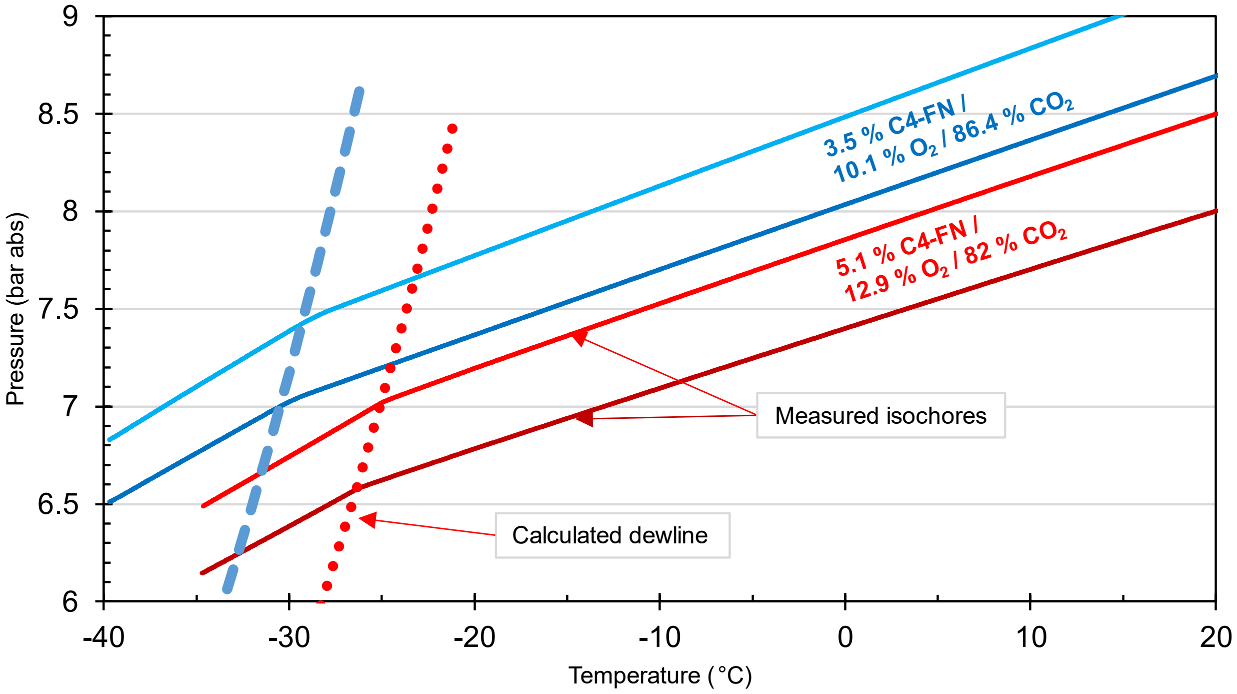


Figure 17: Isochoric scans of two gas mixtures at two densities each compared with corresponding dew line calculated according to Eq. (3)

Verification approach 3 – Dew point measurements from LTP (previously existing data)

A third approach was used to check the dew line model. It is based on dew point determination experiments where a mixture is prepared in a pressure cell using partial pressure method (sequential filling of single gas). The cell is then cooled to a certain temperature and its volume reduced until the resulting pressure approaches the dew pressure, visible by a reversible formation of droplets.

Results from 2016 to 2020 [43] were considered to check the correlation between the measurements and the developed Wagner equation. The results are limited to values below 10 % C4-FN and below 30 % O_2 along with one data series which appears off compared to all others and could be related to an invalid mixture preparation. Overall, the Wagner equation, itself based on RefProp standard implementation provides accurate results up to -10 °C dew temperature. Above -10 °C dew temperature, the accuracy decreases but the Wagner equation is conservative by providing a slightly lower dew pressure.

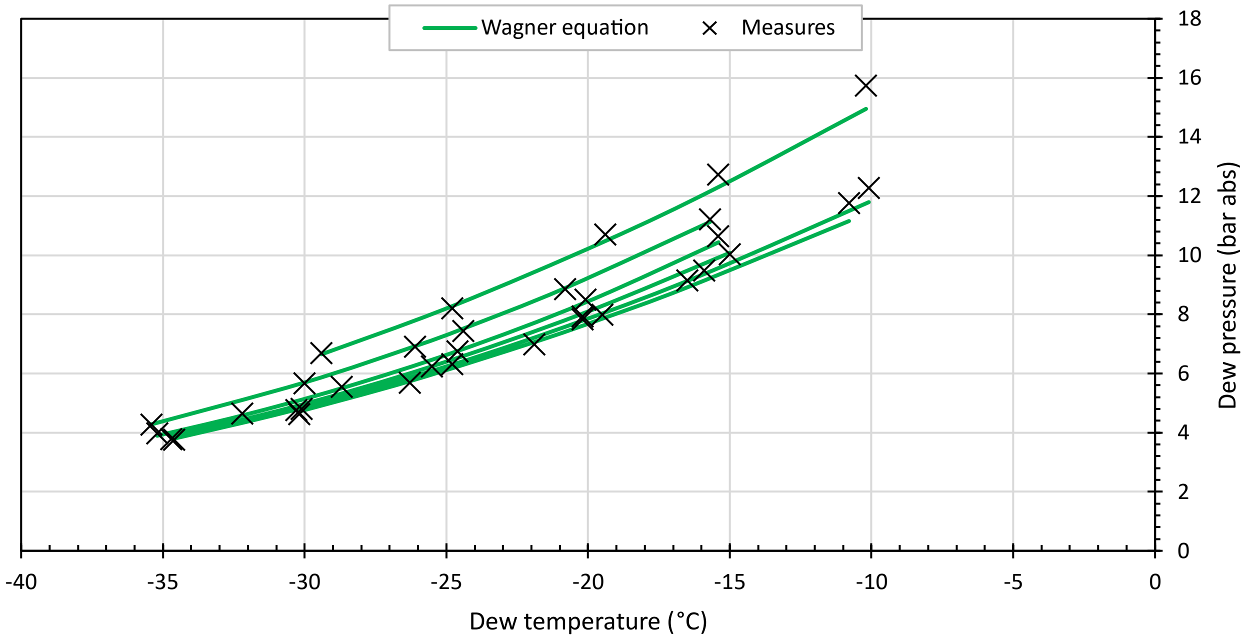


Figure 18: Comparison of the Wagner equation model with previous dew points measurements (2016-2020)

The equation is therefore valid to be used for high-voltage equipment operating near its minimum temperature and provides conservative results for gaseous phase containers.

For mixtures operating at high density and/or high temperature like liquefied containers, sufficient data for their use is known, but more research is needed to validate a model fully capable of describing these cases and especially regarding the liquid phase. In such applications, the Peng-Robinson model is known to have intrinsic limits, and Helmholtz equations are preferred. There is ongoing work to build such model and results will be published later.

2.4.4 Isochoric pressure variation with temperature

In Figure 13 and Figure 17, it is visible that for fixed volume and gas density, as it is typically the case for gas compartments in high-voltage equipment, the pressure changes with changing temperature. Having a model for this pressure variation is of great practical relevance for:

- Gas handling: pressure corrections for filling operations (e.g., for a filling operation performed at 32 °C, which pressure corresponds to 8 bar at 20 °C?).
- Gas monitoring: Ensuring the temperature-compensation during the monitoring of the gas pressure (densimeters, alarms, digital sensors).
- Design of equipment: Determine the filling pressures given at 20 °C for a corresponding a dew temperature and dew pressure (see section 2.4.3).
- Design of equipment: Determine pressure increase in high-voltage equipment due to temperature rise and its impact on pressure vessel dimensioning.

The model and formulas described in this section can be used to calculate the isochoric pressure variation for C4-FN/O_2/**CO_2** mixtures. For C4-FN/O_2/**N_2** a similar description is in preparation and will be included in a future revision of the handbook.

Virial Equation of State

A way to describe real gases is the virial equation, which is an extension of the ideal gas law by a series development (see Eq. (4)). For the handbook, RefProp [40] with a custom implementation of C4-FN was used to derive a Virial equation of state for C4-FN/O_2/CO_2 mixtures.

$$\frac{p}{RT} = \frac{1}{V_\mathrm{m}} + \frac{B}{V_\mathrm{m}^2} + \frac{C}{V_\mathrm{m}^3} + \cdots$$

with

$$V_\mathrm{m} = \frac{M_\mathrm{mix}}{\rho_\mathrm{mix}} \tag{4}$$

With T the gas temperature (in Kelvin)
p the pressure at the temperature T
ρ_mix the gas mixtures mass density
V_m the molar volume as defined above
M_mix the molar mass of the gas mixture, see Eq. (5)
$R = 8.314 \frac{\mathrm{J}}{\mathrm{mol \cdot K}}$ the gas constant

For application to C4-FN mixtures in gaseous state in high-voltage equipment up to around 15 bar pressure, it is sufficiently accurate to use the second virial coefficient *B* and truncate the series there, for higher pressures at least the 3rd virial coefficient *C* would have to be considered. The viral equation can be rearranged to yield the pressure:

$$p = RT\left(\frac{\varrho}{M_\mathrm{mix}} + \frac{\varrho^2}{M_\mathrm{mix}^2} B\right) \tag{5}$$

with

$$M_\mathrm{mix} = x_\mathrm{C4-FN} \cdot M_\mathrm{C4-FN} + x_\mathrm{O2} \cdot M_\mathrm{O2} + (1 - x_\mathrm{C4-FN} - x_\mathrm{O2}) M_\mathrm{CO2}$$

$$B = f(\vartheta, x_{C4-FN}, x_{O2}) \text{ see Eq. (7)}$$

An expression for the mass density ρ_mix of the gas mixture can be derived by solving the quadratic formula (5):

$$\rho_\mathrm{mix} = -\frac{M_\mathrm{mix}}{2B} - \sqrt{\frac{M_\mathrm{mix}^2}{4B^2} + \frac{pM_\mathrm{mix}^2}{BRT}} \tag{6}$$

The virial coefficient B is a function of temperature and gas mixture.

$$\frac{B}{\mathrm{cm^3 mol^{-1}}} = \sum_{i=0}^{5} \left\{ \left(b_i \cdot \left(\frac{\vartheta}{°C} + 273.15 \right)^i \right) \cdot \right\} \tag{7}$$

with

$$b_i = f(x_\mathrm{C4-FN}, x_{O2}) \text{ see Table 7 or Annex 6.2}$$

To calculate the virial coefficient B for a certain temperature ϑ, the coefficients b_0… b_5 need to be known. They are constant for a given mixture. As an example, coefficients for typical mixtures used in high-voltage equipment are given (see Table 7).

Table 7: Coefficients b_0… b_5 for determination of virial coefficient B with Eq. (7) for typical gas mixtures

	5 % C4-FN / 13 % O_2 / 82 % CO_2	**3.5 % C4-FN / 13 % O_2 / 83.5 % CO_2**	**3.5 % C4-FN / 10 % O_2 / 86.5 % CO_2**
b_0	-3.1189E+03	-2.9252E+03	-3.0581E+03
b_1	3.3485E+01	3.1296E+01	3.2712E+01
b_2	-1.5475E-01	-1.4432E-01	-1.5083E-01
b_3	3.7004E-04	3.4460E-04	3.6013E-04
b_4	-4.4960E-07	-4.1825E-07	-4.3707E-07
b_5	2.2009E-10	2.0458E-10	2.1377E-10

More generally, for arbitrary mixtures, the coefficients b_i can be calculated using Annex 6.2. A sample how to use the equations is given in section 2.4.5

Verification with experimental data

Several isochoric scans have been performed in the low-temperature range (-40 °C / -30 °C … +20 °C) as well as in the high-temperature range (+20 °C … 100 °C). Above the dew temperature, the gas mixture is in the vapor region and the measured pressure can be compared with the value calculated with the Virial equation (5), which gives excellent agreement (Figure 19).

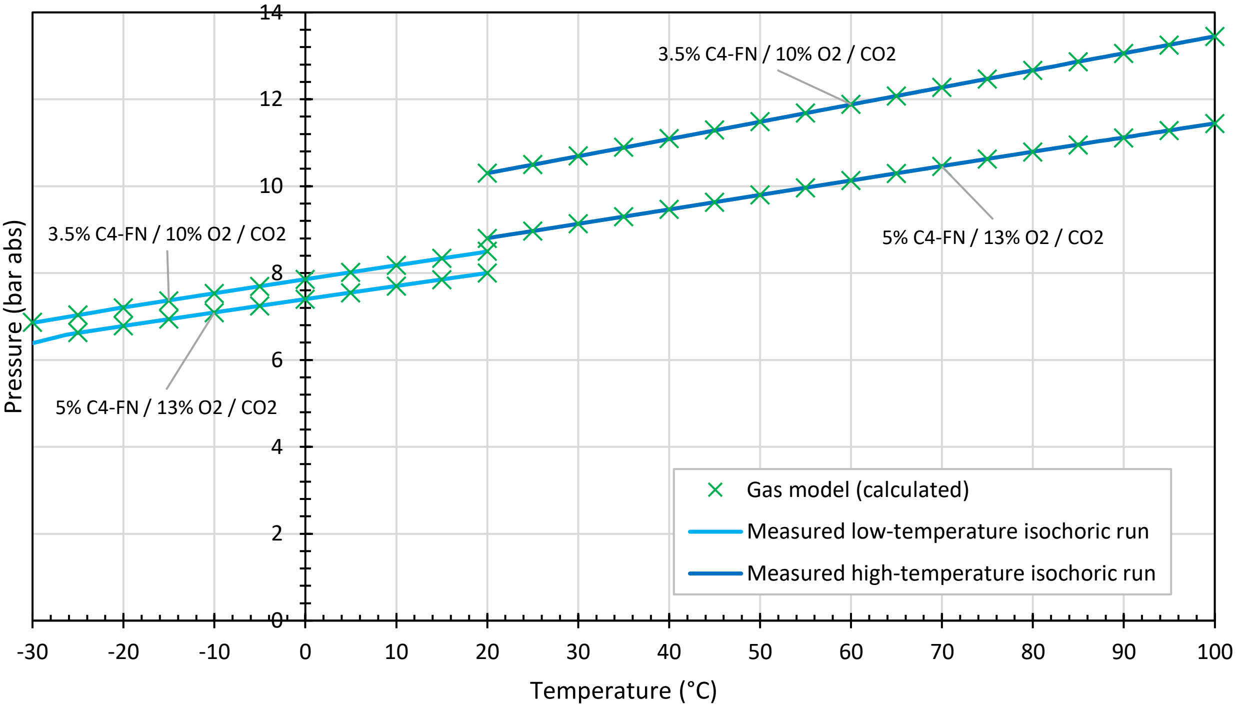


Figure 19: Measured (LTP) and calculated (via Virial equation (5)) isochores for 3.54 % C4-FN / 10.08 % O_2 / 86.38 % CO_2 and 5.01 % C4-FN / 12.80 % O_2 / 82.19 % CO_2 mixtures.

Difference to ideal gas.

To model this pressure variation in the vapor phase, models of different complexities (see Figure 14) are available. For simplified estimations, the ideal gas law is often used. For typical C4-FN/O_2/CO_2 mixtures used in high-voltage applications the results are compared (see Figure 20) for:

1. **Ideal gases and gas mixture**: Assumption of ideal gases not interacting together.
2. **Virial equations**: Gas model based on RefProp as described in this chapter.

With the real gas model available, it can be compared how much the density deviates from this idealized assumption. In C4-FN high-voltage equipment with pressures of 7 to 10 bar, the deviation is in the range of 5 % to 8 % and should not be ignored for technical application (e.g., density monitors, amount of gas need for large scale filling operations).

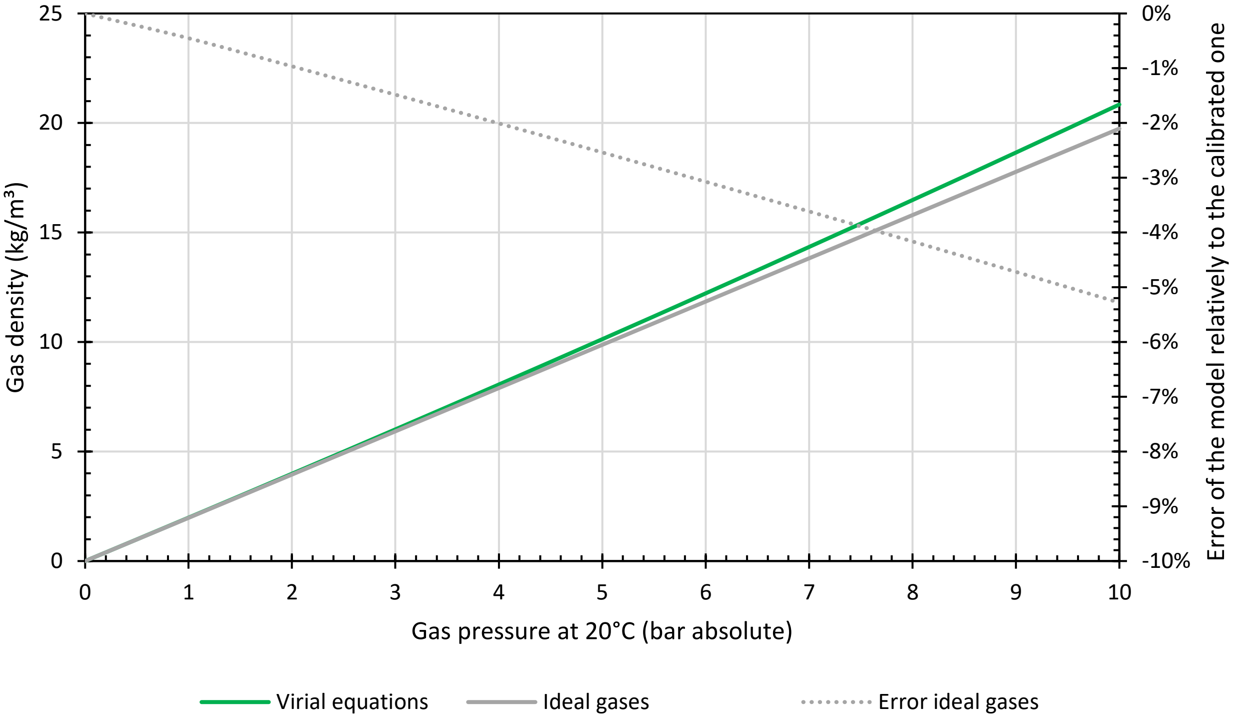


Figure 20: Density calculated with the virial equations vs. ideal gas model (3.5 % C4-FN / 10 % O_2 / 86.5 % CO_2) and the corresponding error made by using ideal gas models.

The virial equations can be applied to any mixture used in high-voltage equipment. The difference of composition impacts slightly the density at identical pressure, but the applied pressures for the different mixtures usually compensate it. C4-FN mixtures as reported for the filling of high-voltage equipment usually have a density of around 20 kg/m³ at filling pressure. Examples for two mixtures and the comparison to SF_6 is visible in Figure 21.

2.4.5 Examples

Dew curves and filling pressures of typical mixtures

For three typical gases used in high-voltage equipment, the models developed in sections 2.4.3 and 2.4.4 are used to:

- In a first step, calculate the dew points, meaning the maximum pressure for typical high-voltage equipment temperature ratings -25 °C, -30 °C and -40 °C (see Table 8). The resulting pressures are valid only at the dew pressures themselves while the high-voltage equipment pressure ratings are usually given at +20 °C, so
- In a second step, the pressures are corrected to +20 °C. This is done by calculating the densities that corresponds to the dew points (see Table 9). With these densities, the isochoric pressure changes to +20 °C and +80 °C are calculated (see Table 10)

Table 8: Dew points of typical mixtures, calculated using equation (3) and coefficients given in Table 6

Gas mixture	**5 % C4-FN / 13 % O_2 / 82 % CO_2**	**3.5 % C4-FN / 13 % O_2 / 83.5 % CO_2**	**3.5 % C4-FN / 10 % O_2 / 86.5 % CO_2**
Dew temperature	**Dew pressures p_{dew} in bar** (not temperature-corrected)		
-25 °C	7.11	9.24	9.10
-30 °C	5.54	7.26	7.16
-40 °C	3.22	4.31	4.25

Table 9: Virial coefficients (via Eq. (7)) and densities (via Eq. (6)) calculated for the gases at different dew points (see Table 8)

Gas mixture	**5 % C4-FN / 13 % O_2 / 82 % CO_2**	**3.5 % C4-FN / 13 % O_2 / 83.5 % CO_2**	**3.5 % C4-FN / 10 % O_2 / 86.5 % CO_2**

Molar mass M_{mix} in g/mol		
50.0	47.7	48.1

Temperature and pressure (see Table 8)	**Virial coefficient B in cm^3/mol**		
at -25 °C	-182	-174	-182
at -30 °C	-191	-182	-191
at -40 °C	-211	-201	-210

Temperature and pressure (see Table 8)	**Density ρ in kg/m^3**		
at -25 °C dew point	18.5	23.4	23.3
at -30 °C dew point	14.5	18.4	18.4
at -40 °C dew point	8.62	11.1	11.1

Table 10: Isochoric pressures calculated with the Virial equation (5), using the densities from Table 9 and Virial coefficients calculated via Eq. (7)

Gas mixture	5 % C4-FN / 13 % O_2 / 82 % CO_2	3.5 % C4-FN / 13 % O_2 / 83.5 % CO_2	3.5 % C4-FN / 10 % O_2 / 86.5 % CO_2
Temperature	**Pressure in bar**		
For gas with -25 °C dew point	**ρ = 18.5 kg/m^3**	**ρ = 23.4 kg/m^3**	**ρ = 23.3 kg/m^3**
-25 °C	7.11	9.24	9.10
+20 °C	8.60	11.2	11.1
+40 °C	9.25	12.1	11.9
For gas with -30 °C dew point	**ρ = 14.5 kg/m^3**	**ρ = 18.4 kg/m^3**	**ρ = 18.4 kg/m^3**
-30 °C	5.54	7.26	7.16
+20 °C	6.82	8.98	8.87
+40 °C	7.32	9.66	9.54
For gas with -40 °C dew point	**ρ = 8.62 kg/m^3**	**ρ = 11.1 kg/m^3**	**ρ = 11.1 kg/m^3**
-40 °C	3.22	4.31	4.25
+20 °C	4.11	5.53	5.46
+40 °C	4.41	5.93	5.86

Comparison with SF_6

The density of SF_6 and typical C4-FN/O_2/CO_2 mixtures is compared (see Figure 21). The main takeaway is, that SF_6 is much denser than C4-FN mixtures. At the same pressure, SF_6 has around 3 times higher density. This factor is reduced, because for same application, C4-FN is used at higher pressure. Typically, SF_6 density as used in high-voltage equipment remains at the double of the one of C4-FN mixtures (compare Table 5).

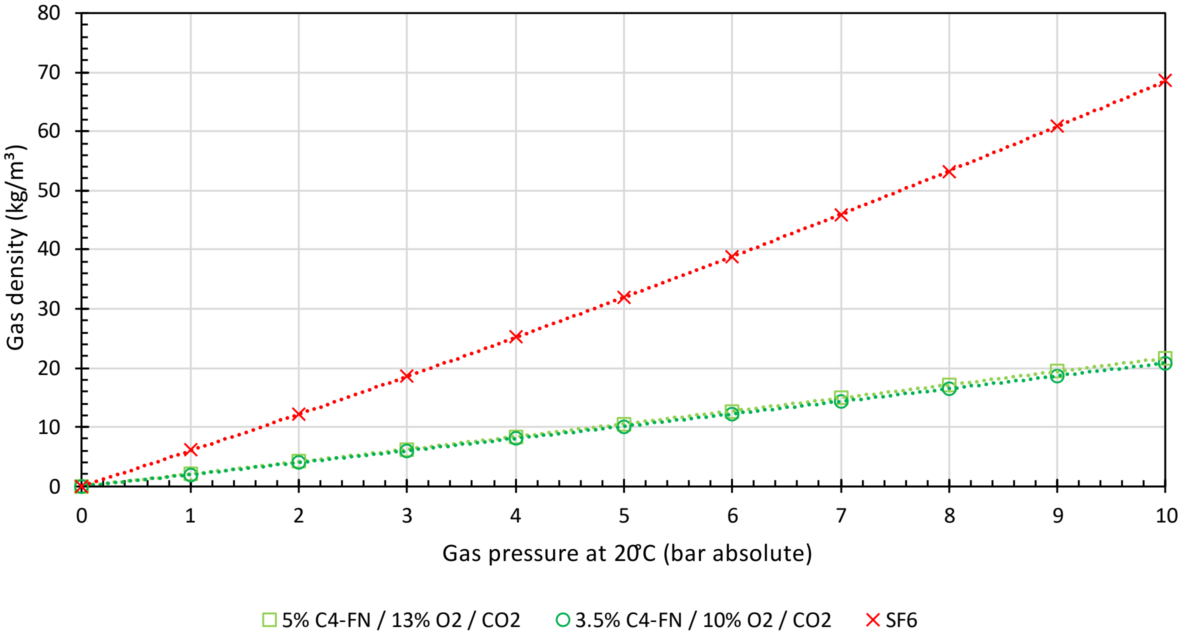


Figure 21: Evolution of the density of SF_6 and two typical C4-FN mixtures for pressures up to 10 bar and using the presented virial equations and a Bettie-Bridgeman model for SF_6.

2.4.6 Partial liquefaction of C4-FN mixtures and comparison with SF_6

As SF_6 or SF_6 mixtures, C4-FN mixtures may partially liquefy if the gas temperature drops below the dew temperature of the mixture. In SF_6, this temperature depends only on the filling pressure while in SF_6 mixtures and C4-FN mixtures, it also depends on the gas mixture composition (see section 2.4.3).

Mixing SF_6 with N_2 allows to keep a higher filling pressure which is useful for insulation while still maintaining the same condensation/boiling temperature. Below, one example is shown for SF_6 and one SF_6/N_2 mixture. The addition of N_2 does not change the SF_6 liquefaction which is still around -40 °C. However, the insulation is improved by the addition of 2.5 bar of N_2. As the mixture crosses its dew line, only the SF_6 partially liquefies, and the pressure drop does not follow the dew line as it was the case with pure SF_6.

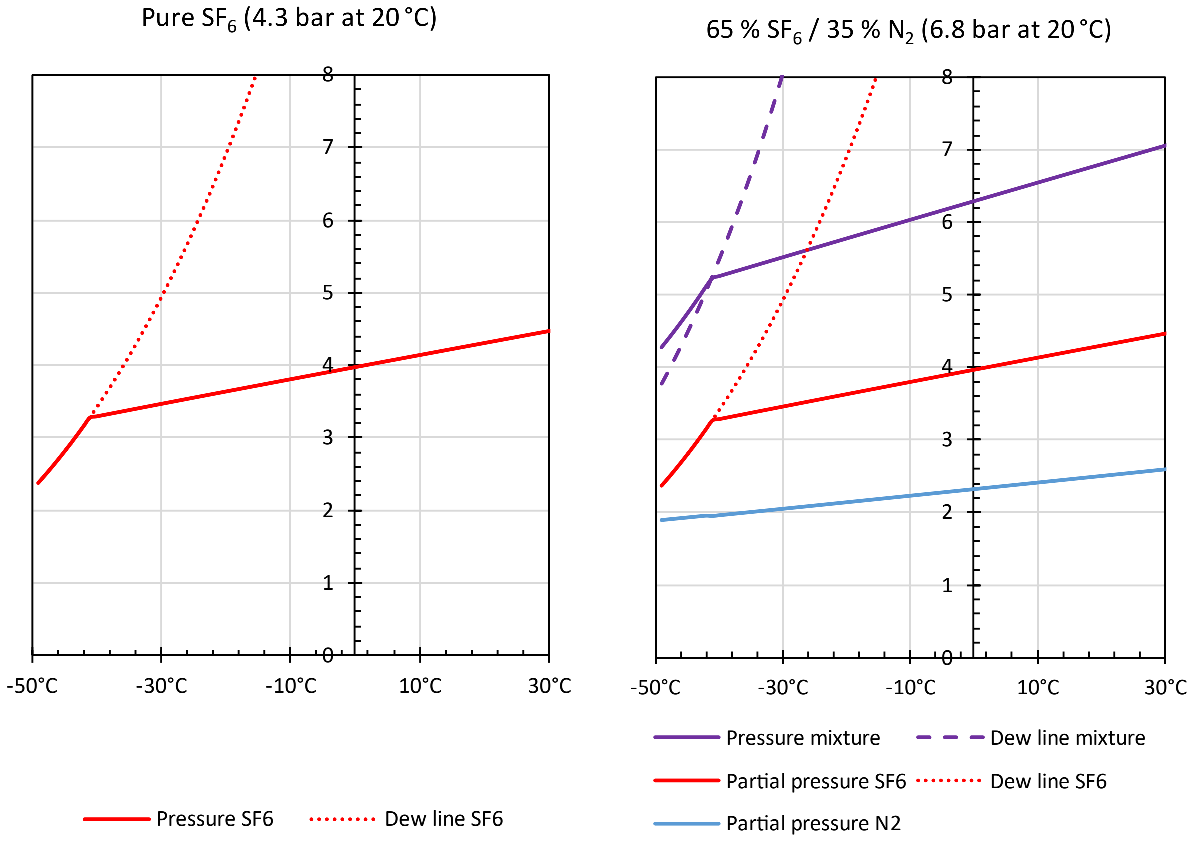


Figure 22: Pressure-temperature curves and dew lines for pure SF_6 and a SF_6/N_2 mixture

In C4-FN mixtures, the same principle was used to reduce the dew temperatures by mixing C4-FN with natural-origin gases which increase the total filling pressure and dielectric insulation with limited impacts on the C4-FN dew temperature. The behavior is slightly different compared to SF_6 mixtures as the liquid also contains CO_2, but the principle is the same.

In some operating conditions, especially at filling pressures, low load current and close to the minimum ambient temperature, partial liquefaction of C4-FN and CO_2 can occur. The impact of liquid itself has been investigated and is not critical, since the liquid is also electrically insulating [4], [43].

An advantage of C4-FN mixtures compared to pure SF_6 is, that for temperatures below the dew temperature, only a portion of the C4-FN starts to liquefy, together with a small amount of the CO_2, dissolved in the liquid C4-FN phase. Other components, like O_2, N_2, and most of the CO_2 stay in the vapor phase. Therefore, the drop in gas pressure and density is much less pronounced than in pure SF_6 when going below the dew temperature (seeFigure 17 and Figure 22).

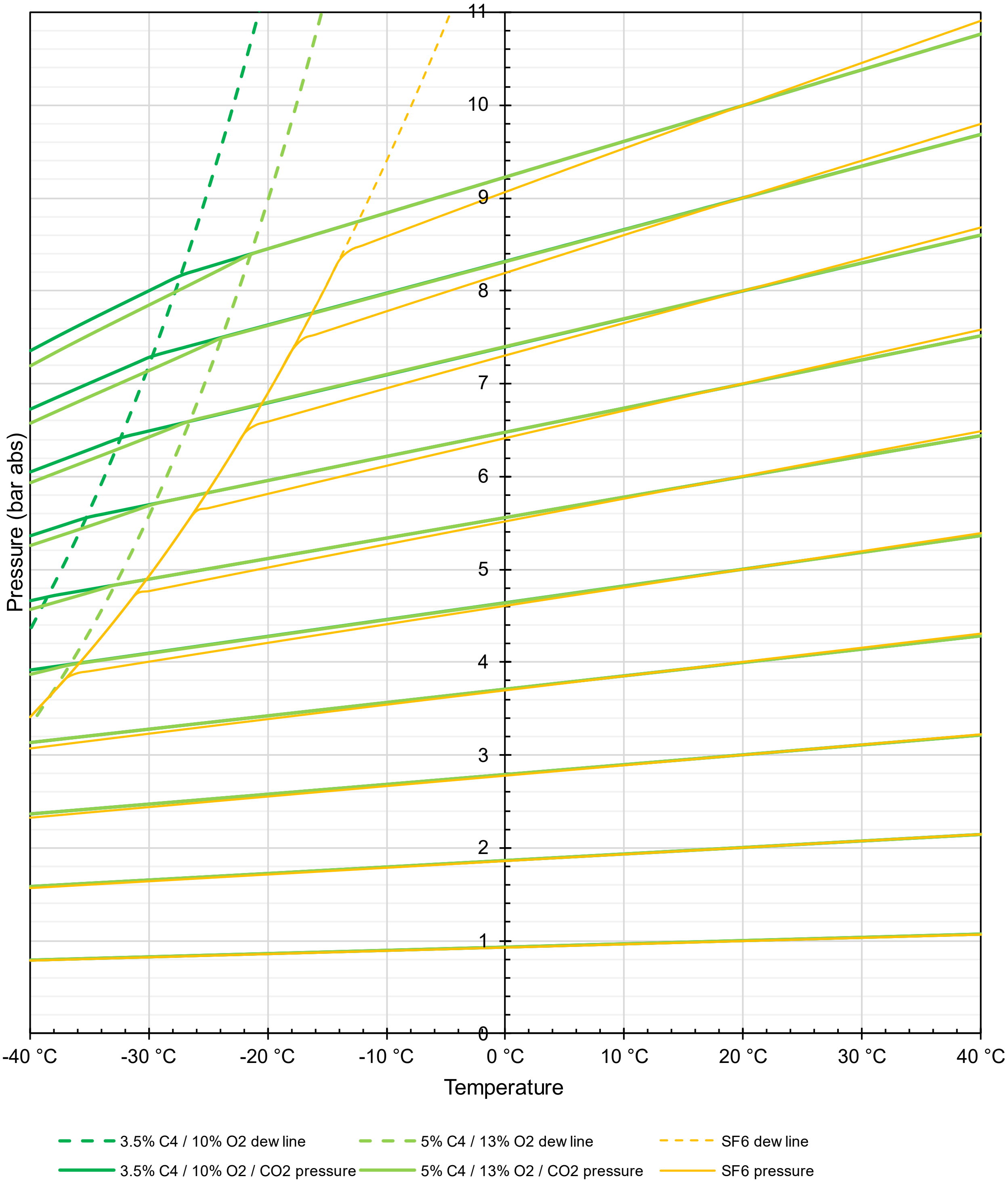


Figure 23: Pressure-temperature curves and dew lines for two typical C4-FN mixtures and SF_6

2.4.7 Gas filling with premixed gas using supercritical and superheated state

For SF_6 applications, the gas is delivered partially liquefied in high pressure bottles. When using the bottle, the liquid phase is compensating the extraction of gas: as long as the bottle contains liquid, the gas phase will remain at the same pressure, the value depends on the temperature inside the bottle (vapor-liquid equilibrium, VLE). By taking gas out of the bottle, the gas expansion usually reduces the temperature inside the bottle, so that the inside pressure drops, which demands for heating to avoid stopping of the filling process.

In the case of SF_6/N_2 or SF_6/CF_4 mixtures used in very low temperature applications, the mixing ratios were usually in the range of 70/30 to 50/50, and the number of projects relatively small. In such cases, the filling was usually done using partial pressures, which impacts the mixture composition accuracy.

For C4-FN mixtures, different methods can be used for on-site filling:

a. On-site mixing of single gases (in separate bottles) in a dedicated mixing cart.
b. Pre-mixed bottles with CO_2 as a carrier gas and with a liquid phase heated above its cricondentherm (slightly higher than the critical temperature) to ensure mixture homogeneity. This operation is done using a service gas cart. In such conditions, the mixture is completely gaseous and homogeneous (supercritical / superheated state). For the example gas shown in Figure 25, this value would be around +30 °C. This temperature depends on the mixture composition, but not on the quantity of gas.
c. Pre-mixed bottles with a gaseous phase with a minimum storage temperature or with heating accessories to ensure homogeneity at the time of filling. Filling operations can then be done by overpressure or with the complement of a simple compressor.

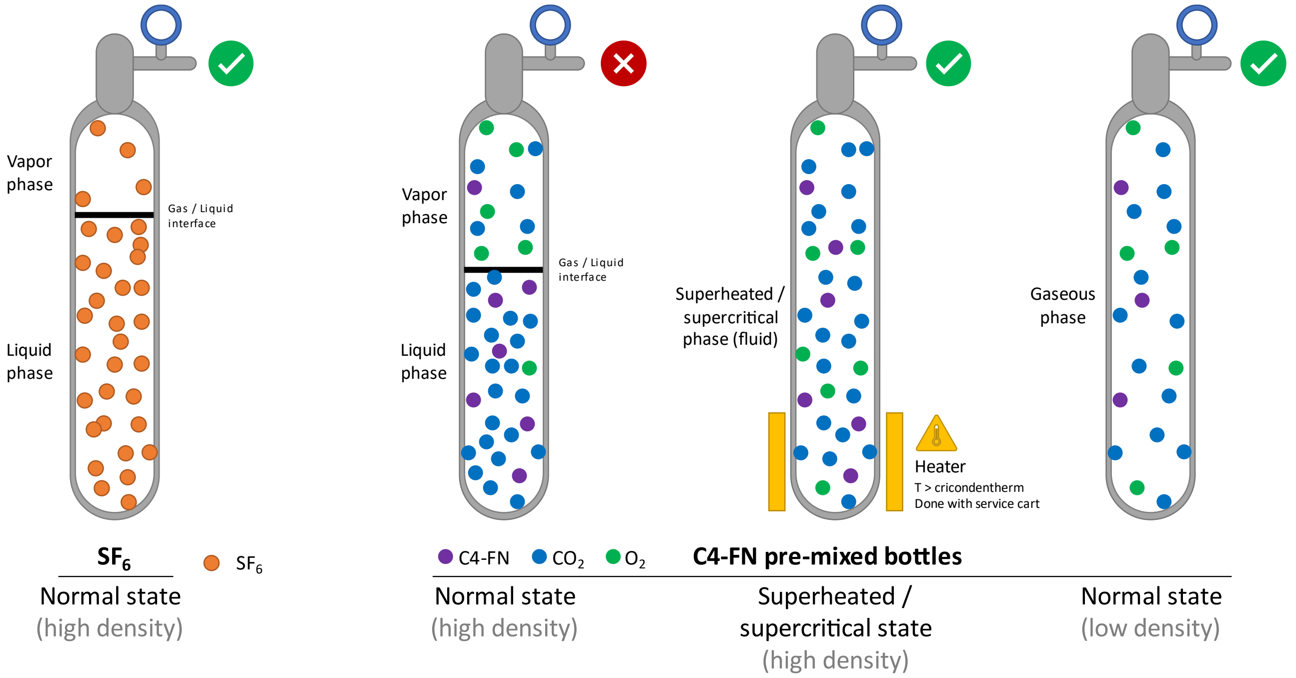


Figure 24: Schematic representation of the various states of the gas containers for SF_6 and C4-FN mixtures

The supercritical state is a well-known phenomenon that appears above the critical pressure and temperature of the mixture. Below that pressure and temperature, the gas mixture exists in two states: vapor and liquid, forming the vapor-liquid equilibrium (VLE). Above the critical pressure and temperature, only one phase exists: gas or fluid. The mixture is therefore homogeneous in its supercritical state (see Figure 25).

The superheated state is similar to the supercritical one. In that case however, the density can be lower. The superheated state indicates that the temperature is sufficient so that, independently of the pressure, it remains fully gaseous, therefore fully homogeneous. The temperature limiting the superheated state is the cricondentherm temperature. In the case of C4-FN mixtures, it is very close to the supercritical temperature (see Figure 25).

For premixed C4-FN mixtures, the partially liquefied gas is homogenized by warming the cylinder (and therefore the gas contained within it).

- If the gas cylinder is full or near its maximum quantity, the heating will cause both temperature and pressure to go up and the mixture will be in supercritical state. The pre-heating phase is indicated in the Figure 25 by the bubble 1 and crosses the VLE limit near the critical point.
- If the gas cylinder was partially used or was not filled at very high density (but still enough to have partial liquefaction), the mixture will become superheated without being supercritical. The pre-heating phase is indicated in the Figure 25 by the bubble 2 and crosses the VLE limit below the critical point and the cricondentherm.
- In both cases, by heating the cylinder above the cricondentherm temperature, it is ensured that the gas is homogeneous (either supercritical or simply superheated).
- With the mixture being homogeneous, it can be pumped out of the gas cylinder. As the equipment maintains the temperature fixed, this result in the phase diagram of the Figure 25 by a vertical arrow marked by the bubble 3. After use, any remaining gas will follow a trajectory similar to a reverse of the one marked by the bubble 2 but at a lower pressure. It will intercept the dew line at a lower temperature than initially.

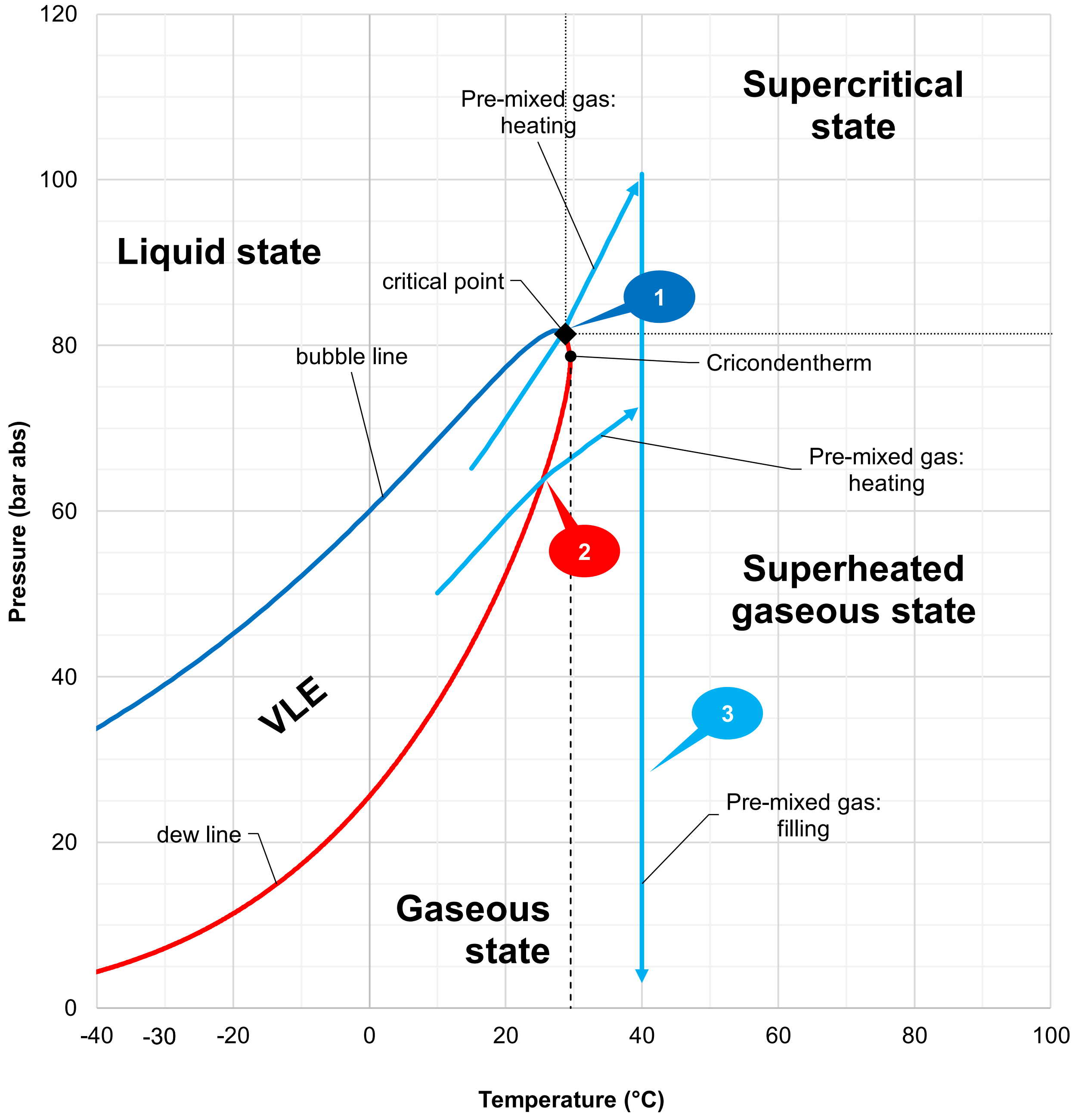


Figure 25: Phase diagram of 3.5 % C4-FN / 10 % O_2 / 86.5 % CO_2 mixture with examples of gas handling scenarios. Bubbles 1 to 3 are described in the text above.

This approach is possible for C4-FN mixture because the cricondentherm corresponds to a relatively low temperature which can be obtained using a simple extension on a typical service gas cart. For the typical mixture chosen for Figure 25, the cricondentherm is approximately at 30 °C. During gas handling operations, refer to the switchgear manufacturer and gas handling equipment manufacturer instructions to ensure proper homogenization of premixed gas and filling operations.

2.5 Mixture Definition

2.5.1 Technical procedure for defining the mixtures

There are three basic steps to define a C4-FN mixture (see Figure 26).

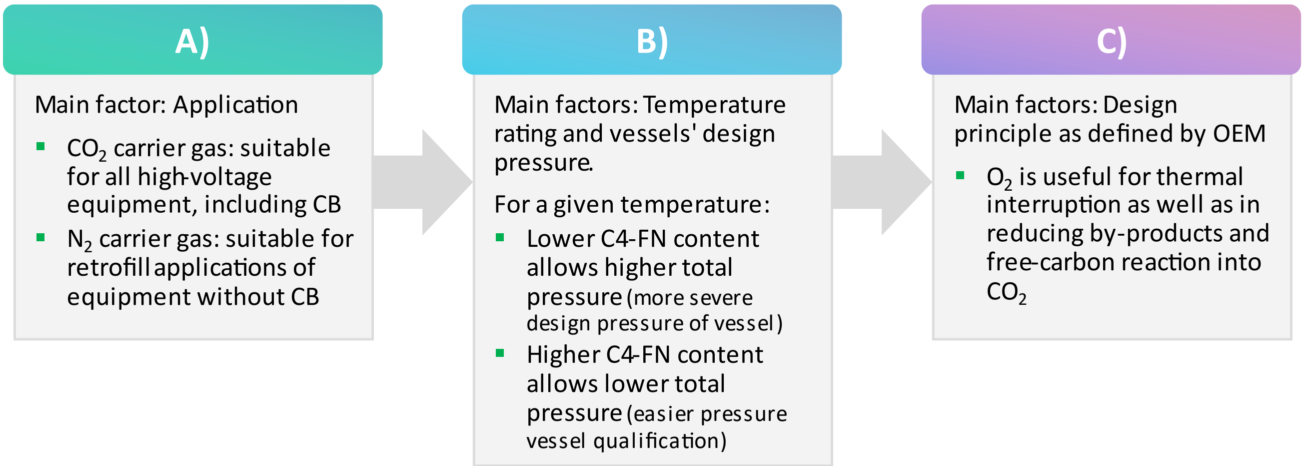


Figure 26: Process to define C4-FN mixture composition.

References for in-depth investigation of each step:
A) Define the carrier gas: [27];
B) Define the C4-FN content: section 2.3 and 2.4;
C) Define the O_2 content: [44], [23], [45].

2.5.2 Typical mixtures

Today there is a certain convergence for the gas mixtures used in the high-voltage equipment [44], [27], [46] (see Table 11 and Table 12). Gas handling and analyzing equipment is commercially available and can be used with all C4-FN mixtures (see section 4.2).

Table 11: Typical gas mixtures used for high-voltage equipment. Concerning "typical minimum temperature rating" it should be considered that lower or higher temperatures are possible e.g., via pressure reduction or increase.

C4-FN concentration	O_2 concentration	Carrier gas	Typical minimum temperature
5 %mol	13 %mol	CO_2	-25 °C
3.5 %mol	10 %mol	CO_2	-30 °C
3.5 %mol	13 %mol	CO_2	-30 °C
5 %mol	0 %mol	CO_2	-25 °C

Table 12: Typical gas mixtures for Retrofill or instrument transformer application. Concerning "typical minimum temperature rating" it should be considered that lower or higher temperatures are possible e.g., via pressure reduction or increase.

C4-FN concentration	O_2 concentration	Carrier gas	Typical minimum temperature
10 %mol	5 %mol	N_2	-25 °C
4 %mol	5 %mol	N_2	-30 °C

2.6 Quality and purity requirements

2.6.1 Gas quality conditions

The approach to define and measure the quality as well as the quality criteria of C4-FN mixtures are very similar to the well-known approach used for SF_6 or SF_6 mixtures [47].

As the gas influences the performance of the high-voltage equipment, its quality must be within allowed limits and tolerances during the whole service life of the high-voltage equipment. Three different gas quality conditions are defined as follows:

- Technical grade gas quality.
- Gas quality suitable for reuse.
- Gas quality of the gas inside the high-voltage equipment.

Technical grade C4-FN mixtures and C4-FN mixtures suitable for reuse must comply with the quality requirements for single gases, as set up in the future IEC standards 63360 and 63359, where the maximum allowed percentage of contaminants are given. Any of these two gas qualities can be used to fill the gas compartments of a newly installed high-voltage equipment or after its overhaul (see Figure 27). This is important to ensure the full performance of the high-voltage equipment all along its lifetime. Filling of gas happens during the following two gas handling situations:

- Gas handling (filling or topping-up) during installation, commissioning and after repair or overhaul on site (see IEC 62271-4, clause 4 [29])
- Gas handling (topping-up) during normal service life (see IEC 62271-4, clause 5 [29])

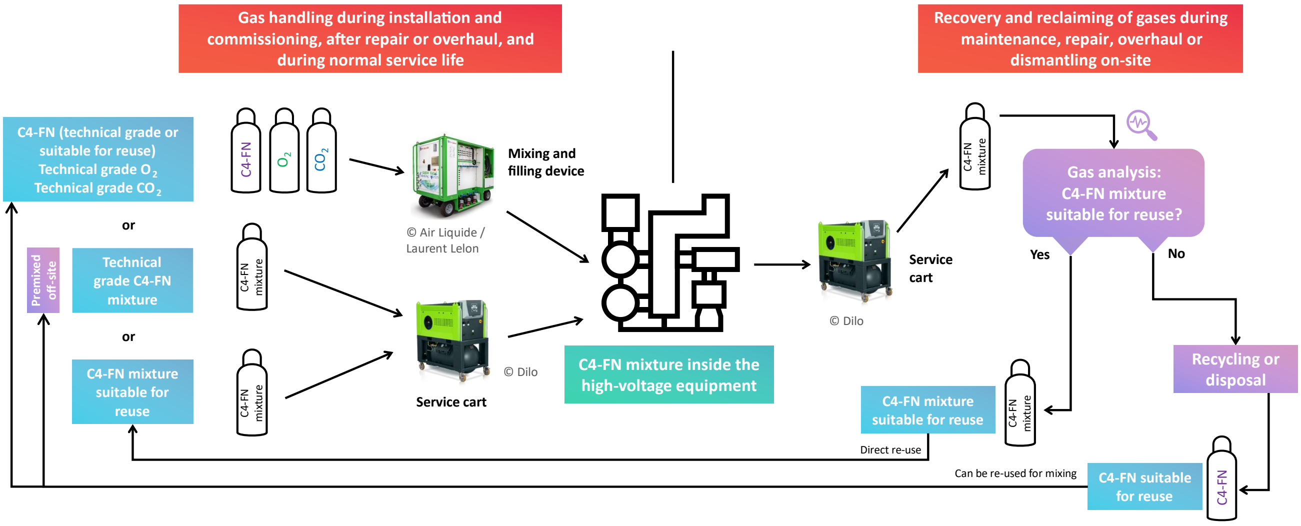


Figure 27: Quality of the gas and their usage in gas handling (compare with IEC 62271-4 [29] clauses 4, 5 and 6, as well as with section 4.2 of this handbook).

In addition, also the tolerances of the mixing ratio of the different components of the C4-FN mixture need to be defined for all three conditions. These tolerances are not defined in an IEC standard and therefore, must be defined by the manufacturer of the high-voltage equipment.

The maximum allowed percentage of contaminants as measured during the operation of the high-voltage equipment, is also not defined in an IEC standard and therefore, must as well be defined by the manufacturer of the high-voltage equipment.

These limits and tolerances as defined by the manufacturer, may depend on the specific requirements of the type of high-voltage equipment, in order to maintain the desired dielectric and/or switching performance all times. Hence, the defined quality limits and tolerances of a C4-FN mixture used in a gas-insulated line can be different to those of a circuit-breaker.

Figure 28 shows possible tolerance bands of the mixing ratio for the three different gas quality conditions of an example C4-FN mixture.

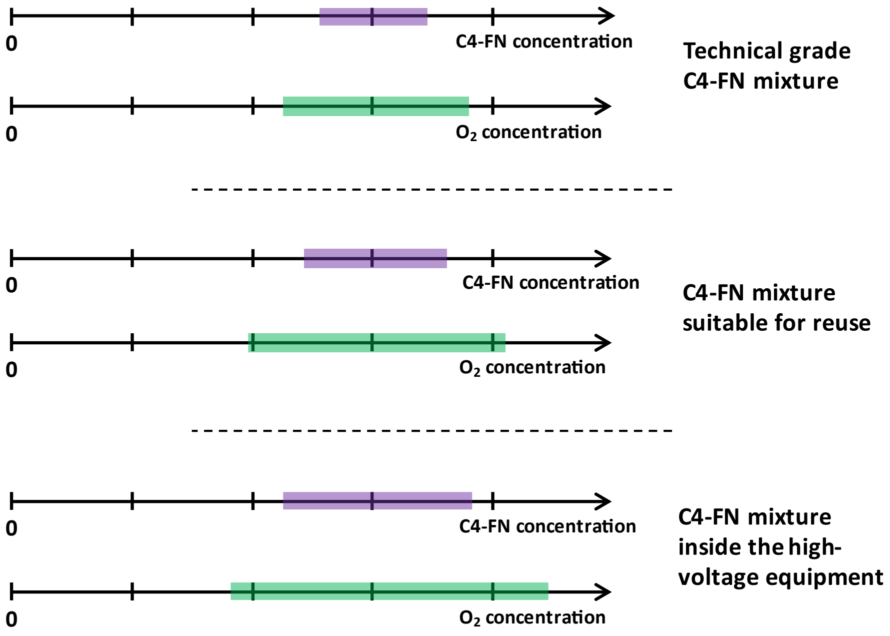


Figure 28: Example tolerances of the different conditions of an example C4-FN mixture

2.6.2 Technical grade gas

Standardization about the gas quality of technical grade single gases used in C4-FN mixtures is ongoing in IEC TC 10, WG 41 (IEC 63360 10/1166/CD). Maximum levels of contaminants are summarized in the tables below:

Table 13: Gas quality requirements for technical grade single gases

C4-FN	≥ 99.3 % $(CF_3)_2CFCN$ (Also known as i-C4-FN molecule)	As proposed in the draft of IEC 63360
	≤ 0.7 % $CF_3CF_2CF_2CN$ (Inherent isomer from C4-FN production, known as n-C4-FN)	As proposed in the draft of IEC 63360
	≤ 0.3 % of other gases (For example, N_2, O_2, etc.)	As proposed in the draft of IEC 63360
	≤ 270 ppmv H_2O	As proposed in the draft of IEC 63360
O_2	≥ 99.5 % O_2	As proposed in the draft of IEC 63360
	≤ 200 ppmv H_2O	
CO_2	≥ 99.5 % CO_2	As proposed in the draft of IEC 63360
	≤ 200 ppmv H_2O	
N_2	> 99.7 % N_2	As per the IEC 60376 Table 2
	< 200 ppmv H_2O	
SF_6	> 98.5 % SF_6	As per the IEC 60376 Table 1
	(> 99.7 % SF_6 when used in mixtures)	
	< 200 ppmv H_2O	

Table 14: Gas quality requirements for technical grade gas mixtures

C4-FN mixtures	Percentage of technical grade C4-FN within manufacturers requirements	
	Percentage of technical grade O_2 within manufacturers requirements	
	Percentage of technical grade CO_2 or N_2 within manufacturers requirements	
	Maximum concentration of H_2O within manufacturers requirements Proposal: ≤ 200 ppmv H_2O	
SF_6 mixtures	Percentage of technical grade SF_6 within manufacturers requirements	
	Percentage of technical grade N_2 or CF_4 within manufacturers requirements	
	< 200 ppmv H_2O	As per the IEC 60376 Table 1

2.6.3 Gas suitable for reuse

Criteria for gases suitable for reuse are needed to evaluate, whether the gas recovered from the high-voltage equipment (and maybe additionally reclaimed) can be reused in the high-voltage equipment.

The definition of the gas quality of gases suitable for re-use will be part of the standardization within IEC TC 10, WG 41 (IEC 63359). Maximum levels of contaminants are proposed in the tables below. Please note that the C4-FN mixture needs to be separated for creation of C4-FN suitable for reuse.

Table 15: Gas quality requirements for single gases suitable for re-use

C4-FN	Proposal: ≥ 97 % $(CF_3)_2CFCN$	Final values will be defined in IEC 63359
	Proposal: ≤ 0.7 % $CF_3CF_2CF_2CN$	
	Proposal: ≤ 2.3 % of other gases like CO_2, N_2, O_2	
	Proposal: ≤ 270 ppmv H_2O	
SF_6	> 97 % SF_6	As per the IEC 60480 Table 2
	< 3 % Air and/or CF_4	
	< 200 ppmv H_2O	

Table 16: Gas quality requirements for gas mixtures suitable for re-use

C4-FN mixtures	Percentage of C4-FN within manufacturer's requirements	
	Percentage of O_2 within manufacturers requirements	
	Percentage of CO_2 or N_2 within manufacturers requirements	
	Maximum concentration of H_2O within manufacturers requirements Proposal: ≤ 200 ppmv H_2O	
SF_6 mixtures	Percentage of SF_6 within manufacturers requirements	
	Percentage of N_2 or CF_4 within manufacturers requirements	
	< 200 ppmv H_2O	As per the IEC 60480 Table 3

2.6.4 Gas inside the high-voltage equipment

As described in 2.6.1 the tolerances of the percentage of the gas components and the amount of acceptable by-products can increase during the service life of high-voltage equipment, e.g., due to gas permeation across sealings or due to switching operations. It is the duty of the manufacturer to define upper limits to ensure the correct operation of the high-voltage equipment at all times.

Usually, identical criteria as for the gases suitable for re-use are defined, except for circuit-breakers where – due to arcing – the gas quality decreases during the service life.

Table 17: Gas quality requirements for the gas inside the high-voltage equipment after installation, commissioning, after repair or overhaul on site, or during operation of the high-voltage equipment

C4-FN mixtures	Percentage of C4-FN within manufacturer's requirements
	Percentage of O_2 within manufacturer's requirements
	Percentage of CO_2 or N_2 within manufacturer's requirements
	Percentage of by-products (CO or others) within manufacturer's requirements
	Percentage of H_2O (humidity) after filling: ≤ -10 °C frost point at filling pressure as per the IEC 62271-1 (volume with adsorber) ≤ -15 °C frost point at filling pressure as per the IEC 62271-1 (volume without adsorber) (Conversion to atmospheric pressure or ppmv depends on the filling pressure of the high-voltage equipment.)
	Percentage of H_2O (humidity) during service life: ≤ -5 °C frost point at filling pressure as per the IEC 62271-1 (Conversion to atmospheric pressure or ppmv depends on the filling pressure of the high-voltage equipment.)
SF_6 mixtures	Percentage of SF_6 within manufacturer's requirements
	Percentage of N_2 or CF_4 within manufacturer's requirements
	Percentage of H_2O (humidity) after filling: ≤ -10 °C frost point at filling pressure as per the IEC 62271-1 (volume with adsorber) ≤ -15 °C frost point at filling pressure as per the IEC 62271-1 (volume without adsorber) (Conversion to atmospheric pressure or ppmv depends on the filling pressure of the high-voltage equipment.)
	Percentage of H_2O (humidity) during service life: ≤ -5 °C frost point at filling pressure as per the IEC 62271-1 (Conversion to atmospheric pressure or ppmv depends on the filling pressure of the high-voltage equipment.)

2.7 Long-term behavior

The long-term stability of the insulating and interrupting medium is of major importance for the performance of the high-voltage equipment over its service life. From the beginning of the technology development of C4-FN mixtures, their stability has been a major focus [48], [49], [50], [51]. Since 2017, high-voltage equipment using C4-FN mixture is running reliably in grid operation in various places in Europe, confirming the successful technology qualification [21], [52], [53].

2.7.1 Gas composition stability

C4-FN mixtures contain several molecules with different molecular weight (from 32 g/mol for O_2 to 195 g/mol for C4-FN). The capacity of the C4-FN to remain homogeneously mixed within the $(O_2)/CO_2$ or $(O_2)/N_2$ gas has been studied to check impact of the gravity. It was experimentally demonstrated that no separation of the mixture occurred, in accordance with calculations [54].

Once mixed, the gas components remain mixed. The operating temperatures are sufficient to ensure enough diffusion and prevent any decantation, which is similar to SF_6 mixtures.

The gas composition can slightly change when components leak in a proportion different than the mixing ratio (see section 2.7.2), or when the gas is arced during switching operations (see section 2.7.3). These effects are considered by the OEM during the design of the high-voltage equipment and the service life composition acceptable band.

2.7.2 Tightness and effects of leakages

Tightness is a key aspect of high-voltage equipment as a minimum density must be ensured in service. When the pressure drops under a certain level, the pressure must be topped-up, requiring an on-site operator with direct impact on OPEX for the TSO/DSO. Therefore, good tightness is an important characteristic for high-voltage equipment.

The leakage of the high-voltage equipment is the sum of two effects. This has been already partially covered in the TB 871 [4] and two basic phenomena coexist:

- Interface leakage: A defect of gasket, sealing surface, or mis-assembly leads to a (microscopic) channel for the gas to go out of the material. This failure mode is investigated during the tightness routine tests in the factory. This effect has been demonstrated to be independent of the gas and mostly related to the pressure of the high-voltage equipment. With C4-FN mixtures, the detection of this defect is still possible using C4-FN as tracer gas, e.g., with the volume accumulation method or sniffing method.
- Permeation diffusion: This effect is present with all gases but will change depending on the gas/material combination. Permeation can be seen as a sort of chemical porosity of one material to a gas. Just like sugar can dissolve into water, SF_6 or CO_2 can enter the material, especially elastomers, and through it, slowly leak to the outside. Permeation of CO_2 through elastomers poses a challenge to existing SF_6 equipment using EPDM rubber sealings, because the leakage rate was higher at normal operating temperatures. Butyl rubber ((X)IIR) sealings, also known in high-voltage equipment, allowed to reduce the CO_2 permeation coefficient significantly (see Figure 29). N_2 and O_2 have lower permeation coefficient than CO_2 in EPDM or (X)IIR. Therefore, using a C4-FN/O_2/N_2 mixture is interesting for retrofill application with the sealings staying in place. SF_6 and C4-FN have very low permeations, meaning permeation is not critical for these gases.

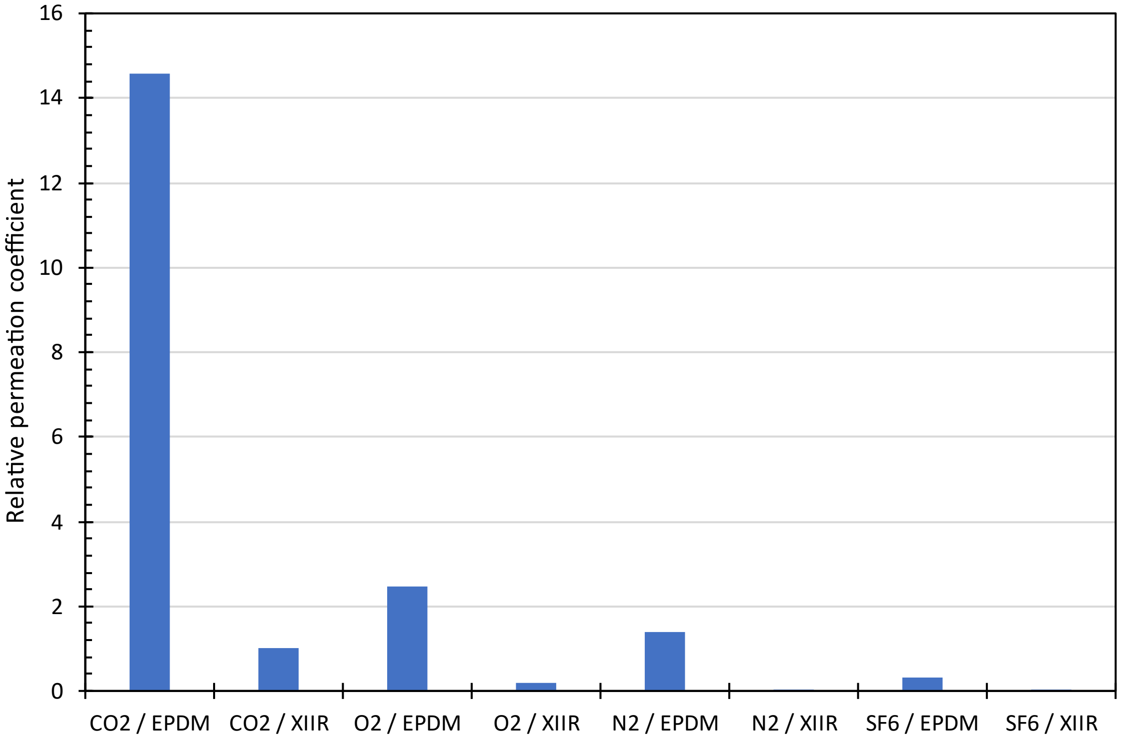


Figure 29: Relative permeation coefficients for EPDM and (X)IIR rubbers and CO_2, O_2 and N_2 gas at 20 °C, using CO_2 / (X)IIR as reference

Because permeation is gas-dependent, it will slightly change the gas composition over time. This change is very limited because the leakage is small, but as CO_2 leaks out and C4-FN and O_2 remain in the high-voltage equipment, the mixture will become slightly richer in additives over long time, while the gas pressure decreases.

After topping-up to the filling pressure, which can be done with the original mixture, the gas will be richer in a bit richer in additives than the initial gas mixture. The change of composition has a positive impact on the dielectric performance of the high-voltage equipment. A visual representation was presented in the TB 871 [4].

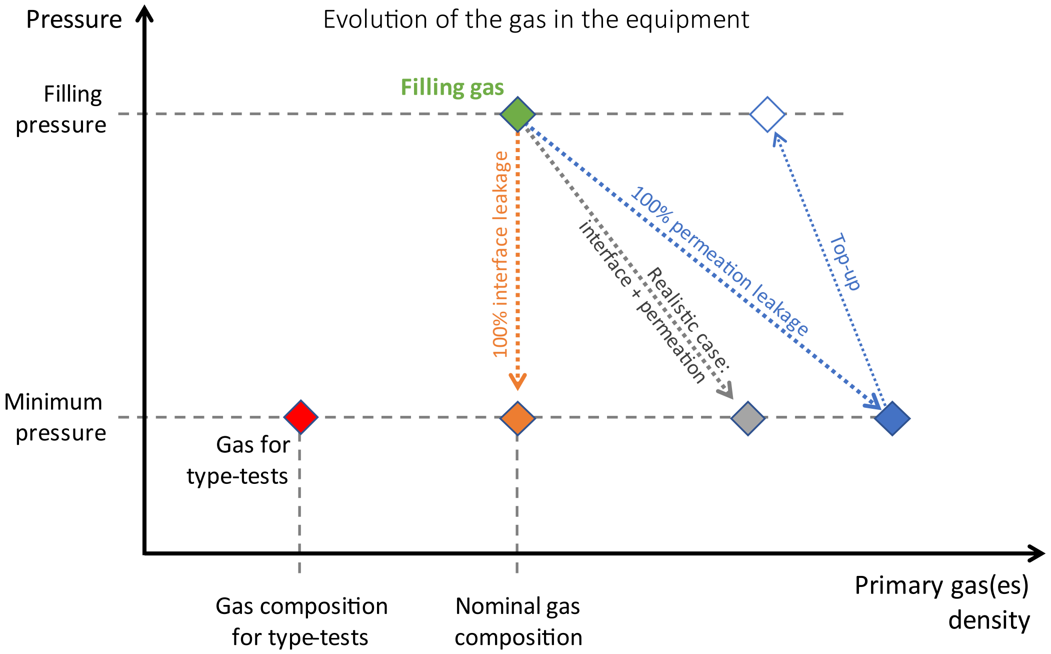


Figure 30 - Primary gas density variation because of the two leakages mechanism (based on [4])

2.7.3 Switching and gas decomposition

When a switching operation is performed, an electric arc exists in the gas for a short time. The intense power of the arc ionizes the medium, creating a high temperature plasma. After the extinction of the arc, the ions will recombine as per their own chemical preference, which depends on present ions, temperature, and pressure. Globally, long and complex molecules like C4-FN will not recombine after arcing as shorter ones will be more stable. Instead, small by-products like CF_4 will be created. The by-products of arcing are the results of the decomposition of gases (C4-FN, O_2, CO_2) and solids (PTFE, WCu, Cu, Fe, etc.). Most of the by-products originating from the metals are solid, while the ones from gas decomposition and PTFE are predominantly gaseous.

Despite being a random process at single ion level, statistically, the decomposition and recombination rates can be studied and quantified at the level of the complete high-voltage equipment. The gas mixture, design and switching duty are important factors of these parameters. Typical rates have been published by various sources, mostly for CBs. Values for disconnector and earthing switches are less documented, mostly by the difficulty to reach high enough energies to have visible trends. Finally, wear of gas is usually more important during breaking operations as arcs during making operations are usually shorter in both distance and duration.

In the table 3.8 of [4], some are values summarized from the literature. Generally, the decomposition and production rates can be more accurately provided by the OEM as they are dependent of the design and gas mixtures. The addition of O_2 for example, tends to increase the recombination into CO_2 and decrease the production of CO [44], therefore reducing the toxicity of arced gas. It also strongly influences the solid by-products by significantly decreasing the generation of free-carbon deposits (black conductive powder) [23].

Additionally, as the gas volume depends on the specific design of the high-voltage equipment. For bigger volumes, the gas composition variation due to arcing is reduced. It is therefore maximum for the most compact high-voltage equipment, having the highest short-circuit rating.

The rated voltage does not influence much the decomposition rates as usually similar arcing times are obtained on all voltage levels. Compared to type tests, in service easier conditions will lead to shorter arcing times, which will reduce the gas wear. Site measurements on a GIS having cleared two short-line faults demonstrated that predictions were accurate, and the CO content could be used to check for the short-circuit activity [52].

It is important to note, that the gas decomposition is not the limiting factor of the electrical endurance of the circuit-breaker [4], [23]. The limiting factor is usually the ablation of the PTFE nozzles, whose erosion impacts more the interruption performance as the gas wear. The rate of erosion of PTFE is sensibly the same between SF_6 and C4-FN mixtures, but arc energies in C4-FN high-voltage equipment can be slightly higher due to the increased pressure and opening velocity. Nevertheless, the achieved electrical endurance with C4-FN mixtures is not limited by the gas and can be further improved by overall CB design, like it has been for SF_6 CBs over the last decades.

The voltage test as a condition check, performed after high short-circuit current switching type-tests, is an efficient demonstration, that the combination of eroded contacts and arced gas are not critical for the performance of the switchgear [4].

As with SF_6, safe handling of arced gas needs specific procedures. A safety assessment for arced C4-FN mixtures, as well as detailed gas handling procedures, are included in sections 3.2 and 4.2 respectively.

2.7.4 Humidity and by-products

Humidity

As for SF_6, the humidity content in the gas should be maintained at a low level for high-voltage equipment that is in service to avoid liquid water. As per the IEC 62271-1, the limit of humidity is defined through the frost point at the filling pressure. During commissioning and maintenance, it should be below -10 °C, and in service, below -5 °C (compare section 2.6.4). These values apply to any gas medium, including SF_6 alternatives. More stringent criteria can be applied by the manufacturers.

The humidity content conversion from the ppmv to the dew or frost point can be computed the same way for SF_6 and for gas alternatives. The IEEE Guide for Moisture Measurement in SF_6 (IEEE Std C37.122.5-2013) and CIGRE SF6 Measurement Guide TB 723 [55] are particularly complete and can be used as references.

One aspect with the transition from SF_6 to C4-FN mixtures is that usually the pressure is increased to compensate for the slight reduction of dielectric strength of the medium. Therefore, assuming the same frost point limits, the admissible content of H_2O (ppmv) is lower in a C4-FN mixture than in SF_6 but corresponds to the same frost point temperatures (see Figure 31).

A plot chart is presented below to show the humidity content (ppmv) corresponding to a given pressure and various frost point temperatures. It is valid for C4-FN mixtures and also as an approximation also for SF_6.

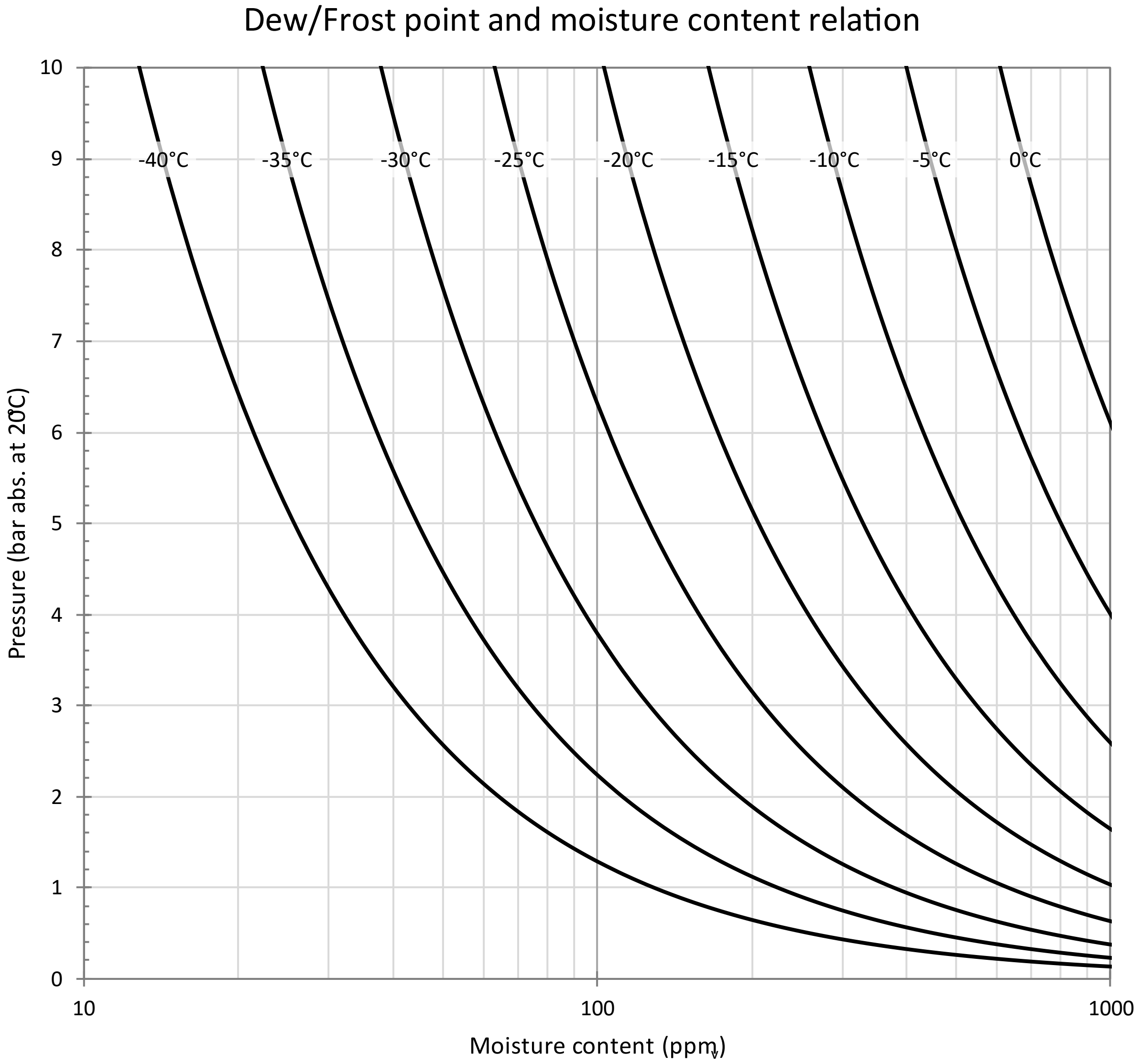


Figure 31: Frost point (°C) and moisture content (ppmv) relation up to 10 bar filling pressure

C4-FN hydrolysis

It has been demonstrated that C4-FN can, under certain conditions, react with humidity (H_2O) in a hydrolysis reaction [54]. The formed molecule, called amide (Perfluoroisobutanamide, CAS: 662-20-4, molecular formula $C_4H_2F_7NO$) has the appearance of white crystals. Amide can react further with C4-FN to form a dimer. Two dimers then usually react with a metallic ion (e.g., copper) to form a metal-dimer complex. Formation of amides usually appears at high temperatures with high humidity. Since the hydrolysis depends on the availability of moisture, the control of humidity (similar to SF_6) inside the equipment is important to ensure gas stability and minimize amide formation. Additionally, a careful selection of materials, especially of the adsorber, is essential to minimize or avoid formation of amide in the gas compartment [56].

The amide will condensate at low temperature locations, following its solid-vapor equilibrium. Usually, dimer molecules remain solid in normal conditions as they have a high sublimation temperature (130 °C). Both, the monomeric amid as well as the dimer typically appear as needle shaped, crystalline structures of up to 15 mm in length. They have been already studied [54], [57] and it was shown that they do not cause dielectric breakdowns or measurable partial discharges.

Amide molecules will vaporize at a slow rate with increasing temperature (solid-vapor equilibrium, vapor pressure at 20 °C = 13.3 Pa). Similarly, during gas recovery, amide crystals may vaporize after the end of the gas recovery process, leading to some amide vapor in the gas compartment.

Amide is classified for some hazards [58]. PPEs for C4-FN (technical grade or suitable for reuse) are appropriate in case of presence of amides, as described in section 4.2.3. The correct PPEs are also covered by the ones to handle normally arced C4-FN mixture. Procedure for recovery and reclaiming of gases during maintenance, repair, and overhaul in the presence of amide is covered in section 4.2.8.

Adsorber

In high-voltage equipment, that uses SF_6 or C4-FN mixtures, adsorbers are used to maintain low humidity and low content of gaseous switching by-products [50]. The low humidity level is also effective in controlling or preventing the C4-FN hydrolysis. Appropriate adsorber selection is needed to minimize C4-FN intake and material compatibility, while still effectively adsorbing humidity and most switching by-products [56]. Like in SF_6, not all by-products can be adsorbed. The non-adsorbed by-products, like CO can be used to track arcing activity.

2.7.5 Long-term stability

SF_6 is very inert and does not easily interact with other materials, except under arcing. Guidelines and best practices for gas quality and choice of materials have been established: e.g., low dew point (humidity control), careful selection of desiccants, lubricants, and contact materials. SF_6 alternatives can also contain components that might be more reactive like O_2 or fluorinated compounds.

Long-term effect of O_2

O_2 is present in some C4-FN mixtures to improve switching performances. O_2 is an oxidizing agent that may react with materials such as metals and elastomers. The higher the quantity of O_2 in the mixture, the stronger the effect of O_2. Impact on typical C4-FN mixtures is however expected to be lower than in dry air due to the lower ratio of O_2.

Ageing effect must be checked for several points:

- Ensure mechanical integrity of metallic parts: with limited amount of H_2O in the gas mixture, the risk of corrosion is mitigated.
- Ensure thermal properties of electrical contacts and connections: O_2 can create an oxide layer on metals. For some materials, like aluminum, the oxide layer is an insulator and can impact contact performance [59]. This is of relevance for contacts that move in operation, like plug-in or sliding connections in CB or DS. Here a growing oxide layer can lead to increased resistance after switching operation, when the reestablishment of the contact is hindered by the non-conductive oxide layer. It is the responsibility of the OEM to properly choose and test the contact systems. For example, silver-plated contacts are a system that has been thoroughly investigated and that can perform well in the long-term, even in oxidative environments at temperature of 115 °C and beyond [60], [61]. When type testing is done according to IEC or IEEE standards, allowed temperature rise depends on [41], [62]:
    - Type of electrical connection (e.g., bolted connection, movable contact)
    - Contact surface (e.g., bare copper, silver plated)
    - Whether the gas is oxidizing or non-oxidizing (e.g., SF_6, air)
- Ensure proper tightness of the gaskets: O_2 can react with elastomer and decrease tightness performances with time. The phenomenon is often known as the diffusion-limited oxidation (DLO) of the gasket. The selection of the proper material and design is mandatory to avoid any accelerated decrease of gasket performance.

Numerous ageing tests have been done and the effects of O_2 are mitigated through using proper material selection and design, which is the responsibility of OEMs.

Long-term effect of C4-FN

Like for SF_6, a robust material selection process should be established by the OEM for C4-FN mixtures, based on chemical understanding and testing. One step of the selection and qualification process are thermal aging tests for C4-FN mixture in a temperature range of 70 °C to 120 °C [56]. Here it is important to note, that the compatibility of materials depends on the experimental conditions. C4-FN has a higher chance of reacting with materials when in very high concentrations or in the presence of high amounts of humidity, while reactivity drops when C4-FN is diluted. Additionally, the considered temperature and humidity play an important role in the definition of the test, just like the evaluated properties of aged materials, e.g., some discoloration might be acceptable, while a strong decrease in yield strength is not acceptable.

In summary, C4-FN is generally chemically stable. The theory of chemical decomposition with humidity is now well understood [54]. The hydrolysis reaction, whose effects are treated in detail in section 2.7.4., can be controlled in high-voltage equipment by proper adsorber selection and dimensioning, as well as by selection of materials with low moisture content [56].

Return of experience

C4-FN mixtures have been in service within the power grid since 2017 for GIL and since 2018 for GIS, and additionally since 2021 in a retrofilled GIL. The technology demonstrated its stability by the continuity of service observed on the pilot installations [21], [44], [30].

With over 250 bay-years for the 145 kV GIS based on 2021 data (Figure 5), and likely more when accounting for newer projects, C4-FN technology demonstrated reliability. Successful short-circuit interruptions have been performed by equipment in service [52]. It is also the only SF_6-free solution with significant return of experience for 420 kV equipment.

Regarding negative returns of experience, most are related to issues not unknown to SF_6 equipment. The first is the sensitivity to cleanliness, which is generally higher for increased gas pressures, also in SF_6 [63]. Additionally, higher sensitivity is an intrinsic property of the natural origin carrier gases CO_2 and N_2 [64]. Overall, the sensitivity to cleanliness needs to be considered to some degree in equipment using C4-FN mixtures (moderate pressure increase compared to SF_6), but also in equipment using natural origin gases (significant pressure increase). The leakage rates due to the use of CO_2 as a carrier gas also create a step back in the tightness performance compared to state-of-the-art SF_6 high-voltage equipment but can be mitigated by appropriate sealing system design. The gas handling and gas quality measurements initially required some iterations on the gas handling equipment to reach their full potential. In some cases, the hydrolysis of C4-FN created some solid by-products even when humidity was kept at moderate values. This made modifications of materials necessary to avoid them or limit the quantity of the solid by products.

These are all normal points in the introduction of a new technology. C4-FN technology now has around one decade of experience in R&D and half a decade in grid operation. The technology is mature, with more OEMs and TSOs using C4-FN based high-voltage equipment and providing feedback. The recent acceleration of adoption shows the success of C4-FN mixtures to provide a viable and reliable alternative to SF_6. With return of experience and continuous improvement the technology will mature even further.

3 Health, safety, and environmental aspects

It is the vital to quickly launch high-performing high-voltage equipment with a low carbon footprint to efficiently and rapidly replace SF_6 high-voltage equipment. C4-FN mixtures have been selected because they can maintain both, the performance and the safety of SF_6, while reducing the CO_2-equivalent of the gas by approximatively 99 %. In this paragraph, the environmental impacts of a high-voltage equipment are introduced and guidelines to have comparable assessments are provided, referring to LCA and standardized methods and product category rules. Several studies from the literature are analyzed to show the estimated gains of replacing SF_6 by C4-FN mixtures depending on the type of equipment and ratings.

Introducing a new substance is a regulated process and HSE aspects were investigated as a priority since the beginning of the research of SF_6 alternatives. Multiple experiments on the interaction of C4-FN mixtures with arcing were performed by diverse and recognized parties. Based on this data, an understanding of the gas mixture evolution was developed, and the adequate gas conditions categories were defined to have efficient and safe operations. The provided gas conditions are based on the IEC categories and classified with respect to the CLP regulation. This allows the harmonization of safety data sheets and therefore of recommendations for gas handling.

3.1 Environment

3.1.1 Environmental impacts of high-voltage equipment

Manmade products always impact the environment. These impacts can be evaluated in different categories. The study of these impacts is called a Life Cycle Assessment (LCA). LCAs are recognized as the best method possible because of their cradle-to-grave approach which covers all the impacts of the product [28].

A high-voltage equipment has many impacts on the environment. Directly, it requires raw materials, energy, and fuel to be made and transported. During its lifetime, it consumes energy and emits gases. At the end-of-life, it must be dismantled and recycled. Indirectly, the high-voltage equipment impacts furthermore the environment because it requires civil works where it is installed, factories to be produced, maintenances, etc. and these contributions must be accounted for and reduced too. For sure, the use of SF_6, the most potent GHG, negatively impacts the climate change at all steps of the equipment life cycle.

The best solutions are only found performing system-wide LCAs, not at the level of the high-voltage equipment, but at the substation’s one. They approach the problem heuristically. For example, reducing the footprint of a car may be done by upgrading the motor to a new generation. However, assuming that in order to reduce the motor consumption by 20 %, it is bigger and heavier, then the car frame must be adapted, aerodynamics may be impacted, and non-recovered breaking energy is lost. While the motor is more efficient by 20 %, in the complete system, the actual gain could be reduced to, for example, 16 %. The actual gain of the new motor must be evaluated at the system-level (car).

LCAs are standardized methods [65] [66], that assess the product’s footprint. These methods are easily comparable when used with product category rules (PCR), which define exactly the scope, methodology and assumptions for the studies. Some PCRs exist already [67], some are defined at a country or TSO level [68], and the IEC 62271-320 (TC 17) should provide a valuable reference when effective (expected mid-2024).

Back to the previous example, the same motor might be used in various car models, addressing different applications of vehicles and performance. When comparing the impacts of two motor generations, they should be compared for the same defined conditions, e.g., same type of vehicle, load, use, etc. Otherwise, the results cannot be directly compared. For example, the car average consumption should be computed for the same speed and road type.

LCAs show the relation between each part of the product and its impacts on the environment. In many cases, the impact on climate change, whose characterization factor is GWP or CO_2-equivalent, is one of the most important ones. The LCAs performed for SF_6 high-voltage equipment show that around 59 % to 96 % of the CO_2-equivalent are due to the use of SF_6 only (see section 3.1.3). When removing SF_6, some of the necessary changes may increase the other contributions, but globally removing SF_6 is the most efficient solution to decrease the global footprint of high-voltage equipment.

3.1.2 GWP of the gas itself

GWP is a characterization factor of climate change, very close to the CO_2-equivalent. Anything has a GWP: 1 kg of SF_6 just like 1 kg of screw. In the high-voltage sector however, GWP has mostly been associated with the gas, while at a product level, people refer mostly to CO_2-equivalent.

The GWP of a gas is not a valid indicator of the environmental footprint of a high-voltage equipment. It only informs of the contribution of the gas to the climate change if released in the atmosphere. It does not represent the product's contribution to global warming. However, the gas GWP is an important factor to decide if a gas can be released in the atmosphere, assuming the other criteria are also met such as toxicity, harmfulness to biodiversity, etc. The IPCC AR6 report provides all the necessary information for the GWPs [3].

For C4-FN, the GWP_{100} (value of the impact over 100 years compared, with CO_2 as reference) is 2750. When mixed with other gases, the GWP of the mixture can be computed by weighting the GWP of each component by the mass fraction in the mixture:

$$GWP_{mix} = \sum_i w_i * GWP_i = \frac{\sum_i M_i * x_i * GWP_i}{\sum_j M_j * x_j} \tag{8}$$

with GWP_{mix} the GWP of the gas mixture
GWP_i the GWP of the compound i
w_i the mass fraction of the compound i in the total mixture
x_i the molar fraction of the compound i in the total mixture
M_i the molar mass of the compound i

The GWP can be computed as a function of the C4-FN content in C4-FN mixtures as presented below. The content of O_2 has a negligible influence. Mixtures with N_2 as carrier gas will show negligible difference too (<1).

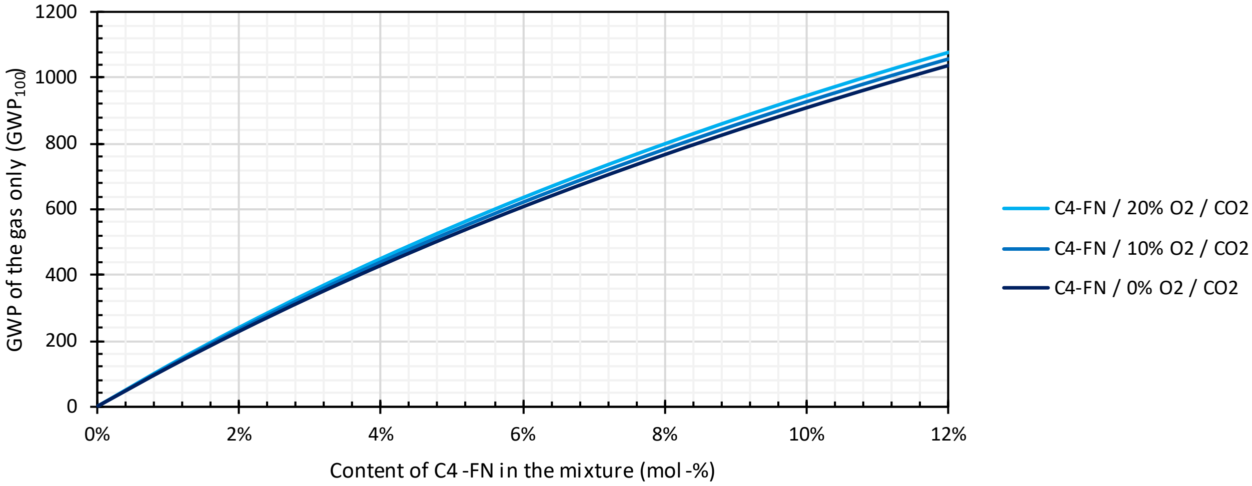


Figure 32: GWP for C4-FN/O_2/CO_2 mixture depending on amount of C4-FN

GWP is an indicator giving the impact of 1 kg of mass. It means that the total mass used is of major importance and must also be provided. Usually, mass of C4-FN mixtures is about twice lower than mass of SF_6 for the same performances.

C4-FN mixtures have a significatively lower GWP than SF_6 but still require proper gas handling to reduce emissions in the environment. This is achieved by using appropriate gas handling equipment and complete reclaim of gas before opening gas compartments. The use of the C4-FN is limited to specific and controlled environments where such conditions are already achieved.

3.1.3 Typical environmental results of C4-FN technology compared to SF_6 technology

Several LCAs have been published and focus on the comparison of C4-FN products against their SF_6 equivalent. C4-FN mixtures usually achieve 59 % to 92 % reduction of the total carbon footprint of high-voltage equipment compared to state-of-the-art SF_6 products, which is a significant improvement for the environment.

These studies were mostly made by manufacturers. Without a complete PCR (see section 3.1.1), they cannot be compared between OEMs as the estimations maybe have different scopes or hypotheses. Similarly, comparisons to other technologies like vacuum interrupters with air insulation is removed from the results, when possible, as the results can be biased by the difference of quality dataset (extrapolated values).

High-voltage equipment with C4-FN mixture is compact and light, allowing a low-carbon footprint associated to its manufacturing (emissions at the time of project executions). The low-GWP in comparison to SF_6 avoids important CO_2-equivalent emissions during the use phase and maintenances, especially considering the very low permeation rate of C4-FN through the sealing material (see 2.7.2). This maintains a relatively low carbon footprint of the use-phase, dominated by Joule losses of the main and secondary circuits, including instrument transformers and anti-condensation heaters. This footprint can be optimized and will reduce with the improving energy mix of the grid.

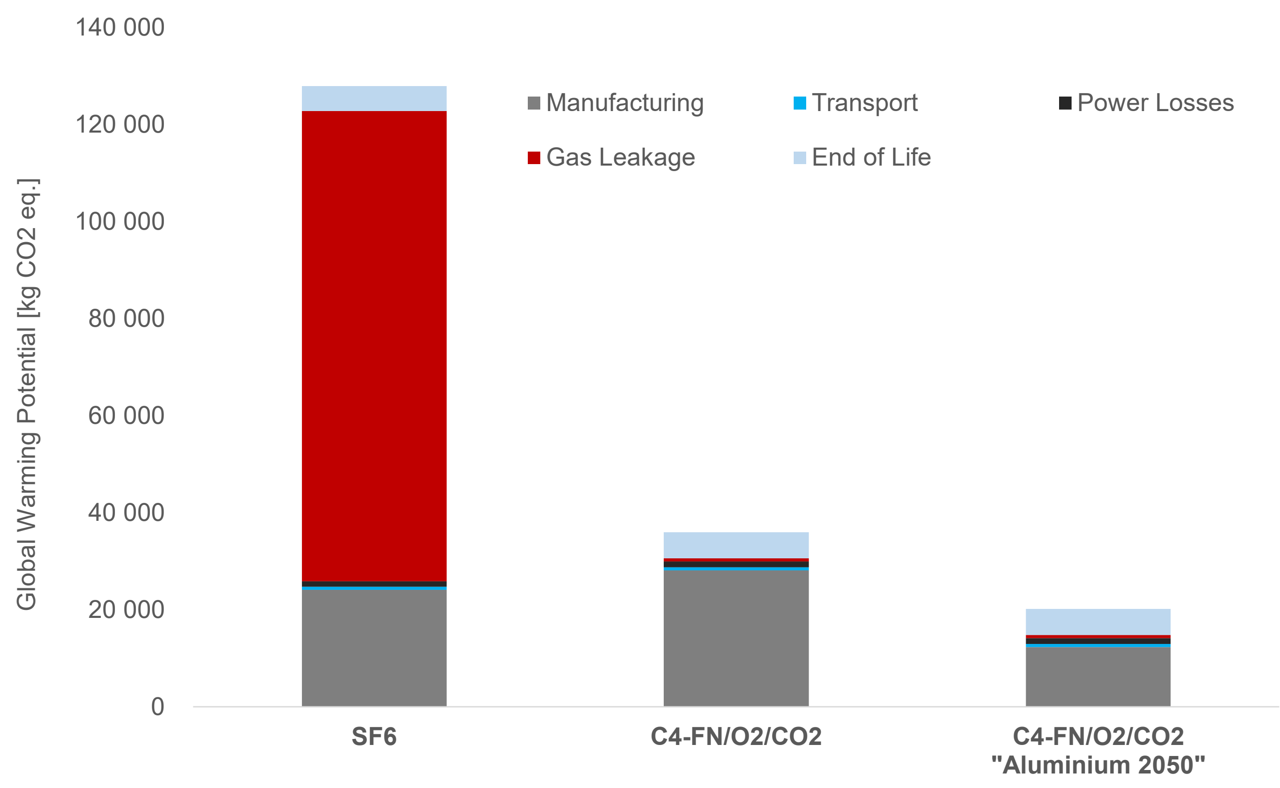
Some LCA results are presented below and grouped by category of product, as each one has its own inherent differences that change how the replacement of SF_6 impacts its CO_2-equivalent.

Dead-tank CB 72.5kV

An LCA was done to compare environmental performances of a dead-tank circuit-breaker at 72.5kV level using SF_6 and alternatives [69]. It appears that the carbon footprint was decreased by 59 % going from SF_6 to C4-FN mixture which means about 80 teq_{CO2} saved per product. The paper also highlighted that to use a lower mass of material helps to reduce CO_2-equivalent emissions at the manufacturing phase.

GIS 145 kV

A third party verified LCA was performed according to ISO 14040/14044 for a 145 kV GIS [70], [71]. A SF_6 GIS was compared to a C4-FN/O_2/CO_2 GIS with an identical specification comprising one double-busbar-bay including CB, CT, DES, FES, VT, cable connection, LCC and steel support. Over the whole life cycle, a 71 % reduction in carbon footprint could be achieved for the C4-FN/O_2/CO_2 solution (see Figure 33). This reduction is due to the lower carbon footprint of the gas that leaks during production and use phase. Additionally, there was a projected scenario “Aluminium 2050” included, where 100 % recycled aluminum was used for production of C4-FN/O_2/CO_2 GIS. This allowed a reduction of carbon footprint by 84 % compared to today’s SF6 equipment. Even in this optimistic future scenario the Aluminum consumption during manufacturing remains the main contributor to carbon footprint.



145 kV GIS: One double-busbar-bay including CB, CT, DES, FES, VT, cable connection, LCC and steel support.

Continuous current = 800 A, operation in a grid with renewable energy.

Left column: SF_6 equipment, leakage rate = 0.1 %/year.

Middle column: Equipment filled with C4-FN mixture, leakage rate = 0.2 %/year, production incl. aluminium in Europe (global carbon footprint of aluminum would be higher); 0 % recycled aluminum is used for production, 95 % is recycled at end of life.

Right column: Equipment filled with C4-FN mixture, leakage rate = 0.2 %/year, production incl. aluminium in Europe, “aluminum 2050 scenario” (= 100 % recycled aluminum is used for production, 100 % is recycled at end of life), circular economy.

Figure 33: LCA (carbon footprint over 40 years) for a 145 kV GIS

It is also possible to assess environmental impact with a simplified tool even though it is less accurate than full certified LCA. The key benefit from simplified tool is the much lower time needed to compare some data. Especially, a quick tool can be developed to check and compare impacts from different material scenarios (mass and proportion) to make a product. Such approach was developed in [72] where a 145 kV GIS is calculated using SF_6 and C4-FN mixture.

During the manufacturing stage, the best candidate is C4-FN mixture due to the small impact of C4-FN mixture GWP compared to SF_6 GWP. C4-FN mixture uses a little bit more material than SF_6 due to pressure increase. This could result in a larger carbon footprint for manufacturing, but the SF_6 emissions during the gas manufacturing and the GIS manufacturing counterbalance it (see Figure 34).

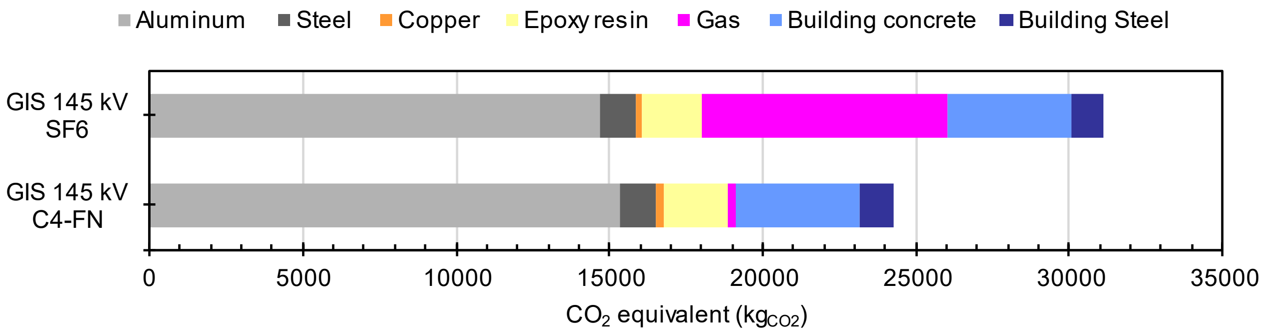


Figure 34: Simplified CO_2 footprint during manufacturing (145 kV GIS)

Then, C4-FN is much less impacting than SF_6 during the use phase. Calculations are done considering that the GWP of C4-FN mixture leaks equals the GWP of the C4-FN mixture, which is conservative as the main molecule leaking is CO_2 due to permeation effect (see section 2.7.2): C4-FN does not leak as much as CO_2 and the GWP of the leak is actually much lower than the GWP of the gas. Globally, the CO_2 footprint per year is clearly dominated by gas losses for SF_6 equipment, while for the C4-FN mixture insulated equipment electric (Joule) losses are most relevant.

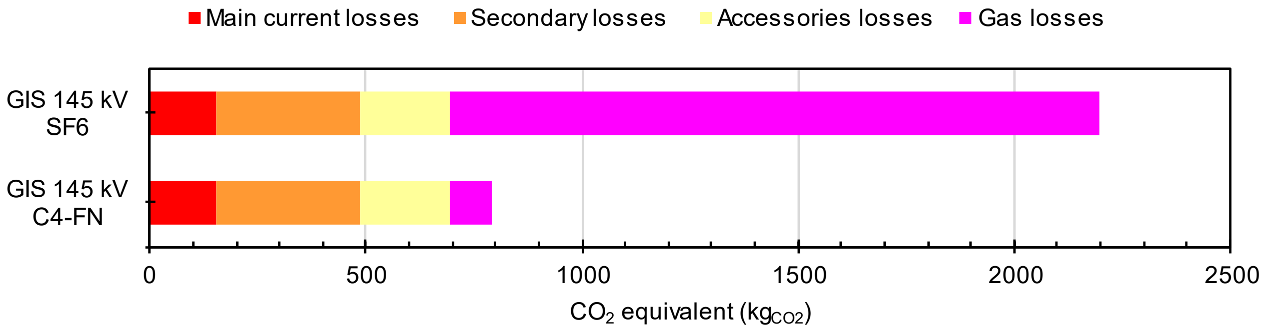


Figure 35: CO_2 footprint per year of use (145 kV GIS)

The reference result shows 58 % CO_2-equivalent reduction, but various other scenarios are presented and range from 49 % to 68 % carbon footprint reduction (Figure 36).

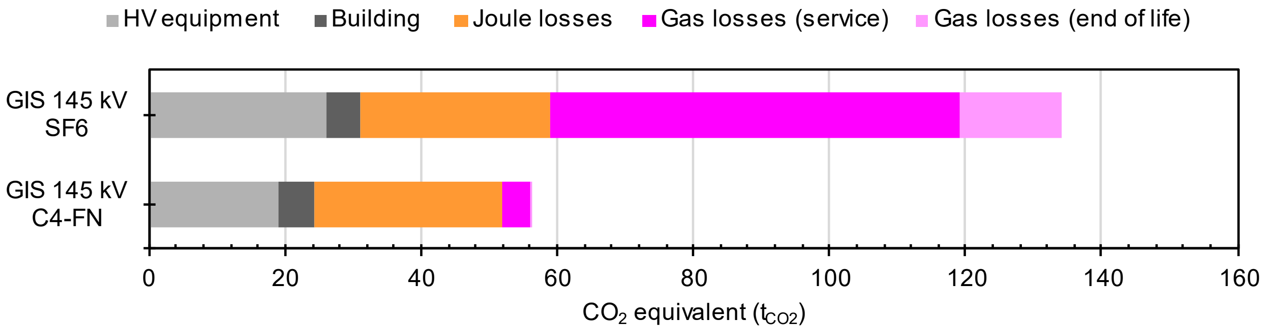


Figure 36: Simplified LCA (carbon footprint over 40 years) for a 145 kV GIS

GIS 420 kV

A new installation of a 420 kV GIS bay with 100 m GIL was assessed using SF_6 vs. C4-FN/O_2/CO_2 (see Figure 37 a) and b) respectively) [27]. For SF_6 equipment, gas losses are the dominant contribution to the equipment's carbon footprint, with more than 90 % share of CO_2-equivalent emission over the life cycle for the base scenario. Further, less important contributions are transport of components and product, resources used in assembly, testing, installation, commissioning, and maintenance and finally recycling as well as power losses due to load current.

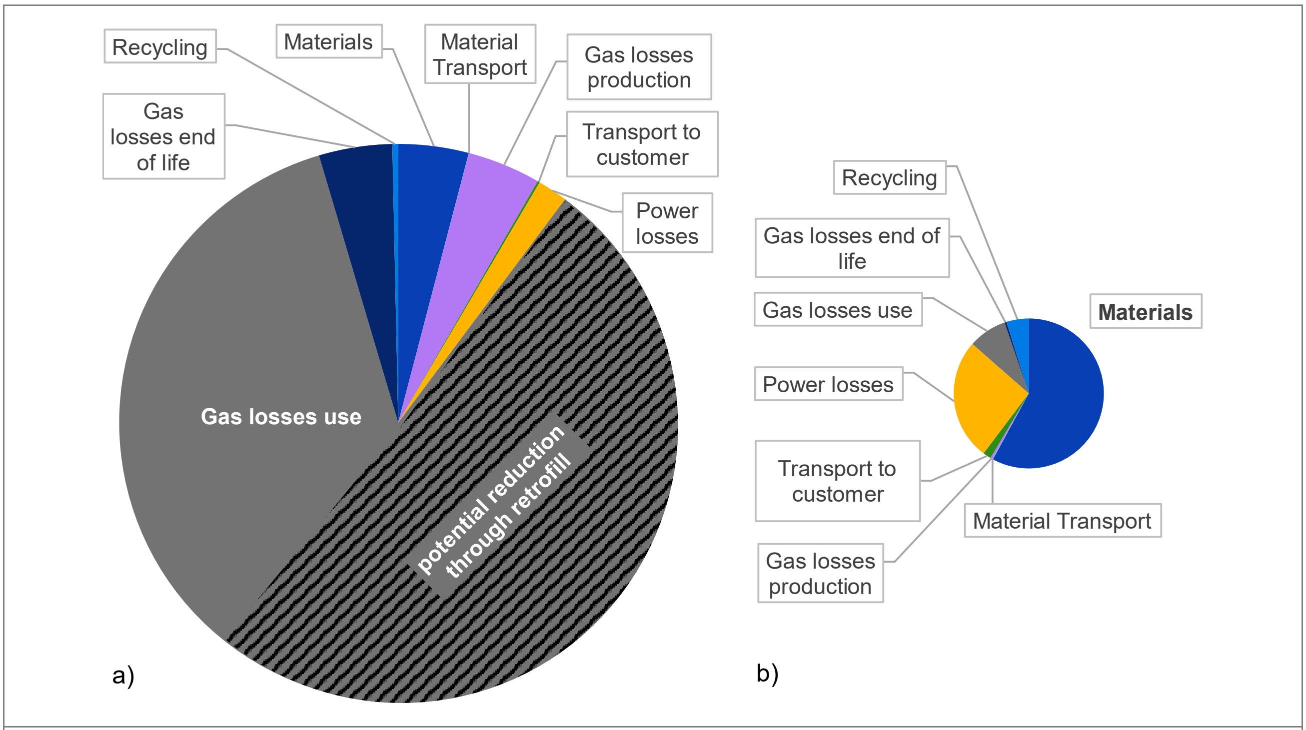
By switching to C4-FN/O_2/CO_2, the impact of gas loss on carbon footprint is virtually eliminated as CO_2-equivalent of leaked gas is reduced by 99 %. Size, material consumption and power losses of the C4-FN/O_2/CO_2 equipment are similar to the SF_6 equipment, so that the overall carbon footprint is reduced by more than 90 %. In the study [27], it is also demonstrated, that the relative numbers can change e.g., if a different load current or a lower leakage rate due to better equipment maintenance is assumed. However, the significant reduction of carbon footprint by the switch to C4-FN/O_2/CO_2 equipment, persists with an overall reduction in the range from 78 % to 92 % for the assessed scenarios.

It is confirmed by another paper claiming a 96 % reduction of carbon footprint for a 420 kV GIL [73]. On top of that, there is no transfer of pollution on other indicators such as ionizing radiation or metal depletion. The mean improvement is even 14 % on all indicators other than climate change.

GIS 420 kV Retrofill

A retrofill scenario of a 420 kV GIS bay with 100 m GIL/exit was assessed. Initially the equipment is installed, filled, and commissioned completely with SF_6 [27]. For the GIL part, a retrofill is available, meaning SF6 will be swapped with C4-FN/O_2/N_2 gas mixture. The GIS bay remains with SF_6. In case the retrofill of the GIL is performed right after commissioning, around 50 % of the total carbon footprint (59 % of total gas losses) can be avoided (see Figure 37). Since retrofit is only available for the GIL part, it should be considered, that the reduction of carbon footprint is strongly dependent on the specific layout of the installation.

SF_6 installations with long GIL can have a large share of their future CO_2-equivalent emissions removed by retrofill. The point in time after installation when the retrofit is performed is also relevant. The earlier in the life cycle the retrofill is performed the larger the share of avoided CO_2 emissions.



420 kV GIS installation: GIS bay and 100 m GIL. Continuous current = 800 A.

a) Carbon footprint for equipment filled with SF_6. Leakage rate = 0.5 %/year. Also shown is a possible reduction of the CO_2-equivalent, by filling the GIL with a C4-FN/O_2/N_2 mixture.

b) Carbon footprint for equipment (GIS and GIL) filled with a C4-FN/O_2/CO_2 mixture.

Figure 37: LCA (carbon footprint over 40 years) for a 420 kV GIS installation

3.1.4 Remaining carbon footprint with C4-FN gas mixture – Example of a 145 kV GIS

With the replacement of C4-FN by SF_6, a huge part of the product carbon footprint is removed. However, the remaining part is not null and must be addressed to further decrease the climate change impact.

For a C4-FN 145 kV GIS, the remaining footprint is mainly coming from Joule losses (46 %) and aluminum parts (41 %). The gas is a minor contributor: C4-FN mixture leaks represent 3 % of the carbon footprint [74].

Figure 38: Carbon origins for a 145 kV C4-FN mixture GIS

To decrease the CO_2-equivalent of the product, it is now of major importance to decrease the mass of aluminum part. The good dielectric performances of C4-FN mixture allow an optimal reduction of the pressure and / or distance between active parts and earth [44]. It will decrease burst pressure values to design enclosures and allow thinner enclosures. C4-FN mixture optimizes the amount of metal required to make the product.

Joule losses can be converted to CO_2-equivalent using the data about the power generation emissions. While the European energy mix is constantly improving, important differences exist at country or regional levels, and it will never be null but only compensated (offset).

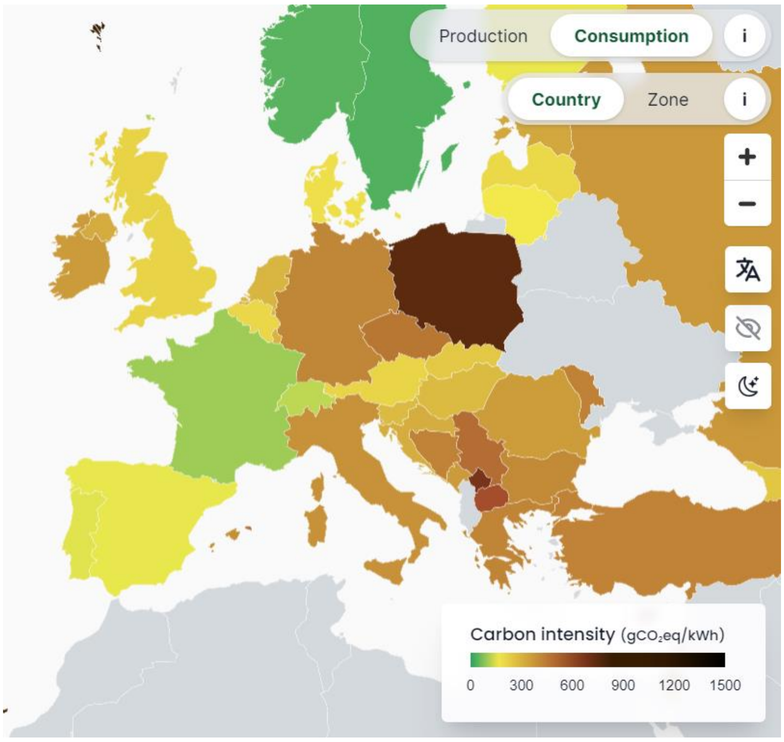


Figure 39: Carbon intensity of the electricity consumed in Europe per country – Mean value over 1 year. Data from https://app.electricitymaps.com/map from the 13th of April 2023

Relying on the improvement of the energy mix to decrease CO_2-equivalent emissions of a product during its use phase is not proactive and can only deliver lower results. It is important to start addressing the root causes leading to Joule losses.

3.1.5 LCA and European Union directives

In March 2023, a directive on green claims was proposed at EU Commission that calls to end greenwashing [75] and resonates with certain elements of this handbook. Among the claims are:

- A life cycle approach needs to address transfers of pollution.
    - For example, LCAs performed as per international standards [76] [66] investigate these effects and include multiple environmental indicators additionally to the carbon footprint.
- A claim about a certain aspect of a product cannot be extended to the complete product.
    - For example, GWP of the gas is not the carbon footprint of the product.
- Results can only be compared if they are based on an equivalent set of data and information.
    - For example, an OEM comparing its solution to a product he doesn't have or that is in preliminary development phase is subjected to important bias because of one dataset being only estimated. Comparison should be done in the scope of product category rules (PCR) like the future IEC 62271-320 [77].

To have a timely and efficient reduction of GHG emissions, Greenwashing should be avoided. Any solution such as C4-FN mixtures already available on the market can be implemented to remove SF_6, reduce the carbon footprint of the equipment, and avoid transfers of impacts like acidification and material depletion.

In order to reach ambitious objectives, the transition should not wait, especially considering the actual and forecasted growth of electric installations and their impact over the environment for the next 40 years if they were done with SF_6.

3.2 Health and safety information

3.2.1 Gas conditions

For high-voltage equipment, the relevant standard IEC 62271-4 [29] and future IEC 63360 describe properties, requirements and handling of those gas mixtures containing C4-FN. It is practical to categorize gas mixtures containing C4-FN in one of the three following conditions regarding applicable health and safety measures:

- Non-arced C4-FN mixture (see section 1.5.2)
- Normally arced C4-FN mixture (see section 1.5.2)
- Heavily arced C4-FN mixture (see section 1.5.2)

For guidance regarding which gas conditions apply to which equipment types (e.g., CB, GIL) and to which phase of the life cycle (e.g., commissioning, maintenance, end-of-life), please refer to section 4.2.2. Also compare with the definitions listed in section 1.5.2.

3.2.2 Toxicity

Basics

According to the (EC) No 1272/2008 (CLP regulation) [78], substances and mixtures must be self-classified if no harmonized labelling for the substances or mixtures exist. Regarding toxicity, the regulation distinguishes different means of exposure (e.g., dermal exposure, oral exposure, or inhalation). It also defines acute toxicity versus other long-term effects on health or the environment.

For insulation gases, inhalation toxicity is the most important, both for SF_6 as well as for C4-FN mixtures. In Table 18, the four CLP toxicity categories are shown, together with the converted acute toxicity estimate (ATE; corresponding to an LC50 value). Category 1 is used for the most toxic substances, while Category 4 is used for the least toxic substances that still warrant a classification. Substances that are even less toxic than Category 4, or practically non-toxic are not categorized.

To estimate the toxicity of mixtures, the point estimates of the individual substances are used to calculate the ATE value of the mixture, according to the following equation:

$$\frac{100}{ATE_{\text{mixture}}} = \sum_{n} \frac{C_i}{ATE_i} \qquad (9)$$

With $ATE_{mixture}$ the estimated toxicity of the mixture
C_i the concentration of ingredient *i*
ATE_i the acute toxicity point estimate of substance *i* based on its individual acute toxicity classification (in this case for inhalation exposure).

Note that the ATE of the mixtures is an estimate based on individual substances and not a measured value and should be considered as such. For a relative comparison, the calculated inhalation toxicity ATE of the mixture corresponds to the four-hour inhalation exposure LC50.

Table 18: Acute toxicity classification for inhalation toxicity (gases) according to the CLP regulation [78]

Acute toxicity classification	Converted acute toxicity point estimate [ppm]	Gas mixtures used in high-voltage equipment	Hazard statement for acute inhalation toxicity	GHS pictogram
Category 1	ATE ≤ 100		H330: Fatal if inhaled	☠
Category 2	100 < ATE ≤ 500		H330: Fatal if inhaled	☠
Category 3	500 < ATE ≤ 2 500	Used SF$_6$, heavily arced C4-FN mixtures	H331: Toxic if inhaled	☠
Category 4	2 500 < ATE ≤ 20 000	Normally arced C4-FN mixtures, C4-FN (technical grade or suitable for reuse)	H332: Harmful if inhaled	❗
Not categorized	ATE > 20 000	New SF$_6$, non-arced C4-FN mixtures	None	N/A

Application to C4-FN mixtures and comparison with SF$_6$

Both C4-FN mixtures and SF$_6$ form toxic by-products when subjected to electrical arcs. The formation of SOF$_2$ is known to dominate gas toxicity for SF$_6$ circuit-breakers and appropriate care must be taken when handling circuit-breakers that have been subjected to arcing. Similarly, C4-FN mixtures form by-products under arcing, some of them toxic, such as CO (see section 2.7.3). Depending on arc energy, cooling of the arc, solids subjected to the arcing and adsorbers in the gas compartment, the by-product concentration in the C4-FN mixture will change over the equipment's life cycle. Specifically for a CB, the gas can go from non-arced to normally arced condition, and even to heavily arced condition in case of failure (compare section 3.2.1, section 4.2.2).

Extensive development and type testing of CBs (LTB, DTB, GIS, 72 kV to 420 kV) using a range of C4-FN/O$_2$/CO$_2$ mixtures was performed over the last few years. Broadly applicable maximum concentrations of all gas components and by-products could be assigned to the three gas conditions (see Table 19,). For each gas condition associated safety data sheets were created. In regulations (EC) No 1272/2008 (CLP regulation) [78], (EC) No 1907/2006 Annex II (REACH) [79] and (EU) 2020/878 (amendment to REACH Annex II) the ATE value is calculated based on the limit gas composition which in turn results in classification of gas mixture toxicity. Both CLP regulation and IEC 62271-4 provide a classification of gas mixtures based on calculated ATE values.

To have a conservative assessment of the mixture toxicity, for the three presented mixtures several assumptions were taken:

- COF$_2$ and SOF$_2$ are both known to decompose rapidly to HF in a 1:2 ratio (1 molecule of COF$_2$ or SOF$_2$ forming 2 molecules of HF); to accommodate this, the presented compositions for C4-FN mixtures include both, COF$_2$ as well as HF in a 1:2 ratio. However, in reality, neither will be present in the full concentration at the same time.
- In addition to the substances listed in Table 19, the calculated ATE contains an additional buffer for a substance having the most severe acute toxicity category and a concentration of 0.01 % (normally-arced C4-FN/O$_2$/CO$_2$) or 0.1 % (heavily-arced C4-FN/O$_2$/CO$_2$) respectively.

For **non-arced C4-FN/O_2/CO_2** the calculated ATE is so high / the acute toxicity is so low, that the mixture is not categorized (see Table 19). This gas condition is applicable for equipment at the commissioning stage (see section 4.2.2). Since the low CO concentrations below 1 000 ppm are included, this gas condition applies also to gas that has experienced dielectric flashovers from routine tests.

For **normally arced C4-FN/O_2/CO_2**, the concentration of by-products, including buffer, warrants a classification of the mixture in Category 4 for acute inhalation toxicity (see Table 19), the lowest classified acute toxicity category in CLP (see Table 18). This gas condition is applicable for CBs in service, that have not failed (see section 4.2.2).

For **heavily arced C4-FN/O_2/CO_2**, the concentration of by-products, including buffer, warrants a classification of the mixture in Category 3 for acute inhalation toxicity (see Table 19). This gas condition is applicable for equipment that experienced an internal arc fault (see section 4.2.2).

To compare with SF_6, by-product concentrations are listed in Table 20 and ATE is calculated based on published safety datasheets for SF_6 and used SF_6. SF_6 is not categorized for acute inhalation toxicity, like non-arced C4-FN/O_2/CO_2. Used SF_6 is categorized in Category 3, same as heavily arced C4-FN/O_2/CO_2. Note in the used SF_6 datasheet, the concentration of HF is likely too low, considering the high limit concentration of SOF_2 stated and considering the rapid decomposition of 1 molecule of SOF_2 to 2 molecules of HF in the presence of moisture.

Table 19: Upper limits of composition of C4-FN/O_2/CO_2 mixtures considered in the SDS

C4-FN mixture [1]	C4-FN [%]	O_2 [%]	CO [%]	HF [%]	COF_2 [%]	C_2N_2 [%]	C_2F_3N [%]	Inhalation acute toxicity class [2]	ATE [2]
Non-arced	8.0	19.0	0.1	-	-	-	-	Not categorized	>20 000
Normally arced	8.0	19.0	5.0	0.1	0.05	-	-	4	6 209
Heavily arced	8.0	19.0	10.0	2.0	1.0	0.1	0.1	3	675

1 % equals to 10 000 ppm. For example, 0.1 % equals 1 000 ppm.

[1] Classified as per the definitions of the section 1.5.2.

[2] As per the CLP regulation (plus buffer and always considering COF_2, even if below the 0.1% threshold) [78].

Table 20: Upper limits of composition of SF_6 in different conditions in published SDS

	SF_6 [%]	SOF_2 [%]	S_2F_{10} [%]	HF [3] [%]	CF_4 [%]	Inhalation acute toxicity class [2]	ATE [2]
SF_6 [80]	≥99	-	-	-	-	Not categorized	>20 000
Used SF_6 [81]	≥95	2.0	1.0	0.1	3.0	3	826

1 % equals to 10 000 ppm. For example, 0.1 % equals 1 000 ppm.

[1] Classified as per the definitions of the section 1.5.2.

[2] As per the CLP regulation [78].

[3] the concentration of HF is likely too low for the condition of the gas, considering the high limit concentration of SOF_2 stated and considering the rapid decomposition of 1 molecule of SOF_2 to 2 molecules of HF in presence of moisture.

3.2.3 Other properties

Flammability

The combination of C4-FN and O_2 is not flammable in the proportions defined in the SDSs. Based on test evidence from three different laboratories, flammability has not been observed up to high pressures (140 bar), up to high temperatures (90 °C), and a high concentration of the mixture components (C4-FN up to 9 %, oxygen up to 19 %). Additionally, short-circuit and internal arc faults tests confirm that there is no sustained reaction in operation or fault conditions.

Users should always refer to the gas handling equipment manual to ensure its correct use.

Oxidizer

C4-FN mixtures contain less O_2 than air and are therefore not defined as oxidizers [82].

The term oxidizer in this chapter is different from the “oxidizing gas” category from the IEC 62271-1, or “reactive gas” from the IEEE C37.04 which are related to material compatibility and electrical contact degradation as mentioned in section 2.7.5.

It should be noted that, when compressed into a liquified state as during gas recovery or within pre-mixed bottles, most C4-FN gas and some CO_2 liquefies, leading to a gaseous phase rich in O_2. Although the quantity is limited, opening a bottle in these conditions would release for a short time a gas rich in O_2 (depending on the mixture, mostly below +15 °C, with up to 30 % O_2 at 0 °C, or 40 % O_2 around -10 °C). After a short-time, a CO_2-rich mixture (> 85 %) would be released. As per the regulations, this does not change the definition of the mixture which is still non-oxidizing.

Users should always refer to the gas handling equipment manual to ensure its correct use.

Solubility in water

C4-FN is essentially insoluble in water (0.272 ppmw at 25 °C) and has a high vapor pressure (3 bar at 25 °C) [83]. In simple terms, this means that:

- In the event of leakage from high-voltage equipment, C4-FN will escape in gaseous form directly to the air.
- In the event of spillage of liquid C4-FN from a C4-FN cylinder, the C4-FN liquid will evaporate into the air within minutes (calculated according to [84])

In both cases, C4-FN spreads within the atmosphere instead of being dissolved in the ground water. Quantitatively, the partition coefficients available in ECHA dossier [83] can be used to evaluate how C4-FN emissions will distribute between air, water, and soil/sediment [85]. The partition coefficients of C4-FN are several orders of magnitude removed from partitioning to water, specifically, log $K_{AW} = 4.4$ (K_{AW} being the air-water partition coefficient) and log $K_{OA} = -0.1$ (K_{OA} being the octanol-air partition coefficient) [83].

4 User guide

This chapter gives clear guidance on how to handle and interact with C4-FN mixtures, used in high-voltage equipment. The changes for installation and commissioning, maintenance, and end of life – induced by the transition from SF_6 to C4-FN mixtures – are investigated.

A special focus will be on gas handling procedures which are based on the different gas quality classifications. Scenario-based guidelines with relevant safety information, personal protective equipment and gas handling equipment are defined. Considered scenarios are:

- Installation of new high-voltage equipment using premixed gas including liquefied bottles, as well as on-site preparation of the gas mixture.
- Maintenance of high-voltage equipment, including gas quality checks and topping-up.
- Retrofilling of SF_6 insulated high-voltage equipment with C4-FN mixture.
- End of life treatment of the high-voltage equipment including fault scenarios, recycling, and disposal of used or arced gas.

4.1 Comparison of high-voltage equipment using SF_6 and high-voltage equipment using C4-FN mixtures from a user's perspective

SF_6 and C4-FN mixture technologies for high-voltage equipment have a lot in common. Both technologies use gas circuit-breakers and pressurized gas as an insulation. Dimensions are similar, and performances are achieved similarly, so that the architectures are similar with past and present SF_6 equipment. Switching devices rely on the same principles, thus using the same type of operating mechanism. One difference is the use of a double-chamber design for the highest voltages (e.g., 420 kV) but this was also the case until 10 years ago for SF_6 and could be improved in the future for C4-FN mixtures. Globally, there are not more differences between C4-FN and SF_6 high-voltage equipment as between SF_6 high-voltage equipment from two different manufacturers.

For users, very few external details show the use of a C4-FN mixture. This is mostly visible on the nameplates, density monitors, and with the different gas port threads that avoid unvoluntary confusion between handling of SF_6 and C4-FN mixtures.

Besides some differences in gas handling the engineering, installation, commissioning, and maintenance of high-voltage equipment using C4-FN mixtures does not differ from that using SF_6 [21]. Experience and training acquired by users over the last few decades will be easily transposable with minimum effort [53].

Regarding gas handling, the equipment and procedures are very clear but appropriate training and processes must be followed to ensure safe and efficient operations. Most suppliers providing C4-FN mixtures gas handling equipment also have products for SF_6 and ensure similar experience and interfaces for a seamless transition for operators.

The gas medium is monitored using mechanical density monitors or analog or digital pressure sensors. Partial discharge activity can be monitored using the UHF method. Arc detectors can be installed to identify compartments in case of an internal arc fault. Conventional or low-power instrument transformers can also be used [86]. The endurance of switches is based on the number of operations and, for circuit-breakers, on the interrupted currents. Gas quality can be measured using mobile analyzers. Detailed gas analyses can be done by taking a gas sample in a small gas cylinder similar to the ones used for SF_6 and sending it to a specialized laboratory [5].

Regarding service conditions, maintenance guidelines from manufacturers should be followed. Very limited number of maintenances or controls are expected. The gas quality does not need to be monitored other than by the density alarm or during maintenances specified by the equipment manufacturer. The electrical endurance of the circuit-breaker is not limited by the gas [87]. In normal conditions, the high-voltage equipment will reach its end of life before the gas does. Therefore, the gas should not be replaced during service. Top-ups are usually done using overpressure like in SF_6 or with the use of a compressor or a service cart.

In conclusion, for a user with experience in SF_6 high-voltage equipment, the transition to C4-FN mixtures will be fast and capitalize on most acquired knowledge. For workers starting directly with C4-FN mixtures, similar trainings and learning curves as currently with SF_6 can be expected. This is valid for gas operators, but also supervisors and project managers as both technologies are very similar.

4.2 Gas handling

An important part of the user interaction with high-voltage equipment using C4-FN mixtures is gas handling. In the life cycle of high-voltage equipment, there are only few occasions where gas handling is performed. The relevant gas handling scenarios are described in section 4.2.5 and are fully aligned with IEC 62271-4 [29]. An overview of gas handling equipment as well as the recommended personal protective equipment PPE is given in sections 4.2.1 and 4.2.2. Recommended procedures for specific gas handling scenarios are given in the subsequent subsections. However, these procedures are not a binding instruction. It is always in the responsibility of the executing unit to define clear and binding instructions that also consider local conditions. Legislative regulations, international standards, and the guidelines of the plant officer and operating company regarding work safety and accident prevention also apply.

4.2.1 Gas handling equipment

The necessary gas handling equipment categories are equivalent to SF_6 (see Figure 40). Gas handling is performed with gas handling equipment optimized for C4-FN mixtures. The gas handling equipment is not specific to certain C4-FN or O_2 concentration values and can usually be used for all common C4-FN mixtures. Applying and operating the gas handling equipment is comparable to SF_6. A training is necessary on the equipment before use and is similar to their corresponding SF_6 ones. Experience with SF_6 equipment can be mostly transposed to C4-FN equipment but is not necessary.

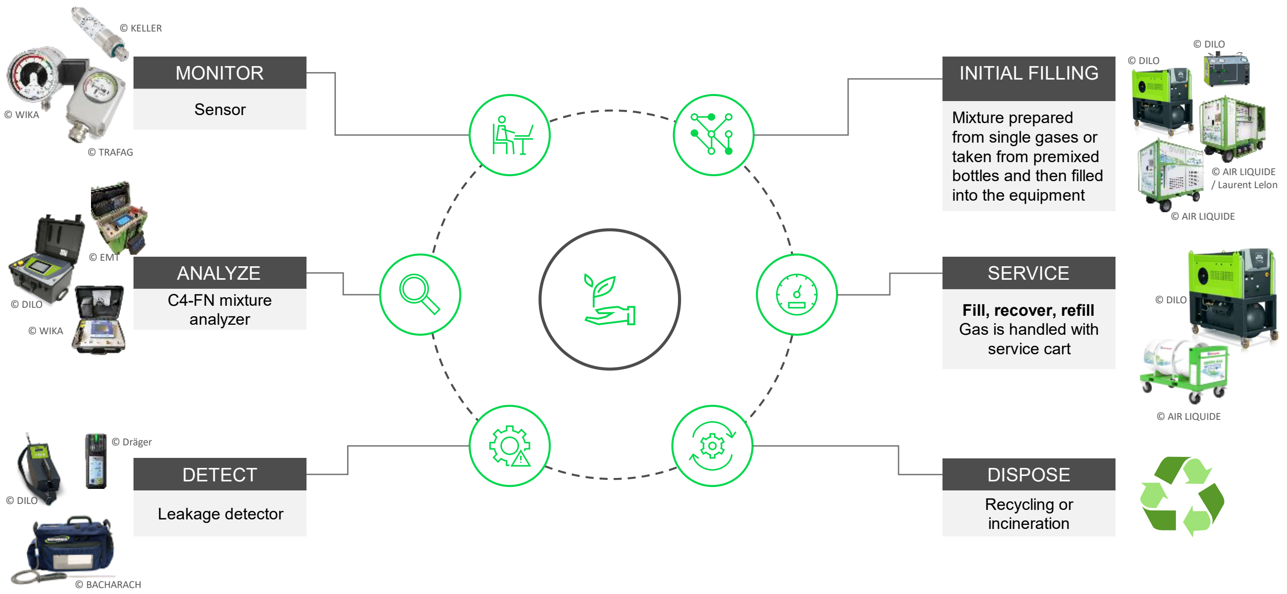


Figure 40: Gas handling concept for C4-FN mixtures

4.2.2 Gas Conditions

The choice of procedure and PPE depends on the condition of the gas (see section 4.2.3). As a general guidance, condition of the gas is chosen based on type of high-voltage equipment and its service life. Background of this approach is explained in sections 2.7 and 3.2.

Table 21: Guidance on the identification of the applicable gas conditions during service life (see section 4.2.3)

Time in equipment's life cycle	**Equipment type**	
	Circuit-breakers	**Non-CB compartments (GIL, disconnectors, earthing switches, …)**
Installation and commissioning	Non-arced C4-FN mixture and C4-FN (technical grade or suitable for reuse) [1]	
Normal service life	Normally arced C4-FN mixture	
Excessive number of short-circuit switching operations or failed to interrupt	Heavily arced C4-FN mixture	N/A
Internal arc fault	Heavily arced C4-FN mixture	

[1] At installation and commissioning, the gas condition and respective safety data sheets for C4-FN (technical grade or suitable for reuse) need to be considered in the following cases:

- Gas filling with on-site mixing is performed.
- The equipment has been filled with gas for more than four weeks (decomposition product amide can be present).

4.2.3 Personal Protective Equipment (PPE)

Similar to other gases used in high-voltage equipment, like SF_6 or natural origin gases, PPE is necessary when gas handling with C4-FN mixtures is performed. The recommended PPE (see Table 22) depends on the condition of the gas (see section 3.2.1).

Table 22: Recommended personal protective equipment (PPE) for gas handling of C4-FN mixtures, depending on the condition of the gas, it is given for C4-FN/O_2/CO_2 mixtures as an example but applies to C4-FN/O_2/N_2 mixtures analogously

Handling of	Non-arced C4-FN mixture	Normally arced C4-FN mixture	Heavily arced C4-FN mixture	C4-FN (technical grade or suitable for reuse)
Applicable safety data sheet	**SDS non-arced C4-FN/O_2/CO_2** or non-arced C4-FN/O_2/N_2****	**SDS normally arced C4-FN/O_2/CO_2** or normally arced C4-FN/O_2/N_2****	**SDS heavily arced C4FN/O_2/CO_2** or heavily arced C4-FN/O_2/N_2****	**SDS C4-FN***
Hand protection				
Protective gloves		Recommended Point 3	Recommended Point 3	Recommended Point 1
Work gloves	Recommended Point 2			
Eye protection				
Safety goggles		Recommended Point 6	Recommended Point 6	Recommended Point 4
Safety glasses	Recommended Point 5			
Respiratory protection				
Mask	Under conditions Point 7	Recommended Point 8	Recommended Point 8	Under conditions Point 7
Self-contained breathing apparatus		Under conditions Point 8	Under conditions Point 8	
Protective suit				
Protective coverall			Recommended	
Carry-on or room monitoring				
CO		Recommended	Recommended	
C4-FN	Under conditions Point 9	Under conditions Point 9	Recommended	Recommended
CO_2	Under conditions Point 9	Under conditions Point 9	Recommended	
O_2	Under conditions Point 9	Under conditions Point 9	Recommended	

Comments:

- “Recommended” indicates PPEs that are recommended for the work with the corresponding gas conditions.
- “Under conditions” indicates PPEs that are recommended under certain conditions for the work with the corresponding gas conditions.
- Empty cells indicate no particular recommendation related to the gas itself.

As mentioned in the 4.2, it is always in the responsibility of the executing unit to consider all parameters when defining the PPEs to be used, in accordance with local and contractual regulations. For example, the use of head protection (helmet) or safety shoes.

* Available from C4-FN supplier.
** Available from high-voltage equipment manufacturer.

Point 1: Use protective gloves (consult the safety data sheet of C4-FN for appropriate materials, for example polymer laminate protective gloves. Nitrile rubber gloves may be worn additionally on top of polymer laminate gloves to have more grip.).
Point 2: Work gloves.
Point 3: Use protective gloves (consult the safety data sheet of heavily arced C4-FN/O_2/CO_2 for appropriate materials, for example polymer laminate protective gloves. Nitrile rubber gloves may be worn additionally on top of polymer laminate gloves to have more grip.).
Point 4: Use safety goggles according to the safety data sheet C4-FN.
Point 5: Use safety glasses.
Point 6: Use tightly fitting safety goggles according to the safety data sheet of normally arced or heavily arced C4-FN/O_2/CO_2.
Point 7: If it cannot be guaranteed that C4-FN concentration is below the relevant OEL TWA value, use respiratory protection (consult the safety data sheet C4-FN for appropriate mask and filter). Masks and filter do not protect from lack of oxygen.
Point 8: Use self-contained breathing apparatus:

- when compliance with the occupational exposure limit values according to the safety data sheet cannot be guaranteed (for example ventilation and monitoring systems).
- when it is required to work in an environment with lack of oxygen.
- when it is required to enter indoor applications after major leakage with high concentrations of C4-FN, CO_2, CO, or by-products.

Point 9: It is recommended to monitor the substances in accordance with local safety regulations to maintain the occupational exposure limits.

4.2.4 Transport of gas

Use the locally applicable safety data sheets of the gases provided by the gas manufacturer to organize a safe and compliant transport according to local regulations. As an overview, see Table 23 below.

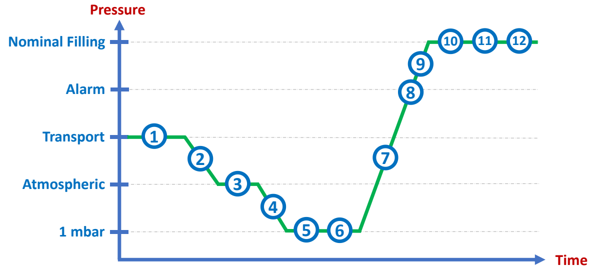
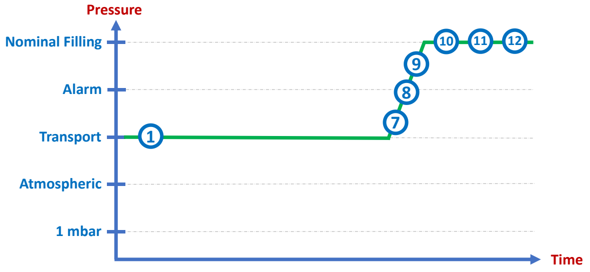
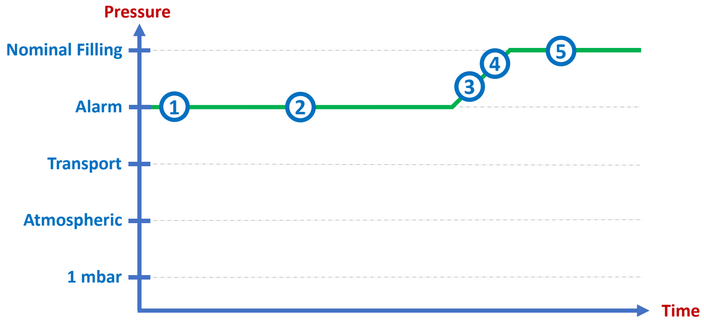
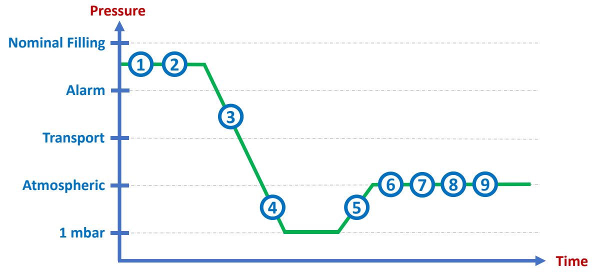
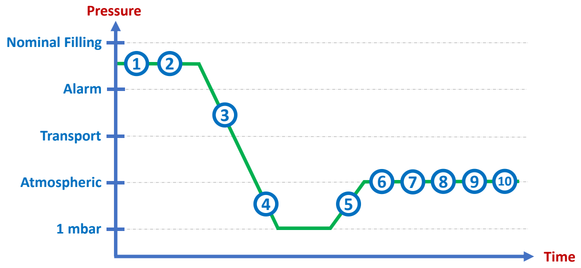
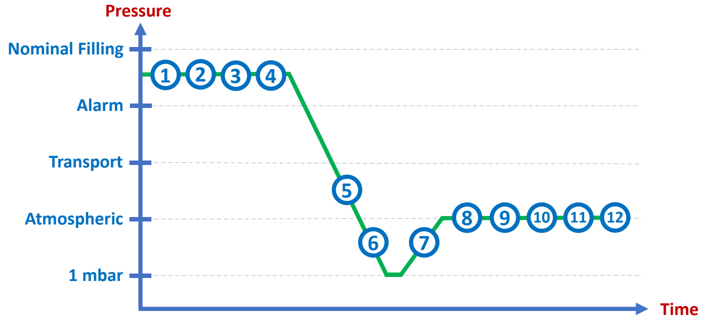
Table 23: Overview of transport-related information. For binding information, always consult the up-to-date local safety data sheet of the substances.

Gas	**UN number** **always confirm with local SDS**
C4-FN	UN 3163 Liquefied gas, n.o.s. [1]
CO_2	UN1013 Carbon Dioxide
N_2	UN 1066 Nitrogen, compressed
O_2	UN 1072 Oxygen, compressed
Non-arced C4-FN/O_2/CO_2 or Non-arced C4-FN/O_2/N_2	UN 3163 Liquefied gas, n.o.s. [1] or UN 1058 Liquefied gases, non-flammable, charged with Nitrogen, Carbon dioxide or Air
Normally arced C4-FN/O_2/CO_2 or Normally arced C4-FN/O_2/N_2	UN 3163 Liquefied gas, n.o.s. [1]
Heavily arced C4-FN/O_2/CO_2 or Heavily arced C4-FN/O_2/N_2	UN 3162 Liquefied gas, Toxic, n.o.s. [1]
[1] “Liquefied gas” is correct, even in case C4-FN / C4-FN mixture is fully gaseous during transport due to high enough temperature or low cylinder content (low density). Any gas is considered liquefied if not fully gaseous at -50 °C under normal pressure (CLP Annex I §2.5.2, Table 2.5.1 [78]). “n.o.s.” stands for “not otherwise specified”.	

4.2.5 Scenarios

The basic scenarios for gas handling are described in IEC 62271-4 Ed. 2.0 [29]. The scenarios are based on the life cycle of the high-voltage equipment and are identical whether the high-voltage equipment uses SF_6 or C4-FN mixtures. They can be visualized by a pressure diagram (see Table 24). It should be noted that the procedures outlined in IEC 62271-4 Ed. 2.0 [29] fully apply.

Table 24: Gas handling scenarios according to IEC 62271-4 Ed. 2.0 [29]

Gas handling during installation, commissioning and after repair or overhaul on site (description of steps in section 4.2.6)	
Compartments pre-filled with air or N_2	Compartments pre-filled with C4-FN mixture
	
Gas handling during normal service life (description of steps in section 4.2.7)	
	
Recovery and reclaiming of gases during maintenance, repair, overhaul or dismantling on-site (see section 4.2.8)	
Non-arced or normally arced	Heavily arced
	
End-of-life of high-voltage equipment (description of steps in section 4.2.9)	
	

4.2.6 Gas handling during installation, commissioning and after repair or overhaul on site

In this scenario, the focus is on filling the high-voltage equipment to its rated filling pressure. Note that a general procedure is outlined here. There might be high-voltage equipment specific adaptions from the OEM, e.g., for removing moisture or installing the adsorber.

Prerequisites

- Correct PPE (see Table 22)
  - PPE for non-arced or normally arced C4-FN/O_2/CO_2 (depending on condition of the gas in the compartment(s))
  - PPE for technical grade C4-FN (in case on-site mixing with gas mixing device is used, see step 7A below)
  - Wear (e.g., gloves) and activate (e.g., carry-on or room monitoring) the PPE
- Safety regulation for all gases that will be handled (single gases and gas mixtures, compare Table 21)
- Mixing machine or service cart (see Figure 40)
- Optionally vacuum pump (might be integrated in mixing machine or service car)
- Enough gas cylinders for filling the gas compartments in scope.
- Metal bellows hose with DN20 (M48x2) connection
- Gas leakage detector
- Gas compartments are either
  - Filled with air or N_2 up to 1.5 bar abs
  - Prefilled with C4-FN mixture at pressures up to typically 1.5 bar abs

Procedure: compartments filled with air or N_2

This procedure applies, when the gas compartments are filled with air or N_2 up to typically 1.5 bar abs. The steps are aligned with the steps in chapter 4 of IEC 62271-4 [29].

Step 1: Prepare gas handling equipment and documentation report

1 Prepare the documentation report.
2 Check that the gas handling equipment is working properly.
3 Make sure that the gas connections are clean and dry to avoid contamination.
4 Check the validity of the calibration of instruments subject to calibration.
5 Prepare the gas mixing and filling device.
6 CAUTION! Obey all safety regulations for the handling of gas. Put all gas cylinders on the device and connect.
7 Recover remaining air or nitrogen in the device and hoses using a gas recovery or gas service device.

Step 2: Reduce pressure to ambient pressure

1 CAUTION! Consider the permissible differential pressure at the insulator. It might be necessary to evacuate in several steps in order to keep the differential pressure below the permitted differential pressure. Obey the applicable differential pressure and safe working procedures instruction.
2 Check the labels at the gas connection to make sure that only nitrogen or air is inside the gas-insulated module.
3 Reduce the pressure to ambient pressure by connecting ventilation adaptor to the high-voltage equipment.
4 Mark the gas compartment that it has been ventilated.

Step 3: Adsorber installation

1 Install the desiccant in the high-voltage equipment according to the specifications of the OEM.

Step 4, 5, and 6: Evacuation

2 CAUTION! Consider the permissible differential pressure at the insulator. It might be necessary to evacuate in several steps in order to keep the differential pressure below the permitted differential pressure. Obey the applicable differential pressure and safe working procedures instruction.
3 Check the labels at the gas connection to make sure that only nitrogen or air is inside the gas-insulated module.
4 Connect the vacuum pump and the gas inlet of the gas-insulated module with the hose.

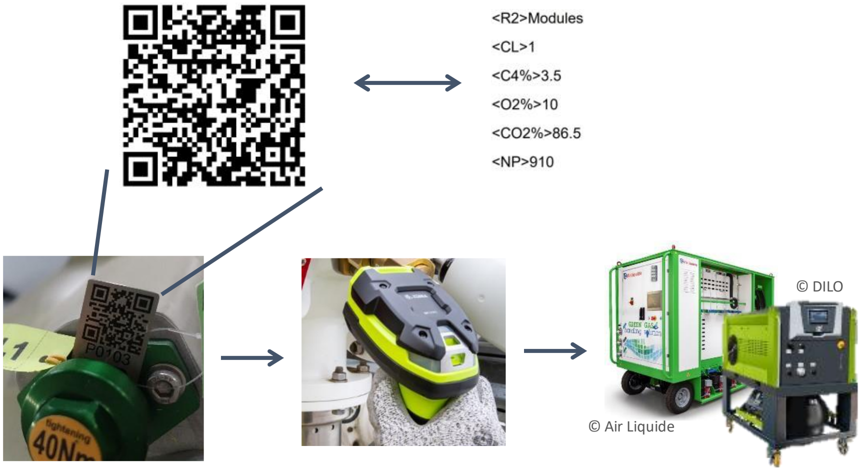
5 Evacuate nitrogen or air from the gas-insulated module to reach ≤ 1 mbar.
6 Leave the vacuum pump running for at least 30 min (Step 5 in [29]).
7 Leave the vacuum pump running for an additional period if prescribed by the high-voltage equipment manufacturer, this can be included e.g., to remove moisture from the high-voltage equipment (Step 6 in [29])
8 Switch off the vacuuming equipment.
9 Read the pressure gauge.
10 Mark the gas compartment that it has been evacuated.

*Step7A: Filling with the gas mixing and filling device **(on-site mixing)***

1 Connect separate tank for used gas according to the manual of the gas mixing and filling device.
2 Connect the gas filling device to the gas inlet connection of the gas-insulated module.
3 Set the correct gas mixture and filling pressure p_{rated} at 20 °C
  - Preferably scan the QR-code of the gas mixture that is placed at the gas connection of the module (see Figure 41).
  - Alternatively enter values manually from the rating plate of the module.
4 Consider the relation between temperature and pressure.
  - Preferably use the integrated temperature compensation of the gas filling device for the output pressure or refer to the documentation provided by the OEM (e.g., tabulated compensation table).
  - Alternatively calculate the compensated filling pressure p_{fill}:

$$\frac{p_{fill}}{\text{bar}} = \frac{\frac{\vartheta_{fill}}{°\text{C}} + 273.15\ \text{K}}{293.15\ \text{K}} \cdot \frac{p_{rated}}{\text{bar}}$$

  - Filling pressure tolerances at 20 °C, 0 / +0.1 bar.
5 CAUTION! Consider the permissible differential pressure at the insulator. It might be necessary to fill in several steps in order to keep the differential pressure below the permitted differential pressure. Obey the applicable differential pressure and safe working procedures instruction. Fill the gas-insulated module to the desired filling pressure.
6 When the gas filling device has confirmed that the filling procedure is completed, disconnect the gas filling device from the gas-insulated module.
  - Filling of another compartment: Continue with connecting the device to the gas compartment.
  - No further gas compartment needs to be filled: Stop the gas filling device according to the operating instructions, which includes closing all gas valves in the defined sequence and recovering the remaining gas from the gas filling device including hose.
7 Record the identity of the gas compartment, the final filling pressure, the ambient temperature, and the date for further reference.
8 Measure the pressure directly at the gas inlet connection of the gas-insulated module using a manometer (the pressure value in the gas mixing and filling device serves as reference only).
9 Measure the gas quality directly after filling (checking the gas quality).
10 Mark the filling status of the gas-compartment clearly visible at the gas inlet connection (filling pressure, type of gas, date).



Gas inlet connection with gas ID

Gas mixing and filling device or gas service cart

Figure 41: Usage of QR codes for filling pressure and gas mixture identification

Step 7B: Filling with ***liquefied premixed gas***

1. Check that the cylinder with the premixed gas contains the correct mixture according to the rating plate of the gas-insulated module.
2. Optional: Before filling, homogenize the premixed gas (according to specifications of the gas service cart manufacturer and in line with the OEM recommendations).
3. Connect the gas service device to the gas inlet connection of the gas-insulated module.
4. Set the filling pressure p_{rated} at 20 °C
   - Enter value manually from the rating plate of the module
   - Alternatively scan the QR-code of the gas mixture that is placed at the gas connection of the module (see Figure 41).
5. Consider the relation between temperature and pressure.
   - Refer to the documentation provided by the OEM (e.g., tabulated compensation table).
   - Alternatively calculate the compensated filling pressure p_{fill}:

$$\frac{p_{fill}}{\text{bar}} = \frac{\frac{\vartheta_{fill}}{^\circ\text{C}} + 273.15\ \text{K}}{293.15\ \text{K}} \cdot \frac{p_{rated}}{\text{bar}}$$

   - Filling pressure tolerances at 20 °C, 0 / + 0.1 bar.
6. CAUTION! Consider the permissible differential pressure at the insulator. It might be necessary to fill in several steps in order to keep the differential pressure below the permitted differential pressure. Obey the applicable differential pressure and safe working procedures instruction. Fill the gas-insulated module to the desired filling pressure.
7. Record the identity of the gas compartment, the final filling pressure, the ambient temperature, and the date for further reference.
8. Measure the pressure directly at the gas inlet connection of the gas-insulated module using a manometer (the pressure value in the gas filling device serves as reference only).
9. Measure the gas quality directly after filling (checking the gas quality).
10. Mark the filling status of the gas-compartment clearly visible at the gas inlet connection (filling pressure, type of gas, date).

Figure 42: Gas Handling during filling of a 420 kV GIS substation with a pre-mixed cylinder – Sellindge, UK [38]

Figure 43: Gas quality routine check of a recently prepared gaseous premixed mixture using a mixing cart

Step 7C: Filling with ***gaseous premixed gas***

1. Check that the cylinder with the premixed gas contains the correct mixture according to the rating plate of the gas-insulated module.
2. Check that the requirements defined by the OEM for the use of the identified gaseous premixed gas are met, especially regarding the storage / ambient conditions (to ensure the gas is homogeneous).
3. Connect the gas cylinder to the gas inlet connection of the gas-insulated module by using the equipment recommended by the OEM. Typically, the gas cylinder can be connected directly using a pressure reducer or to a compressor.
4. Set the filling pressure p_{rated} at 20 °C
    - Read the value from the rating plate of the module
    - Alternatively scan the QR-code of the gas mixture that is placed at the gas connection of the module (see Figure 41).
5. Consider the relation between temperature and pressure.
    - Refer to the documentation provided by the OEM (e.g., tabulated compensation table).
    - Alternatively calculate the compensated filling pressure p_{fill}:

$$\frac{p_{fill}}{\text{bar}} = \frac{\frac{\vartheta_{fill}}{°\text{C}} + 273.15\ \text{K}}{293.15\ \text{K}} \cdot \frac{p_{rated}}{\text{bar}}$$

    - When using pressure reducers, the setting of the pressure is usually done with the output closed or disconnected. Please refer to the gas equipment instructions.
    - Filling pressure tolerances at 20 °C, 0 / + 0.1 bar.
6. CAUTION! Consider the permissible differential pressure at the insulator. It might be necessary to fill in several steps in order to keep the differential pressure below the permitted differential pressure. Obey the applicable differential pressure and safe working procedures instruction. Fill the gas-insulated module to the desired filling pressure.
7. Record the identity of the gas compartment, the final filling pressure, the ambient temperature, and the date for further reference.
8. Measure the pressure directly at the gas inlet connection of the gas-insulated module using a manometer (the pressure value in the gas filling device serves as reference only).
9. Measure the gas quality directly after filling (checking the gas quality).
10. Mark the filling status of the gas-compartment clearly visible at the gas inlet connection (filling pressure, type of gas, date).

Figure 44: Filling of a GIL with C4-FN mixture during a retrofill in 2021

Step 8: Density monitor calibration

1. This optional step can be done according to the instruction of the high-voltage equipment or density monitor manufacturer.

Step 9: Functional test of density monitor

1. Check the function of the density monitor. This operation can be performed during the filling operation and must not be considered as a calibration. Obey the operating instructions of the gas-insulated application.

Step 10: Tightness Inspection

Generally, for C4-FN mixtures, the C4-FN itself is used as a tracer gas. Below, an instruction for an on-site tightness test using a sniffing device is described.

1. NOTICE! Make sure that the probe of the leakage detector does not become dirty or clogged. As the insulating gas is heavier than air, testing must start at the top of the gas-insulated high-voltage equipment and continue down the enclosures towards the floor.
2. Scan all relevant connections slowly with the sniffer probe. Areas: flange joints, equipment on enclosure, compensator modules, pressure relief-device, gas density monitors:

   Speed: maximum 10 mm/s

   Distance: maximum 5 mm

   - Alarm signal: retrace the previously tested area. If the alarm signals again, move the probe away from the potential leakage location until the alarm expires. Repeat the procedure of moving away and back again to the suspected leakage location three times.
   - Alarm signal (repeated): put on safety glasses and flush with compressed air for at least 10 s. If the use of compressed air is not possible, a vacuum cleaner can be used. Wait for at least 10 minutes and repeat the test.
   - Alarm signal (repeated): A possible leakage has been detected. Mark the affected module and cordon off the leakage area.

Step 11 and 12: Quality Checking and Documentation

1. Prepare and check the measuring equipment. Check for proper maintenance and calibration. Measurement unit of gas concentration: %mol. Measurement unit of humidity: as per the OEM instructions (e.g., frost point or ppmv). It may be required to change the settings of the measurement device.
2. Connect the adapter to the gas hose of the measurement device.
3. First use: evacuate the hose.
4. Connect the gas measurement device with the adapter to the gas inlet connection of the module.
5. Start the automatic measuring procedure of the gas quality.
6. Read the values and compare with tolerances provided by the OEM (see section 2.6).
   - Out of tolerance: repeat measuring.
   - Out of tolerance (repeated): more investigations are necessary.
7. Record at least the gas compartment, the functionality of the pressure/density sensor, the humidity content, the C4-FN content, the oxygen content, ambient temperature (measured 1 m above ground level in the shade) and date for reference (Step 12 in [29]).
8. Pump the gas back after the measurement.
9. Disconnect the gas measurement device, hose, and adapter. Keep for future reuse.

Procedure: compartments prefilled with C4-FN mixture

In this case, adsorbers have already been installed and the compartments were prefilled with C4-FN mixture, typically up to 1.5 bar abs. Essentially, the gas handling starts at step 7 of the previous procedure and is otherwise identical.

Figure 45: Example of step 11 - Gas quality check

Note on alternative filling methods described in step 7A, 7B, and 7C

In principle, we can distinguish between two common practices for the preparation of the required C4-FN mixture (see Figure 46):

- On-site mixing (procedure described from user perspective in Step 7A above)
- Off-site mixing (procedure described from user perspective in Step 7B or 7C above).

Each practice has its specific characteristics, that can make it more preferred for a certain application or project. It is important to note, that the high-voltage equipment is compatible with both practices and that the filling method has no influence on the gas quality in the high-voltage equipment [88].

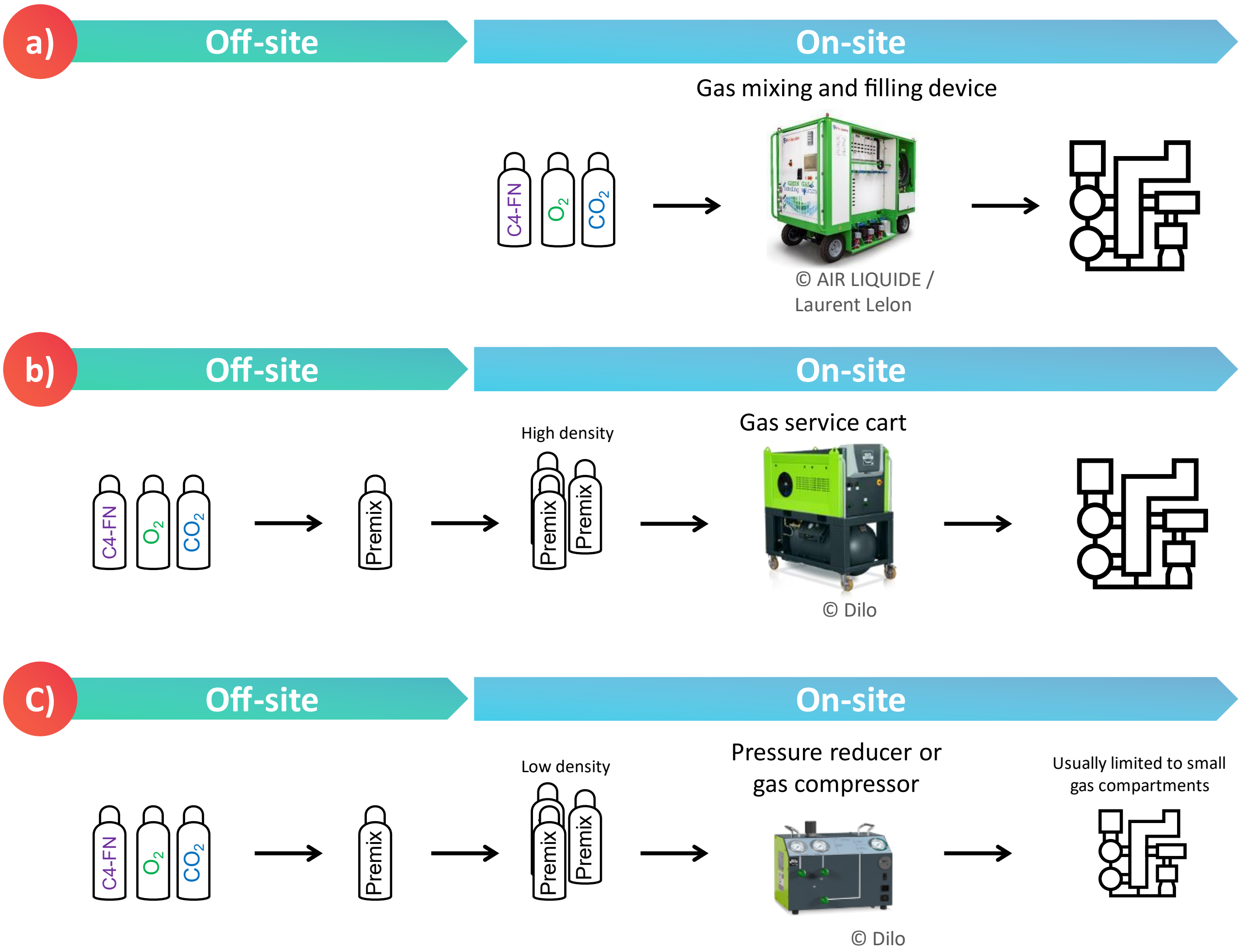


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Figure 46: Comparison of on-site and off-site mixing

4.2.7 Gas handling during normal service life

In this scenario, the focus is on filling the high-voltage equipment to its (rated) filling pressure, typically after the density monitors have indicated that the pressure / density has fallen to alarm level. In case the pressure drop is caused by abnormal leakage, e.g., a damaged sealing system, this defect should first be repaired (see section 4.2.8) before the topping-up is performed to avoid further leakages.

Prerequisites

- Correct PPE (see Table 22)
  - PPE for non-arced or normally arced C4-FN/O_2/CO_2 (depending on condition of gas in compartment).
  - PPE for C4-FN (in case on-site mixing with gas mixing device is used, see step 7A below).
  - Wear (e.g., gloves) and activate (e.g., room monitoring) the PPE.
- Safety regulation for all gases that will be handled (single gases and gas mixtures, compare Table 21)
- Mixing machine or service cart (see Figure 40).
- Enough gas cylinders for filling the gas compartments in scope.
- Metal bellows hose with DN20 (M48x2) connection.

Procedure

Step 1: Identify nature of pressure / density change

1 Detect if the pressure change is caused by abnormal leakage e.g., a damaged sealing system. Suitable measures include visual inspection or tightness inspection as described in section 4.2.6.
- Abnormal leakage detected: initiate repair (see section 4.2.8).
- No abnormal leakage detected: continue with next step.

Step 2: Prepare gas handling equipment and documentation report

1 Identical to step 1 in section 4.2.6.

Step 3: Topping-up

1 Identical to step 7 in section 4.2.6.
2 Additional option premixed gas in gaseous container.
3 Please consider that the topping-up is always performed with the original gas mixture as defined in the high-voltage equipment rating. A “corrective” mixture is not necessary (see section 2.7.2).

Step 4 Functional test of density monitor

4 Identical to step 9 in section 4.2.6.

Step 5 Quality Checking

5 Identical to step 11 and 12 in section 4.2.6.

4.2.8 Recovery and reclaiming of gases during maintenance, repair, overhaul or dismantling on-site

Prerequisites

- State of used gas in the compartment must be known.
- Correct PPE (see Table 22):
  - PPE for non-arced, normally arced, or heavily arced C4-FN/O_2/CO_2 (depending on condition of gas in compartment).
  - wear (e.g., gloves) and activate (e.g., room monitoring) the PPE.
- Safety regulation for all gases that will be handled (single gases and gas mixtures, compare section 4.2.3).
- Calcium gluconate gel as a remedy after washing for fluoride acid on skin.
- Gas recovery device or gas service device (see Figure 40).
- Optionally vacuum pump (might be integrated in recovery device or service cart).
- Gas storage container.
- Metal bellows hose with DN20 (M48x2) connection.
- Project-specific work procedure.

Procedure for non-arced and normally arced gas

Step 1: Prepare gas handling equipment and documentation report

1 Prepare the documentation report
2 Activate the portable gas monitors. Constantly monitor the air adjacent to the workspace.
- In case of gas alarm: Stop any work. Inform all present. Leave the workspace immediately.

Step 2: Connect external pre filters (Optional)

1 In case the operating manual for the gas recovery or gas service device recommends external prefilters (e.g., for normally or heavily arced gas), connect it accordingly.

Step 3 and 4: Recovery of gas and minimization of residual content of gas

2 Connect the gas outlet of the gas recovery device to the storage container for used gas.
3 Connect the gas inlet of the gas recovery device to the gas inlet connection of the gas-insulated module.
4 Recover the insulating gas from the gas compartment to the container for used gas to the final pressure < 1 mbar (Step 4 in [29]).
5 Close the valve of the gas tank.
6 Release pressure on the connecting pipe and disconnect the connecting pipe between the gas recovery device and the gas tank.
7 Disconnect the gas inlet of the gas recovery device to the gas inlet connection of the gas- insulated module.

Step 5: Flood with air

1 Flood the compartment with air and wait until the pressure inside equalize with surrounding pressure.

Step 6: Open the gas compartment

1 CAUTION! Make sure to wear the appropriate personal protective equipment.
2 For high-voltage equipment that has been filled with a C4-FN mixture for more than four weeks, there is a risk of vapors resulting from the sublimation of solid by-products. Wear PPE for single-gas C4-FN (technical grade or suitable for reuse) when opening the gas compartment.

Step 7 and Step 8: Remove solid by products and adsorbers (if present) and neutralize (if required)

1 CAUTION! Make sure to wear the appropriate personal protective equipment.
2 Remove loose dust with a suitable vacuum cleaner. Use class H vacuum cleaners, approved for dusts which are a health hazard.
3 Remove adhered dust with a clean, dry cloth.
4 Remove and neutralize contaminated parts from the gas compartment as quickly as possible.
5 Collect contaminated parts, such as vacuum cleaner bags, cloths, respiratory filters, disposable clothing and the adsorber material from the gas compartments and from the filter in the recovery device. Store, transport and dispose of according to local and international regulations.

- Parts collected in hard plastic containers according to UN 1H2: store, transport, and dispose of neutralized (pH 7) or non-neutralized parts.
- Removed parts which were once contaminated: if they have been cleaned with a vacuum cleaner or cloths, dispose them as normal waste (for example contact tubes, contact fingers, insulation materials)

Step 9: Documentation

1 Clearly indicate on the storage container which components of uses gas are inside the container.

Procedure for heavily arced gas

Handling heavily arced gas can be necessary:

- In laboratory applications, where the limit of the high-voltage equipment was tested.
- In case the high-voltage equipment has failed in service (internal arc).

It is especially important that the appropriate PPE for heavily arced gas is worn (see Table 22).

Steps 1 to 5

1 Ensure that appropriate PPE for heavily arced C4-FN/O_2/CO_2 is worn and activated (see Table 22).
2 Otherwise, Steps 1 to 5 are identical to the procedure described in Step 1 to 5 for non-arced and normally arced gas above.

Step 6 Settling down of solid decomposition products

1 Wait 1 hour after flooding with air to allow solid decomposition products that have been stirred up during flooding with air. It is possible to shorten the waiting time if workers are protected against exposure to stirred up solid decomposition products (PPE, suction system, etc.).

Step 7 Open the gas compartment

1 CAUTION! Make sure to wear the appropriate personal protective equipment.

Step 8 and Step 9: Remove solid by products, adsorbers and removable parts, additionally neutralization

1 CAUTION! Make sure to wear the appropriate personal protective equipment.
2 Remove loose dust with a suitable vacuum cleaner. Use class H vacuum cleaners, approved for dusts which are a health hazard.
3 Remove adhered dust with a clean, dry cloth.
4 Remove and neutralize contaminated parts from the gas compartment as quickly as possible.
5 Collect contaminated parts, such as vacuum cleaner bags, cloths, respiratory filters, disposable clothing and the adsorber material from the gas compartments and from the filter in the recovery device. Store, transport and dispose of according to local and international regulations.
  - Parts collected in hard plastic containers according to UN 1H2: store, transport, and dispose of neutralized (pH 7) or non-neutralized parts.
  - Removed parts which were once contaminated: if they have been cleaned with a vacuum cleaner or cloths, dispose them as normal waste (for example contact tubes, contact fingers, insulation materials)

Step 10: Documentation

1 Clearly indicate on the storage container that it contains parts submitted to heavily arced gas

In case an internal arc happened, and the pressure-relief device opened, the procedure can start at Step 8.

4.2.9 End-of-life of high-voltage equipment

For high-voltage equipment with C4-FN mixtures, to prepare the dismantling, the steps in section 4.2.8 shall be used:

- In case the high-voltage equipment has operated without failure until the end, the procedure in section 4.2.8 for non-arced or normally arced gas shall be followed
- In case the high-voltage equipment failed with an internal arc or excessive number of short-circuit switching operations in a circuit-breaker, the procedure in section 4.2.8 for heavily arced gas shall be followed.

This is a simplification from IEC 62271-4 Ed. 2.0 which also cover closed pressure system as used in medium voltage applications.

After completing the procedures according to section 4.2.8, send the gas storage container to a company which provides the appropriate recycling and disposal service.

Gas recycling services are available for C4-FN mixtures. Depending on the gas condition C4-FN can be reclaimed and reused to prepare new mixtures [89].

4.3 Emergency procedure in case of pressure relief device opening

The rare event of an internal arc fault or external fire may cause the activation of a pressure relief device (PRD, e.g., bursting disk) as a protection of the equipment against overpressures. The relief of pressure due to internal arc fault releases hot heavily decomposed gas which may cause burns, releases solid and gaseous decomposition products which have poisonous and corrosive properties.

However, the concentration of decomposition products in the gas is diluted by contact with the ambient air after the PRD operated.

The heavily arced gas contains among other substances the following decomposition products (see the SDS for heavily arced gas for more details):

- Carbon monoxide (CO)
  Carbon monoxide is the dominant substance regarding the overall toxicity of heavily arced gas. When released from the gas compartment, carbon monoxide quickly dilutes with ambient air. The carbon monoxide concentration in the surrounding air may exceed the long-term occupational exposure limits but remains far below acute toxic concentrations. We recommend monitoring the CO concentration by mobile or fixed installed CO detectors.

- Carbonyl fluoride (COF_2)
  If in contact with air humidity of the room atmosphere, carbonyl fluoride very quickly reacts to carbon dioxide (CO_2) and hydrogen fluoride (HF). Thus, after a few minutes, carbonyl fluoride will be present only in very low concentrations.
- Hydrogen fluoride (HF)
  Hydrogen fluoride remains even in small concentration a toxic substance which can lead to severe health problems in case of long-term contact. In contact with humidity, hydrogen fluoride will form hydrofluoric acid and then reacts with metals or inorganic materials to very low toxic substances. If HF is quickly removed from the room atmosphere by vigorous ventilation, no long-term risk has to be considered.

  WARNING! In case of skin contact with hydrofluoric acid immediately wash the affected part with cool running water. Apply calcium gluconate gel as a remedy. Seek for professional medical advice.

In the case of a major error during a gas handling operation that leads to the opening of the PRD of one gas compartment, important quantity of gas will be released in the atmosphere. In such case, the condition of the gas is the one that was in the gas compartment prior to the PRD activation. Even with the case of non-arced gases, this situation presents risks for the operators due to the large quantities of C4-FN and CO_2 released in the atmosphere which have defined short-term exposure limits but also as it replaces breathable air. Therefore, the same procedure is recommended as for the case of the opening of a PRD due to an internal arc fault.

Emergency procedure in the case of the activation of a pressure relief device:

1. Leave the hazardous area immediately.
2. Rescue persons.
3. Shut down the system from outside.
4. If necessary, search for medical help.
5. Follow the local emergency checklist.
6. Inform the responsible persons for gas handling.
7. Open the doors and ensure vigorous ventilation.
8. Wait for instructions from the responsible persons.
9. If the safety of the room atmosphere cannot be established, use the appropriate personal protective equipment (for example a self-contained breathing equipment and carbon monoxide detector).

Re-enter the hazardous area only after authorization from the responsible of the area.

To dismantle high-voltage equipment where a burst disk has opened, please follow the instructions given in 4.2.8 and 4.2.9. Cleaning of the area may be necessary in the case of an internal arc fault to completely remove solid by-products. The procedure described to clean a gas compartment are applicable (see section 4.2.8).

5 Conclusion

Over the last few decades, SF_6 has been the standard for high-voltage equipment manufacturers and users due to its excellent properties for state-of-the-art reliable, scalable, and compact high-voltage equipment. However, SF_6 is the most potent GHG and despite years of design improvements, the forecasted demand for power supply and associated networks makes SF_6 a growing contributor to climate change and highlights its incompatibility with net-zero targets.

Users and manufacturers are striving to reduce the carbon footprint of their high-voltage equipment, while retaining the technical benefits of SF_6 technology. The last few years have seen unprecedented development of SF_6 alternatives. C4-FN technology has proved to be a quick and efficient solution to replace SF_6 for switching applications up to 420 kV. Since the first installations in 2017, many products are successfully in service, and more projects are imminent. C4-FN mixtures have the ability to replace SF_6 in new and recent installations within the power transmission and distribution range, where the largest SF_6 quantity is banked today, and development continues to cover the full range and ratings of high-voltage equipment.

This handbook serves as a technical reference for users of C4-FN technology. Relevant points like thermodynamic properties, including quantitative models for dew temperature, density, and pressure, as well as quality and purity requirements are included. The harmonization of such data ensures maximum efficiency and interoperability for all suppliers and users working with C4-FN mixtures by setting a common ground. It integrates itself with the continuation of past and ongoing work within international working groups from CIGRE, IEC, and IEEE.

For practical gas handling, clear definitions of the potentially encountered gas conditions are given and associated with environment, health, and safety assessments. The provided gas conditions are based on IEC categories and classified in accordance with the CLP regulation. This enables the harmonization of safety data sheets and recommendations for gas handling. Guidelines for accurate and fair comparisons of environmental impacts are also provided. The handbook also shows the significant carbon footprint reduction achieved by using C4-FN high-voltage equipment and unlocks comparisons of products from various sources.

Clear recommendations are given on how to translate the basic safety information into efficient HSE gas handling procedures, to cover all practical gas handling scenarios laid out in IEC 62271-4 [29]. It facilitates personal training and ensures best practices for all equipment using C4-FN mixtures.

Any feedback on the handbook is welcomed and can be addressed directly to the authors.

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6 Annex

6.1 Dew curves: coefficients for Wagner equation for arbitrary C4-FN/O$_2$/CO$_2$ mixtures

The coefficients $n_1 \dots n_4$ for Eq. (3) can be calculated for any given C4-FN/O$_2$/CO$_2$ mixture in the validity range using Eq. (10) and values in Table 25 to Table 28, describing linear 3rd and 5th order polynomes to consider the parameter dependance on C4-FN (5th order) and O$_2$ (3rd order) content

$$n_i = f(x_{\text{C4-FN}}, x_{\text{O2}})$$

$$n_i = \sum_{j=0}^{5} \left\{ \left(\sum_{k=0}^{3} a_{i,j,k} \cdot (100 \cdot x_{\text{O2}})^k \right) \cdot (100 \cdot x_{\text{C4-FN}})^j \right\} \tag{10}$$

Table 25: Matrix to determine mixture dependent coefficient n_1 by use of Eq. (10). Coefficient n_1 can then be used in Wagner equation (3) to determine dew curve of this specific C4-FN/O$_2$/CO$_2$ mixture.

$a_{1,j,k}$	j=5	j=4	j=3	j=2	j=1	j=0
k=3	-1.0353E-08	2.0989E-07	-1.4709E-06	1.0332E-05	-1.0150E-04	3.8681E-04
k=2	-2.8754E-07	5.7416E-06	-1.3100E-05	-3.2206E-04	1.4529E-03	2.4346E-03
k=1	-1.9621E-05	4.8513E-04	-3.5623E-03	5.4232E-03	-4.1372E-02	8.2980E-01
k=0	-3.1337E-04	8.5371E-03	-6.2491E-02	-5.8246E-02	-2.7256E+00	-2.6258E+01

Table 26: Matrix to determine mixture dependent coefficient n_2 by use of Eq. (10). Coefficient n_2 can then be used in Wagner equation (3) to determine dew curve of this specific C4-FN/O$_2$/CO$_2$ mixture.

$a_{2,j,k}$	j=5	j=4	j=3	j=2	j=1	j=0
k=3	5.2587E-08	-1.1759E-06	9.4534E-06	-5.5152E-05	4.0086E-04	-1.4368E-03
k=2	1.1881E-06	-2.5343E-05	9.3749E-05	1.0461E-03	-5.9102E-03	-5.8507E-03
k=1	8.3291E-05	-2.1709E-03	1.7969E-02	-4.3593E-02	1.4461E-01	-2.6224E+00
k=0	1.0660E-03	-3.2332E-02	2.9429E-01	-3.6885E-01	7.2982E+00	5.8340E+01

Table 27: Matrix to determine mixture dependent coefficient n_3 by use of Eq. (10). Coefficient n_3 can then be used in Wagner equation (3) to determine dew curve of this specific C4-FN/O$_2$/CO$_2$ mixture.

$a_{3,j,k}$	j=5	j=4	j=3	j=2	j=1	j=0
k=3	-6.0191E-07	1.4861E-05	-1.3502E-04	7.0724E-04	-3.5119E-03	1.0911E-02
k=2	-8.5053E-06	1.9550E-04	-9.5104E-04	-6.2580E-03	4.7206E-02	9.9875E-03
k=1	-5.6214E-04	1.6004E-02	-1.5397E-01	5.4287E-01	-1.3915E+00	1.5586E+01
k=0	4.5680E-03	-7.8742E-02	4.3623E-01	-3.2025E+00	-4.0366E+01	-3.1847E+02

Table 28: Matrix to determine mixture dependent coefficient n_4 by use of Eq. (10). Coefficient n_4 can then be used in Wagner equation (3) to determine dew curve of this specific C4-FN/O_2/CO_2 mixture.

$a_{4,j,k}$	*j*=5	*j*=4	*j*=3	*j*=2	*j*=1	*j*=0
***k*=3**	1.5525E-06	-3.9812E-05	3.7775E-04	-1.9283E-03	8.0671E-03	-2.2522E-02
***k*=2**	5.7068E-06	-9.0352E-05	-9.8671E-04	2.4872E-02	-1.2022E-01	1.3709E-02
***k*=1**	9.3519E-04	-2.7713E-02	2.8029E-01	-1.0774E+00	2.9551E+00	-2.9442E+01
***k*=0**	-2.1116E-02	5.0490E-01	-4.4996E+00	2.2258E+01	4.6451E+01	5.8611E+02

6.2 Coefficients for Virial equation for arbitrary C4-FN/O_2/CO_2 mixtures

For arbitrary C4-FN/O_2/CO_2 mixtures, the coefficients b_i for calculation of virial coefficient using Eq. (7) can be calculated using the Eq. (11) and Table 29:

$$b_i = d_{i0}(1 - d_{i1} \cdot x_{\mathrm{O2}}) + d_{i2}(1 - d_{i3} \cdot x_{\mathrm{O2}}) \cdot x_{\mathrm{C4-FN}} + \ d_4 \cdot x^2_{\mathrm{C4-FN}} \qquad (11)$$

Table 29: Coefficients $d_{i,j}$ for use in Eq. (11) to determine virial coefficient *B* of arbitrary C4-FN/O_2/CO_2 mixtures with Eq. (7)

$d_{i,j}$	*j*=0	*j*=1	*j*=2	*j*=3	*j*=4
***i*=0**	-3.0741E+03	-1.3446E+00	-1.0925E+04	-7.7611E-01	-3.6401E+04
***i*=1**	3.2670E+01	-1.3446E+00	1.2063E+02	-7.7611E-01	4.4106E+02
***i*=2**	-1.5004E-01	-1.3446E+00	-5.6629E-01	-7.7611E-01	-2.1907E+00
***i*=3**	3.5730E-04	-1.3446E+00	1.3673E-03	-7.7611E-01	5.4921E-03
***i*=4**	-4.3282E-07	-1.3446E+00	-1.6723E-06	-7.7611E-01	-6.9024E-06
***i*=5**	2.1139E-10	-1.3446E+00	8.2270E-10	-7.7611E-01	3.4661E-09

Change history

Revision	Date	Change
1.0	09.05.2023	Initial version.
1.1	21.06.2023	Typo of ATE value in Table 18 corrected. Information on the gas composition added to Figure 16. Authors' CV updated. Minor improvements in wording throughout the document.

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