

TECHNICAL GUIDE TO VALIDATE ALTERNATIVE GAS FOR SF6 IN ELECTRICAL EQUIPMENT

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This guide reflects the best knowledge of industry experts from all over Europe and the state of the art at the moment of its publication. The principles contained in this guide are however not legally binding. A binding interpretation of EU legislation is the exclusive competence of the European Court of Justice. T&D Europe also recommends to producers, when applying this Guide and its principles, to always refer to the national legislation of the Member States they are dealing with.

FOREWORD

T&D Europe, the first European Association of the Electricity Transmission and Distribution Equipment and Services Industry, aims to promote the common technical, industrial economic, environmental and political interests of the European electricity transmission and distribution manufacturing, and product-derived solutions industry.

T&D Europe is a driver for advanced solutions and technologies in the field of electricity networks, encouraging an energy-efficient, cost-effective environmentally friendly infrastructure.

In this framework, T&D Europe proposes this technical guide intended to specify the tests, analyses, and criteria necessary to validate a gas ⁽¹⁾ as an alternative to SF6 in electrical equipment.

⁽¹⁾ Gas refers to a pure gas or a gas mixture

1 Scope

The purpose of this guide is to provide manufacturers of electrical equipment with a method to validate a new pure gas or gas mixture as an alternative to SF6. This guide is not dealing with environmental life cycle assessment, which should be also considered by the manufacturers selecting an alternative gas.

The guide aims to define, which characteristics of the gas should be taken into account and to specify the tests, analyses and criteria required to ensure the performance of the electrical equipment throughout its service life, as well as to assess the health and safety risks posed to people who may come into contact with the gas, the environmental impact and the fire hazards.

The results should be documented and communicated to the user of electrical equipment on request.

It is assumed that electrical equipment is tested according to applicable standards.

2 Normative references

IEC 60068-2-17, Basic environmental testing procedures – part 2 – Tests – Test Q: sealing
IEC 60270, High-voltage test techniques – Partial discharge measurements
IEC 62271-1, High-voltage switchgear and controlgear – Part 1: Common specifications
IEC 62271-100, High-voltage switchgear and controlgear – Part 100: Alternating-current circuit-breakers
IEC 62271-102, High-voltage switchgear and controlgear – Part 102: Alternating current disconnectors and earthing switches
IEC 62271-103, High-voltage switchgear and controlgear – Part 103: Switches for rated voltages above 1 kV up to and including 52 kV

IEC 62271-105, High-voltage switchgear and controlgear – Part 105: Alternating current switch-fuse combinations for rated voltages above 1 kV up to and including 52 kV
IEC 62271-200, High-voltage switchgear and controlgear – Part 200: AC metal enclosed switchgear and controlgear for rated voltages above 1kV and up to and including 52 kV
IEC 62271-203, High-voltage switchgear and controlgear – Part 203: Gas-insulated metal-enclosed switchgear for rated voltages above 52 kV
IEC/IEEE 62271-37-013, High-voltage switchgear and controlgear – Part 37-013: Alternating-current generator circuit-breakers
IEC/TR 62271-4, Use and handling of sulphur hexafluoride
IEC 60376, Specification of technical grade sulphur hexafluoride (SF6) for use in electrical equipment
IEC 60480, Guidelines for the checking and treatment of sulphur hexafluoride (SF6) taken from electrical equipment and specification for its re-use

3 Terms and definitions

3.1 Pure gas:

All of the identical loosely bonded atoms or molecules, which occupy the volume available.

3.2 Gas mixture:

Homogeneous mix of more than one pure gas.

3.3 Partial pressure P_i :

The partial pressure of a pure gas i being part of a gas mixture with a total pressure P_T is defined as the pressure P_i that would be exerted by the molecules of gas i if it occupied the same volume on its own at the same temperature.

3.4 Total pressure P_T :

The pressure of a gas mixture with all its pure gases at their defined content. In an ideal gas mixture, the total pressure is the sum of the partial pressures of all the pure gases in the mixture.

3.5 Minimum functional density:

3.5.1 Electrical equipment filled with one pure gas

The manufacturer should define the minimum functional density of the pure gas. The minimum functional density of the pure gas is the density of the pure gas at which and above which the rated insulation and/or switching characteristics of the electrical equipment are

maintained. The minimum functional density of the pure gas must be equal to or smaller than the saturated vapour density of the pure gas at the minimum ambient air temperature for operation.

3.5.2 Electrical equipment filled with a gas mixture

The minimum functional density of the gas mixture is the sum of the minimum functional densities of each pure gas, being part of the gas mixture. The manufacturer should define the minimum functional density of each pure gas, being part of the gas mixture.

The minimum functional density at $T_{amb\ min}$ of each pure gas being part of the gas mixture should be defined by calculation or by analyses after sampling at $T_{amb\ min}$:

- If gases don't interact together, the minimum functional density of each gas in the mixture at $T_{amb\ min}$ is the density of each gas taken separately at $T_{amb\ min}$.

- If gases interact together (see annex A), the functional density of each gas in the mixture is lower than the functional density of each gas taken separately. In this case, the gases analyses of sampling taken at $T_{amb\ min}$ enable to define the minimal functional density

The minimum functional density of the gas mixture is the density of the gas mixture at which and above which the rated insulation and/or switching characteristics of the electrical equipment are maintained. The minimum functional density of each pure gas, being part of the gas mixture must be equal to or smaller than the saturated vapour density of that pure gas at the minimum ambient air temperature for operation.

3.6 GWP:

The GWP (global warming potential) is the ratio of the warming caused by a substance to the warming caused by a similar mass of carbon dioxide. Thus, the GWP of CO_2 is defined to be 1.0.

3.7 ODP:

The ODP (ozone depletion potential) is the ratio of the impact on ozone of a chemical compared to the impact of a similar mass of CFC-11. Thus, the ODP of CFC-11 is defined to be 1.0.

3.8 $T_{amb\ min}$:

Minimum ambient air temperature for operation.

3.9 $T_{amb\ max}$:

Maximum ambient air temperature for operation.

3.10 $T_{gas\ max}$:

Maximum temperature that the pure gas or gas mixture can reach locally during operation at $T_{amb\ max}$ and at the rated continuous current; in the absence of measurement, the default value is 115 °C.

3.11 $T_{gas\ max\ average}$:

Average temperature that the pure gas or the gas mixture can reach during operation at $T_{amb\ max}$ and at the rated continuous current; this average temperature can be calculated from the measurement of the pressure.

3.12 $T_{storage\ min}$:

Minimum temperature at which the electrical equipment is stored or transported.

3.13 $T_{storage\ max}$:

Maximum temperature at which the electrical equipment is stored or transported.

3.14 LC50:

LC50 (50% lethal concentration) means that the concentration of a chemical in air or a chemical in water causes the death of 50% (one half) of a group of test animals within a specified time.

3.15 TLV-TWA:

The **TLV-TWA (threshold limit value - time weighted average)** represents the average concentration of a chemical substance to which workers can be exposed during a 40-hour week over a working lifetime without adversely affecting their health.

3.16 CMR substances

Carcinogenic, mutagenic and reprotoxic chemicals, abbreviated to CMR, make up the first and most toxic category of the toxicity classes into which hazardous chemicals can be subdivided, according to EU legislation. Carcinogenic chemicals can cause or promote cancers. Mutagenic chemicals can cause genetic mutations. Reprotoxic chemicals can damage the reproductive process.

3.17 NOAEL (no observed adverse effect level):

The highest tested dose or concentration of a substance at which no such adverse effect is found in exposed test organisms where higher doses or concentrations resulted in an adverse effect.

Source: EPA glossary for GWP, ODP

Source: ec.europa.eu for LC50, CMR substances

4 Legal requirements and regulations

The equipment manufacturer and users must identify and implement the applicable legal requirements and regulations (for example, the European REACH directive) and review them regularly.

This guide is not a substitute for these requirements.

5 Characteristics of the pure gas/gases and the gas mixture

The electrical equipment can be filled with a pure gas or a gas mixture. The characteristics of the pure gas or the pure gases in the mixture comprise the physical and chemical properties and their impact on environment and health. These characteristics should be considered separately from those of the gas mixture. Similar to SF₆, the characteristics of which are given in Annex B, the basic characteristics of the pure gas/gases and the gas mixture should be available.

5.1 Physical, electrical and chemical characteristics of the pure gases

5.1.1 Identification

The identification of each pure gas (chemical formula, molecular weight, CAS N°) should be available.

5.1.2 Saturated vapour pressure and density

For each pure gas, the saturated vapour pressure and/or the saturated vapour density as a function of temperature should be available (see Annex A, curve 1).

5.1.3 Maximum impurity content

The permissible maximum impurity content should be available for each pure gas

5.1.4 Environmental, health and safety aspects

For each pure gas, a material safety data sheet should be available including the following environmental, safety and toxicity data:

- GWP over 100 years
- ODP

- LC50 4h (on animals)
- TLV-TWA based on tests performed on animals
- CMR classification
- Flammability
- Eyes, hands, body protection required for handling and breathing
- Odour, colour if easy to detect its presence
- Reactivity with other gases, materials, liquids, life stock
- Density (relative to air)
- Solubility in water
- Persistency and degradability (abiotic and biotic)
- Bioaccumulation (BCF)
- Ecological information

5.1.5 Thermal, electrical and chemical characteristics

For each pure gas, if relevant, the boiling point and the melting point at 1 bar or the sublimation point at 1 bar and the flash point data should be available.

Thermal, electrical and chemical characteristics describing the pure gas in more detail should be available, especially those affecting the performance of the electrical equipment over its lifetime.

5.1.6 Permeability through polymeric materials

Equipment manufacturers should consider the results of diffusion tests performed at working temperatures on the different polymeric and elastomeric materials to determine the diffusion coefficient of the pure gas in the materials and, as a consequence, the leakage rate of the electrical equipment.

5.1.7 Gas absorption by moisture absorber

Equipment manufacturers should consider the effect of gas absorption by molecular sieve or moisture absorber

5.1.8 Corrosion, oxidation

When using pure gas, equipment manufacturers should use documented analyses and results of tests such as temperature rise tests carried out on electrical equipment or ageing tests conducted on materials to determine whether or not the gas is corrosive, oxidising or acidic.

5.1.9 Interactions between the pure gas and the materials

When using pure gas, equipment manufacturers should use documented gas analyses and results of tests (cf Note 1) carried out on samples or parts of the electrical equipment or mock-up to determine whether or not the pure gas and the materials are compatible.

The pure gas may be degraded itself and/or it may degrade the performance of the materials. This is particularly important for insulating materials separating live parts from earth or between phases.

The pure gas and the materials should be exposed at $T_{\text{gas max}}$ (default value is 115°C). The parameters of the test (pressure and temperature of the gas, duration of exposure, volume of the gas, quantity of material, etc.) should be available.

Note 1: The tests must be representative of the function of the specific part (e.g. tensile tests, mechanical impact, deformation under load, dielectric withstand in tracking, dielectric strength, viscosity, temperature withstand, etc.). The results of these tests should be compared with those carried out on parts or samples which have been exposed to an inert gas.

5.2 Physical, electrical and chemical characteristics of the gas mixture

Physical, electrical and chemical characteristics should be measured on a gas mixture at its rated mixing ratio as defined by 5.2.1.

5.2.1 Pressures at 20 °C of the different pure gases

The partial pressures with their associated tolerances should be given at 20 °C in order to easily check the gas-mixing ratio at a later stage. For example, with two gases:

- Partial pressure P(pure gas 1) at 20 °C = 0.03 MPa (+0, +0.005)
- Partial pressure P(pure gas 2) at 20 °C = 0.10 MPa (+0, +0.015)
- Total pressure at 20 °C = 0.13 MPa (+0, +0.020)

The ratio of gas 1 (pressure ratio) is defined as Partial pressure gas 1 at 20°C / total pressure at 20°C.

An alternative would be to give the total filling pressure with the ratio of the different components associated with its tolerance. For example:

- Filling pressure at 20 °C = 0.6 MPa
- Gas component X = 4%vol +/- 0.2%vol

5.2.2 Partial pressures of the different pure gases as a function of temperature

The gas mixture should be based on stable gases over the whole temperature range. Hence, chemical reactions between individual pure gases are not allowed, but physical interactions are possible.

The partial pressure P_i (rated) of each pure gas of the gas mixture should be available for the complete temperature range $T_{\min \text{ storage}} - T_{\text{gas max}}$ by means of graphs of the evolution of the partial pressure (see Annex A):

- The total pressure in the electrical equipment at $T_{\min \text{ storage}}$ and $T_{\max \text{ storage}}$
- The total pressure in the electrical equipment at the maximum operating temperature $T_{\text{gas max average}}$
- If, for the rated filling quantity, liquefaction for at least one of the different pure gases occurs within the temperature range $T_{\min \text{ storage}} - T_{\text{gas max}}$ then the liquefaction temperatures for the affected pure gases should be given.

5.2.3 Environmental, health and safety aspects

For each pure gas or gas mixture, a material safety data sheet should be available including the following environmental, safety and toxicity data:

- GWP over 100 years
- ODP
- LC50 4h (on animals)
- TLV-TWA based on tests performed on animals for each pure gas
- CMR classification based on each pure gas
- Flammability
- Eyes, hands, body protection required for handling and breathing
- Odour, colour if easy to detect its presence
- Reactivity with other gases, materials, liquids, life stock
- Density (relative to air)
- Solubility in water
- Persistency and degradability (abiotic and biotic)
- Bioaccumulation (BCF)
- Ecological information

Note: the properties of the mixture only have to be evaluated, if different from the mere addition of the pure gases.

The GWP of a gas mixture is calculated using the method defined in Annex IV of “Regulation (EC) No. 517/2014 of the European Parliament and of the Council of 16 April 2014 on certain fluorinated greenhouse gases”.

The ODP of the gas mixture can be calculated from the measured or known characteristics (in the public domain) of the various components: ODP of mixture is the sum of weight fraction multiplied by the ODP value of each pure gas.

The LC50 characteristics data must be determined from tests carried out on animals or by calculation from the characteristics of the pure gases when they are mixed with air.

5.2.4 Thermal, electrical and chemical characteristics

Optionally, thermal, electrical and chemical characteristics describing the gas mixture in more detail should be available, especially those affecting the performance of the electrical equipment over its lifetime.

5.2.5 Corrosion, oxidation

Equipment manufacturers should use documented analyses and results of tests such as temperature rise tests carried out on electrical equipment or ageing tests conducted on materials to determine whether or not the gas mixture is corrosive, oxidising or acidic.

5.2.6 Interactions between the gas mixture and the materials

When using gas mixtures, equipment manufacturers should use documented gas analyses and results of tests (cf Note 1) carried out on samples or parts of the electrical equipment or mock-up to determine whether or not the gas mixture and the materials are compatible.

The gas mixture may be degraded itself and/or it may degrade the performance of the materials. This is particularly important for insulating materials separating live parts from earth or between phases.

The gas mixture and the materials should be exposed at $T_{\text{gas max}}$ (default value is 115°C). The parameters of the test (pressure and temperature of the gas mixture, duration of exposure, volume of the gas mixture, quantity of material, etc.) should be available.

Note 1: The tests must be representative of the function of the specific part: (e.g. tensile tests, mechanical impact, deformation under load, dielectric withstand in tracking, dielectric strength, viscosity, temperature withstand, etc.). The results of these tests should be compared with those carried out on parts or samples, which have been exposed to an inert gas.

6 Behaviour of the pure gas or the gas mixture

Section 6 concerns the pure gases and gas mixtures, hereafter referred to as “gas”, which are used to fill electrical equipment.

This section assumes that the electrical equipment has passed the type tests according to the relevant electro-technical standards. Since these type tests may not be sufficient or adequate to evaluate the performances of the electrical equipment filled with an alternative gas, the behaviour of the gas under service conditions (examples: ageing, minimum and maximum ambient temperature, arc breaking impact, etc.) needs appropriate evaluation. The behaviour of the gas should be determined on a reference electrical equipment or a mock-up representative of the equipment design.

To be able to take account of any potential gas homogenisation problems (if relevant), these tests should be performed after settling and homogenisation of the mixture. The waiting period after the equipment is filled is determined by the equipment manufacturer.

6.1 Dielectric withstand within the temperature range ($T_{\text{amb min}} - T_{\text{gas max}}$)

In order to define the behaviour of the gas, it is recommended to make dielectric tests at $T_{\text{amb min}}$ and $T_{\text{gas max}}$ on a mock-up. The tests should be performed at the minimum functional density of the gas, according to the definition in section 3.5.

6.2 Making and breaking tests within the temperature range ($T_{\text{amb min}} - T_{\text{gas max}}$)

Making and breaking tests should be performed at the minimum functional density of the gas, according to the definition in section 3.5.

Making/breaking tests should be followed by a dielectric test. The total pressure should be measured before testing and after the making/breaking tests taking into account the temperature increase of the gas or waiting time to recover the ambient temperature of the equipment. These values should be stated in the test report. The maximum total pressure in the electrical equipment at $T_{\text{gas max average}}$ should then be recalculated. The safety features (diaphragm, area of weakness, pin, etc.) should be sized according to the standards in force and should take account of this potential rise in pressure.

Once making/breaking tests are completed, a gas sample should be taken for analysis (cf. 6.4.1.).

6.3 Long term performance of the gas

6.3.1 General

The characteristics of the gas and of any potential by-products of the gas should be determined after the reference electrical equipment or mock-up has been subjected to tests, which characterise the life of the electrical equipment. The characteristics of the gas with by-products to be investigated are:

- Concentration of by-products

- Toxicity: LC50
- Health effect: CMR, metabolic anomalies, ...
- GWP, ODP
- Level of corrosion, oxidation

6.3.2 Evaluation of long term performance of the gas

The long term performance of electrical equipment (service life including operations if applicable) is determined on the basis of the following tests sequence. This sequence can be carried out on 2 or 3 electrical equipment/mock-ups (cf Note 1) or on the same electrical equipment/mock-up:

- Preliminary tests:
 - measurement of the total pressure equivalent to 20 °C
 - partial discharge tests according to IEC 60270
 - dielectric withstand tests (as described in section 6.1)
 - tightness test according to IEC 60068-2-17
 - measurement of the resistance of the main circuit according to IEC 62271-1
- “Short-time withstand current test”
- “Making and breaking test”: making and breaking tests if applicable (as described in section 6.2).
- “Continuous current test”: period of time of operating at maximum rated current in continuous duty I_r ; if the value of the current is different, it should be communicated. The period of time should be communicated.
- “Long term dielectric test”: ageing at ambient temperature or at a higher temperature at rated voltage U_r and no current for a determined period (equipment closed); the duration and temperature of test should be communicated.
- Final tests:
 - measurement of the total pressure at 20 °C, dielectric withstand tests, tightness test, measurement of the resistance of the main circuit.
 - taking of gas samples for analysis.

There should not be significant degradation in dielectric performance, tightness and resistance of the main circuit.

Note 1: For convenience, this test sequence can be carried out with several items of equipment or mock-ups. In this case, several samples of gas have to be taken for analysis. However, the presence of by-products from making/breaking might have an influence on the

performances of the equipment and then the other tests should be performed after making/breaking on the same equipment.

6.4 Evaluation of environmental impacts and toxicity of the gas after the different tests (continuous current, short-time withstand current, making/breaking and long term dielectric tests)

These analyses and tests aim to evaluate the health risk posed to operators and the environmental impact in the event of an accidental gas release and normal handling of gas.

6.4.1 Gas analysis sampled after the different tests

The gas sampled after the different tests should be analysed with special regard to possible by-products. The amount of original gases and each by-product should be measured in ppmv or any other adequate measure.

The sampling instruments should not react with possible by-products likely to be present, like acids such as HF, for example. The results of the analyses should also mention the method and the instruments used.

6.4.2 Determination of the ODP and GWP of the gas after the different tests

Using the analysis results obtained in section 6.4.1., the GWP and the ODP of the gas should be assessed taking into account the by-products with concentrations superior to 1%. These values should be known.

6.4.3 Assessment of the toxicity of the gas sampled after the different tests

Determination of LC50 and NOAEL: the acute toxicity (see Note 1) should be evaluated by determining the LC50 4h on animals according to OECD guideline 403 or similar. The testing, analysis and observation methods should be documented and the results recorded. The NOAEL (no observed adverse effect level) is evaluated too. An example of assessment of toxicity risk in a substation in case of leakage is given in Annex C.

Research of metabolic anomalies and CMR (carcinogenic, mutagenic, reprotoxic) effects should be performed. However, it is difficult to assess this effect, which appears in a long term. The method should be documented and the results recorded.

Note 1: Definition of acute toxicity: single administration of the toxic substance. Signs of toxicity appear in a short space of time. Absorption of the toxic substance and its manifestations occur rapidly.

Note 2: the protocol "OECD guideline for the testing of chemicals: Toxicokinetics" (N°417 adopted the 22/07/2010) may be used for the research of metabolic anomalies.

6.5 Stability of the characteristics of materials in contact with the gas after the different tests

Equipment manufacturers should use documented results of tests carried out on samples or parts of the electrical equipment/mock-up to determine if the gas after tests may degrade the materials. The consequences of this possible degradation should be assessed.

6.6 Internal arc fault

The behaviour of the gas and the materials to be used in the electrical equipment need to be known when exposed to an internal arc fault. For this purpose a representative mock-up filled with the gas should be tested for an internal arc fault situation. The electrical energy supplied and the increase of pressure throughout the test should be measured. The results should be used for adequate design of electrical equipment and pressure release device(s).

The by-products after the internal arc fault test should be evaluated, taking into account that their toxic nature will not be necessarily linked to the gas itself but to the interaction with it and among the conducting, supporting and insulating materials exposed to the arc and the humid air surrounding the electrical equipment.

7 Gas mixture handling during installation and commissioning

Sections 7-10 concern the pure gases and gas mixtures, hereafter referred to as “gas”, which are used to fill electrical equipment.

Section 7 provides guidance for working with gas when a gas compartment is filled after the power equipment has been installed on site.

As a general statement, gas mixture handling during installation and commissioning could be carried out in a similar way to IEC 62271-4 which deals specifically with SF₆. Deviations to SF₆ handling procedures described in IEC 62271-4 are described in the paragraphs below to give guidance for the handling of alternative gases or gas mixture.

7.1 Evacuation, filling and checking the gas quality after filling

As per IEC 62271-4 Clause 3.2.

7.1.1 Evacuation

As per IEC 62271-4 Clause 3.2.

7.1.2 Filling from gas cylinder containing the gas already mixed

If the gas is already available in a single cylinder containing all components in their defined ratios and if there is no liquefaction in the gas cylinder, then after the pipe has evacuated to at

least 20 mbar, connect the pipe to the gas cylinder via an appropriate pressure reducer and to the equipment until the rated filling pressure (density) is reached.

7.1.3 Filling from different gas cylinders, each containing a pure gas

If a gas mixture is not directly available in its mixed state (as described in section 7.1.2), the equipment can be subsequently filled with the different components of the gas according to their partial pressure until the rated filling pressure is reached.

Proceed as follows:

- Once the pipe is evacuated to at least 20 mbar, connect the pipe to the gas cylinder via an appropriate pressure reducer (appropriate to the maximum pressure and gas type).
- Start filling with the gas having the lowest vapour pressure (at filling temperature).
- The partial pressure of each single component is equal to the total pressure multiplied by the ratio of each component in the mixture.
- The total filling pressure is equal to the sum of the partial pressure of each single component.
- Take care to not have liquefaction during filling or install a mass counter for each pure gas

7.1.4 Filling from a dedicated gas mixer

If available, an appropriate gas mixer can be used to fill electrical equipment from the different single components with their proper ratio until the rated filling pressure is reached.

7.1.5 Pressure/density inspection

The pressure has to be checked using a standard gauge but appropriate to the rated filling pressure and/or density with a specific densimeter dedicated to that specific gas, as each gas will have its own pressure-temperature dependence. The densimeter has to be specifically designed for the gas.

7.1.6 Tightness inspection

The tightness must be checked at least at all permanent connections with an appropriate leak detector specific to the gas and/or its specific components.

7.1.7 Gas quality inspection

In case of filling from different gas cylinders containing a pure gas (according to section 7.1.3), a specific wait time of at least 24h or according to the equipment manufacturer specification must be observed before the gas quality can be checked.

Prior to filling, the gas quality has to be verified.

7.1.7.1 Gas quality inspection with portable equipment

Humidity, ratio of components and by-products (if relevant) can be checked on site with appropriate portable equipment, specifically designed for the gas to be analysed. Different technologies can be used derived from the SF₆ analysis but specifically calibrated for the gas.

7.1.7.2 Sampling and shipment of gas for off-site analysis

After the gas sample cylinder and hoses have been cleaned, dried and evacuated to at least 20 mbar, connect the gas cylinder to the electrical equipment compartment to be analyzed using a gas reducer (if relevant) until the gas sample cylinder is filled. The sample pressure must remain lower than the vapor pressure at minimum transportation temperature. The sample should then be sent to an appropriate lab for analysis. Different technologies can be used such as infra-red spectrometry, gas-phase chromatography or other.

7.2 Topping-up of gas pre-filled compartments to the rated pressure/density

This section applies to compartments of pressure systems pre-filled in the factory prior to shipment. Typically, they are filled to slightly above atmospheric pressure. The gas may be the same as at rated pressure (density) or – only possible in the case of a gas mixture – may have a different mixing ratio than at rated pressure.

Depending on the gas composition already prefilled in the electrical equipment, topping-up has to be carried out according to sections 7.1.2 to 7.1.4.

After refilling, the pressure/density should be measured according to section 7.1.5.

Tightness inspection should be carried out according to section 7.1.6 if the electrical equipment was not tightness tested before.

A gas quality inspection should be carried out according to section 7.1.7 if there is a high risk of the gas quality being inadequate.

7.3 Filling sealed pressure systems

Sealed pressure system equipment is filled with the gas in the factory. No further gas handling is necessary on site.

8 Gas handling during normal service life

This section applies to closed pressure systems.

8.1 Re-filling of gas to the rated pressure/density

Before refilling the electrical equipment, if relevant, a gas analysis should be conducted with a dedicated analytical tool to measure the composition of the gas mixture and the ratio of each component. Re-filling should then be carried out according to the appropriate sub-section of 7.1.

8.2 Checking the gas quality

The gas quality has to be checked with dedicated test equipment to measure the humidity, if applicable, the content of each single pure gas of a gas mixture and the by-products.

The gas quality can be checked on site using dedicated portable test equipment or off site via a gas sample taken out of the gas compartment and sent to a dedicated lab according to section 7.1.7.

9 Gas recovery and reclaim during maintenance

This section applies to a gas compartment from which the gas has to be recovered for maintenance and dismantling. The first step is to check the gas quality and the by-product content to determine whether or not the gas is heavily arced.

9.1 Recovery and reclaiming of gas from any compartment containing non-arc'd and normally arc'd gas

As per IEC 62271-4 Clause 5.2.

9.2 Recovery and reclaiming of gas from any compartment containing heavily arc'd gas

As per IEC 62271-4 Clause 5.3.

10 Dismantling of electric power equipment at end of life

As per IEC 62271-4 Clause 6 and sub-clauses.

Annex A (Informative)

Gas pressure curves as a function of temperature

A1: General

This annex presents the graphs representing the evolution, as a function of temperature, of the pressure of each gas or the gas mixture.

A2: Graph of the saturated vapour pressure of a gas as a function of temperature

The graph of the saturated vapour pressure (PVS) as a function of temperature is an intrinsic characteristic of the gas (see Figure 1). At boiling point T_b , the saturated vapour pressure is, by definition, equal to 1 bar (0.1 MPa). This curve is used to determine, at each temperature, and particularly at $T_{amb\ min}$, the maximum pressure in a sealed enclosure.

When, at a given temperature, the partial pressure of the gas is less than the value of the saturated vapour pressure of the gas, there is no liquid. If we have a liquid phase, there is equilibrium between the liquid and its vapour, thus the pressure is equal to the saturated vapour pressure.

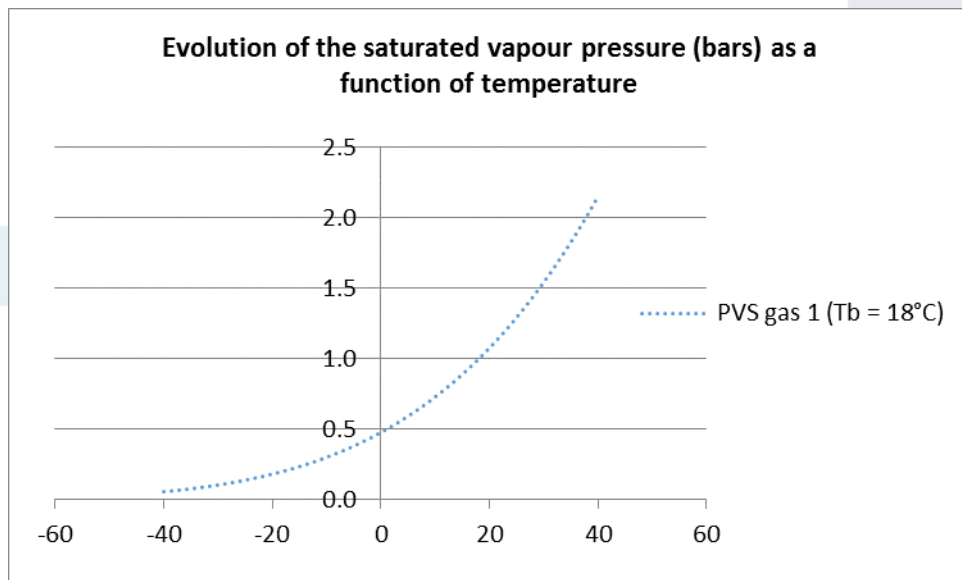


Figure 1: Evolution of the saturated vapour pressure of a gas as a function of temperature

A3: Graph, as a function of temperature, of the pressure of a gas mixture where one of the component gases reaches saturated vapour pressure

This corresponds to a homogeneous gas mixture comprising 2 gases which do not interact with each other:

- A gas 1 with a boiling point of 18 °C
- A gas 2 with a boiling point of less than -100 °C
-

The partial pressure of the gas 2 follows the ideal gas law over the full scale on Figure 2 ($P = f(T)$ is a straight line).

When the partial pressure of gas 1 is less than its saturated vapour pressure, it follows the ideal gas law ($P = f(T)$ is a straight line).

When the temperature of the mixture falls, gas 1 reaches its saturated vapour pressure and starts to liquefy. As the temperature continues to fall, the gas remains in equilibrium with its liquid and its pressure follows the curve of the saturated vapour pressure.

The total pressure of the gas mixture is the sum of the partial pressures of the components in the mixture. This liquid-vapour transformation, known as phase change, is reversible.

For example, consider a mixture of 2 gases at 20 °C:

- $P_{\text{gas 1}} = 0.04 \text{ MPa}$
- $P_{\text{gas 2}} = 0.10 \text{ MPa}$

The total pressure at 20 °C is thus: $P_T = 0.14 \text{ MPa}$

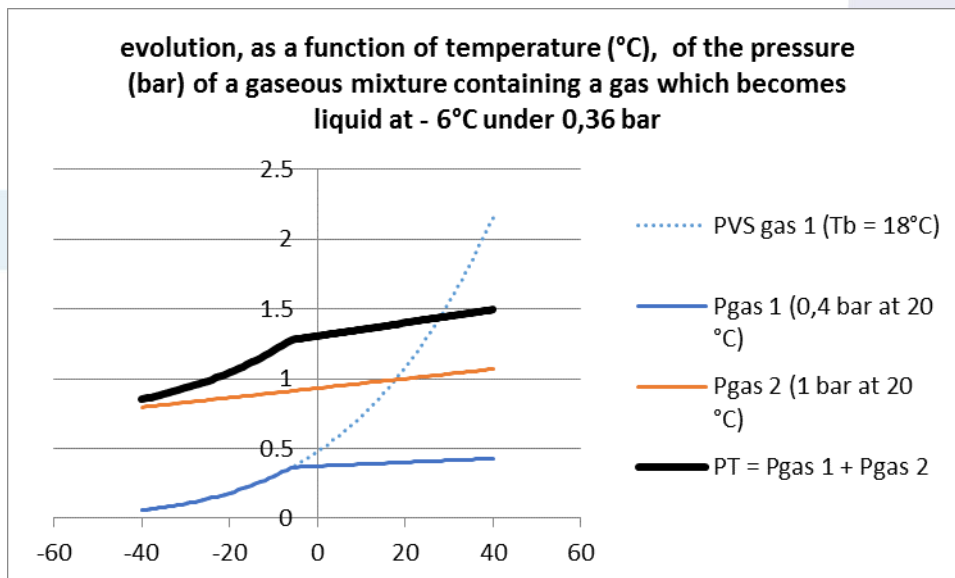


Figure 2: Evolution, as a function of temperature, of the partial pressure of 2 gases and the gas mixture comprising these 2 gases, where gas 1 ($T_b = 18 \text{ °C}$) liquefies at -6 °C at 0.36 bar

There is liquid in the equipment over the temperature range $[(-40 \text{ °C}) - (-6 \text{ °C})]$.

A4: Graph, as a function of temperature, of the pressure of a gas mixture containing 2 components which interact with each other

This corresponds to a homogeneous gas mixture comprising 2 gases interacting with each other and a gas 3 (air, CO₂, N₂, etc.). The 2 gases are characterised by their saturated vapour pressure as a function of temperature curve (Figure 3).

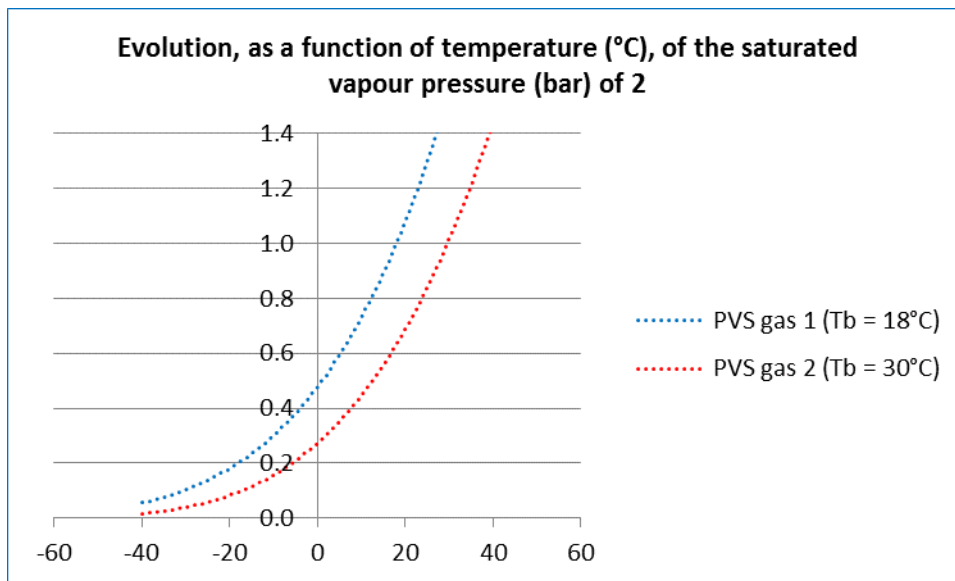


Figure 3: Evolution, as a function of temperature, of the saturated vapour pressure of gases 1 and 2

These 3 gases, in the absence of liquid, can be considered independently of each other as ideal gases with a partial pressure proportional to the temperature ($P = f(T)$ is a straight line).

The interaction between these two gases starts when liquefaction appears above a temperature given by the PVS curve of one of the pure gases. This interaction applies according to Raoult's law.

Raoult's law is a law that states that the vapour pressure of a mix of gases is dependent on the mole fraction of one of the gases.

For example, consider a mixture of 3 gases at 20 °C:

- P gas 1 = 0.015 MPa
- P gas 2 = 0.01 MPa
- P gas 3 = 0.105 MPa

The total pressure at 20 °C is thus: $P_T = 0.13$ MPa

It is imperative to take account of interactions between gases; Figure 4 shows, for example, at -23 °C, that the partial pressure of gas 2 is half that calculated in the case where the 2 gases do not interact.

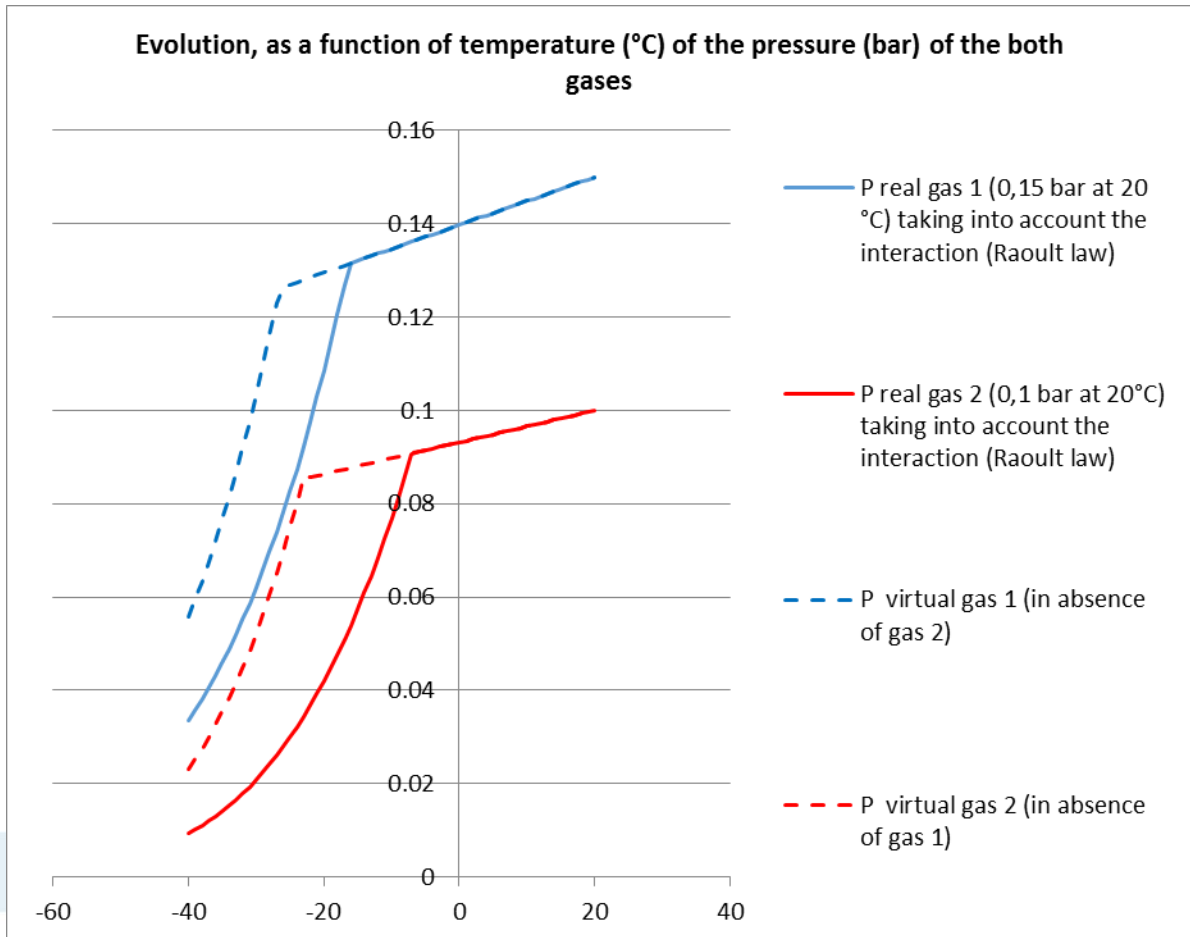


Figure 4: Evolution, as a function of temperature, of the partial pressure of 2 gases interacting with each other

This interaction is greater the closer the sum of the ratios of the partial pressures to the saturated vapour pressure is to 1. In the case of a mixture of 2 gases (gas 1 and gas 2), the maximum quantity of gas that can attain temperature T is given by the following Raoult law equation:

$$\left(\frac{P_1}{PVS_1} + \frac{P_2}{PVS_2} \right) = 1$$
 where PVS_i and P_i represent the saturated vapour pressure and partial pressure respectively of gas i at temperature T.

Figure 5 represents the partial pressures of gases 1, 2, 3 and the total pressure of the mixture.

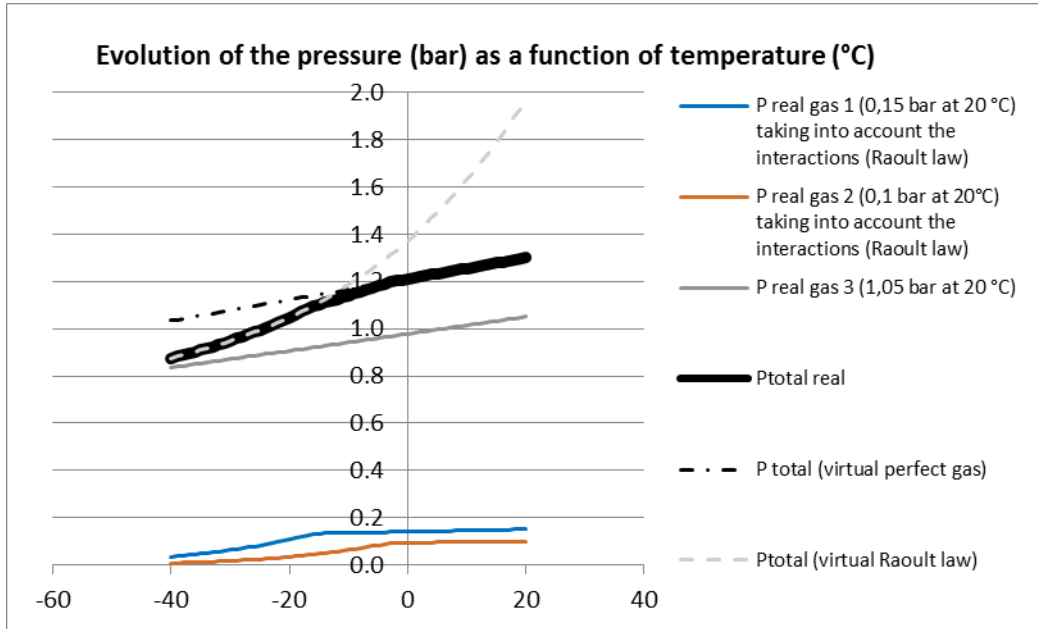


Figure 5: Evolution, as a function of temperature, of the partial pressure of the gases, the total pressure of the gas mixture and the "virtual" pressures used to plot the graphs

Figure 6 represents a zoomed in section of Figure 5 of the total pressure over the temperature range $[(-20^{\circ}\text{C}) - (-5^{\circ}\text{C})]$.

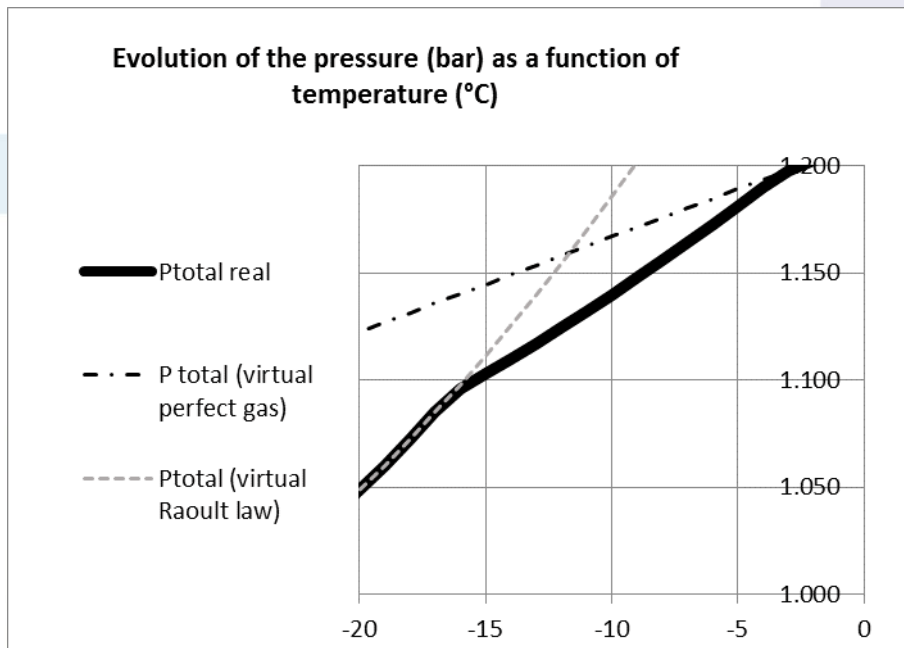


Figure 6: Magnified section of the total pressure curve from Figure 5. There is liquid in the equipment over the temperature range $[(-40^{\circ}\text{C}) - (-4^{\circ}\text{C})]$.

Annex B: SF6 Characteristics

Identification	CAS number	2551-62-4
	Molecular formula	SF6
General properties	Appearance	pressurized liquefied gas
	Molecular weight	146 g
	Melting point at 2,26 bar	- 50,8 °C
	Sublimation point at 1 bar	-63,8 °C
	Flash point	NA
	Flammability	non flammable
	Auto-flammability	NA
	Odour	odourless
	Colour	colourless
	Gas density	6,07 g / l at 20°C for 1 bar
	Vapour / vapour density air	5,1
	Vapour pressure	21,5 bar at 20°C vapour pressure as a function of temperature
	Mollier diagram	enthalpy-entropy chart
	Thermal conductivity	1,3 W /cm.K at 25 °C for 1 bar
	Solubility in water	40 mg / l at 20°C
	Oxydising property	NA
	Specific heat (gas)	97,26 J / mol.K at 25 °C for 1 bar
Viscosity	0,0153 mPa s at 25°C for 1 bar	
Environmental aspects	GWP over 100 years	22800
	ODP	0
	Water, evaporation	$t_{1/2} > 3,5$ hours
	Air photolysis	$t_{1/2} > 1000$ years
	Photolysis	non significant
	Water/soil hydrolysis	$t_{1/2} > 1000$ years
	Hydrolysis	non significant
	Biotic degradation	NA (inorganic compound)
	Bioconcentration	aquatic organisms, BCF = 89
	comments:	product is present in air as inert form
Toxicological aspects	LC50 4h	NA
	NOAEL	NA
	TLV-TWA	1000 ppm
	CMR	NA
	comments:	SF6 has a higher affinity with blood and fatty tissues but is rapidly eliminated (low accumulation potential)
	metabolite	none
By-products by arcing	by-products	depend on the materials and gases (H ₂ O, O ₂ , ...) present in the medium, the energy of electrical arcs, ... SOF ₂ , SOF ₄ , SF ₄ , S ₂ F ₁₀ , SO ₂ F ₂ , SO ₂ , HF, S ₂ F ₁₀ , S ₂ OF ₁₀ , S ₂ O ₂ F ₁₀ , CF ₄ , CO ₂ , CO

Annex C (Informative)

Determination of the concentration of gas in a substation room

The concentration within a substation room is determined on the basis of a potential major leak on the device causing it to reach its atmospheric pressure in a few minutes. This eventuality dilutes the escaped gases in the volume of the substation or plant room taking account of the air exchange. The toxicity of the diluted gas and/or the displacement of the oxygen in the room is then evaluated.

- The plant room or substation is defined by its volume of air V_0 and its air exchange time, which depends on its architecture and insulation.
- The equipment is defined by the quantity of gas it contains, i.e. by its volume of gas V_s at pressure P_T .
- The gas inside the equipment is defined by its concentration C_s (1E6 ppm) and LC50 4h toxicity (ppm).

This concentration is calculated approximately as follows:

The concentration in the plant room or substation where the equipment is located on which a leak may occur is at most (assuming that there is no air exchange) equal to:

$$C_0 = [(P_T - P_{atm}) \cdot V_s / (P_{atm} \cdot V_0)] \cdot C_s$$

If air exchange is taken into account, the average concentration over 4 hours in the plant room equals $C_m = n \cdot C_0$ where:

$$n = \frac{\tau}{4} \cdot (1 - e^{-\frac{4}{\tau}})$$

And τ (h) is the air exchange time.

- For well ventilated room: $\tau = 0.5$ and $n = 0.12$
- For a ventilated room: $\tau = 1$ and $n = 0.25$
- For a very poor ventilated room: $\tau = 10$ and $n = 0.9$

If the calculation gives a value of C_m greater than the fixed limit of NOAEL, an alarm system must be installed in the plant room or substation which, when triggered, emits an evacuation signal. The threshold for this alarm should be less than or equal to the NOAEL. This alarm can take the form of a detector/alarm sensitive to at least one significant component of the gas (the component which gives the greatest part of toxicity).

Displacement of the oxygen in the room can be critical especially if the density of the gas at atmospheric pressure is higher than the density of the air inside the room and if the room is poor ventilated, as may be the case when located in the basement of a building and if the total amount of gas released is high. If calculations show that there is a possibility that the oxygen level is critical (i.e. oxygen concentration down to 160 ml/l (16 % by volume), which is usually considered as the threshold for asphyxiation), oxygen sensors that trigger a "low oxygen alarm" should be installed in that room.