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SF6 Alternatives

Test Methodology

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Prepared by:	David Kilpatrick	09/08/2018
Reviewed by:	Paul Edwards	09/08/2018
Approved (WPD):	Stavros Saouros	09/08/2018

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Contents

Glossary

Abbreviation	Term
AIS	Air Insulated Switchgear
AC	Alternating Current
CO_2	Carbon Dioxide
CAS	Chemical Abstracts Service
DNO	Distribution Network Operator
DSO	Distribution System Operator
EHV	Extra High Voltage
GIL	Gas Insulated Lines
GIS	Gas Insulated Switchgear
GWP	Global Warming Potential
GHG	Greenhouse Gas
HV	High Voltage
IEC	International Electrotechnical Commission
ISO	International Organisation for Standardisation
kV	Kilovolts
LCA	Life-cycle Assessment
MV	Medium Voltage
ODP	Ozone Depletion
PPM	Parts per Million
PFC	Perfluorocarbon
PFN	Perfluoronitrile
RMU	Ring Main Unit
RMS	Root Mean Squared
SIS	Solid Insulation Switchgear
SF_6	Sulphur Hexafluoride
TRL	Technology Readiness Level
TSO	Transmission System Operator
WPD	Western Power Distribution

1 Introduction

This document intends to summarise the relevant testing protocols for SF_6 alternative gases within electrical switchgear, for the purposes of electrical insulation and arc-interruption.

Numerous testing requirements already pre-exist for high voltage switchgear and gases contained within. It is therefore assumed that knowledge of these testing requirements is known by the reader and the information contained in this document is used to supplement it.

As is outlined in preceding project documentation, the intention of the project is to "retro-fit" a SF_6 alternative gas within an existing switchgear enclosure to undertake testing. As such a significant number of tests will have already been conducted and remain valid. This document looks to define those tests that will need to be performed either again or additionally to comply with the necessary requirements.

This document has been compiled by taking relevant consideration from manufacturers and other recognised industry bodies. With work continuously taking place in this area the information included from these parties is intended to present latest best practice approaches as well as recommended processes which may not be covered in existing regulation.

It should also be noted that most available literature on testing of SF_6 alternatives explore only their use as an insulating medium.

2 Background and Normative References

The process for testing gas alternatives to SF_6 takes place in two parts. This document will explore both aspects of this process.

The first is testing of electrical equipment within which a gas may be used. Within the United Kingdom the overarching specification for switchgear in the Distribution Networks is ENA TS 41-36. Therefore, all electrical equipment referred in this document is required to be compliant to this document.

The second, are extra considerations that must be considered in the validation of suggested alternatives. The reader is encouraged to view T&D Europe – *"A Technical Guide to Validate Alternative Gas for SF6 Equipment".* This document is compiled by industry leading experts and explores which characteristics of a gas should be taken into account, specifying 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.

Additionally, the reader is encouraged to be familiar with all relevant parts of the following documents:

- IEC 60068-2-17, Basic environmental testing procedures – part 2 – Tests
- IEC 60270, High-voltage test techniques – Partial discharge measurements
- IEC 62271-1, High-voltage switchgear and control gear – Part 1: Common specifications
- IEC 62271-100, High-voltage switchgear and control gear – Part 100: Alternating-current circuit-breakers
- IEC 62271-102, High-voltage switchgear and control gear – Part 102: Alternating current disconnectors and earthing switches
- IEC 62271-103, High-voltage switchgear and control gear – Part 103: Switches for rated voltages above 1 kV up to and including 52 kV
- IEC 62271-105, High-voltage switchgear and control gear – 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 control gear – Part 200: AC metal enclosed switchgear and control gear for rated voltages above1kV and up to and including 52 kV
- IEC 62271-203, High-voltage switchgear and control gear – Part 203: Gas-insulated metal-enclosed switchgear for rated voltages above 52 kV
- IEC/IEEE 62271-37-013, High-voltage switchgear and control gear – 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 Type Testing of Ring Main Units

In line with initial project proposals it is assumed that the chosen test device for a SF_6 alternative solution will be a pre-existing Ring Main Unit (RMU), either provided without the presence of SF_6 or having had all SF_6 removed. The device will then be filled with the chosen gas or gas mixture for testing.

Such fundamental alternation to the device will result in the originally undertaken type tests to be deemed invalid and full recertification will be required. To be compliant for use in the UK network, testing will have to be performed in accordance with type testing requirements of ENA TS 41-36 and all relevant standards contained within.

Table 1A, in Appendix A, includes a list of all tests that will be required during recertification.

4 Additional Consideration for SF6 Gas Alternatives

The initial stage of this project involved a literature review being undertaken to explore the current position of SF_6 alternatives in industry. In summary, it was found that there are several potential alternative solutions for replacing SF_6 in electrical switchgear but these are at differing levels of maturity.

Primarily the alternatives in question are also favoured to replacing SF_6 as an insulating medium with vacuum technology offering the most likely solution to interruption capability. Based on this approach the information contained here after explores primarily the use of alternative gases as an insulation medium only.

The information in this section explores the use of additional testing or practice in addition to compliance with existing relevant electro-technical standards referred in Section 3. This is offered as further guidance in areas where existing type testing does not explore the effects of alternative gases.

In assuming that existing test structures would be sufficient there is significant risk that improper evaluation will have taken place. Where already relevant electro-technical standards are applicable, previously knowledge of these has been assumed and in most cases passing reference is made.

4.1 Gas Characteristics

Before any physical testing is undertaken characteristics of the gas to be used for testing shall be made available. As a minimum this should include the details of the gas or gas mixture, chemical and physical properties and the impact to both health and environment. Particularly, information detailing the effect of the given gas over a life cycle shall be available.

Table 1 shows a minimum expectation for information to be made available, while a full example data sheet is included in APPENDIX B for SF_6.

Gas Characteristics	Boiling point at 1 bar	
	Buffer gas if mixture	
	GWP of gas or mixture	
	ODP of gas or mixture	
	Flammability	
Toxicological	Toxicity (LC50 on mice and TWA)	
	By-product analysis after long duration test under electrical field	
	By-products analysis after internal arc test	

Table 1 - Minimum Information of Test Gas Composition

4.2 Gas Behaviour

As has been explored previously in the literature review, finding an alternative gas to SF_6 but with similar properties has proved a challenge to researchers in this field. Through these findings a number of additional tests or considerations have been made by T&D Europe in the testing of alternative gas solutions which are deemed fit for purpose. These additional tests aim to evaluate the behaviour of a gas during normal service life.

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

In addition to dielectric tests outlined in ENA TS 41-36 and IEC 62271 -1 it is recommended to make dielectric tests at minimum ambient operating temperature ($T_{amb\ min}$) and maximum gas temperature ($T_{gas\ max}$), which is the maximum ambient operating temperature when at rated continuous current (if this value is unknown or cannot be measured a default of 115°C is deemed acceptable).

For pure gases this is defined as the density of the pure gas ≥ where the rated insulation and/or switching characteristics of the electrical equipment are maintained. Minimum functional density of pure gas must also be ≤ the saturated vapour density of the pure gas at the minimum ambient air temperature for operation.

For gas mixtures the minimum functional density of the gas mixture is the sum of the minimum functional densities of each pure gas which comprise the gas mixture. Notably, if gases interact together, the functional density of each gas in the mixture is lower than the functional density of each individual gas in isolation.

4.2.2 Making and Breaking tests within the temperature range

Making/breaking tests should be conducted throughout the temperature range of the new gas or gas mixture. The temperature range should be the same as that for dielectric testing outlined in 4.2.1

Measurements of total pressure must be taken before and after making/breaking tests to consider the temperature increase of the gas and/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 $T_{gas\ max\ average}$ (the average temperature the gas/gas mixture can reach during operation at maximum ambient temperature) should then be recalculated.

Making and breaking tests should be followed by dielectric testing and performed at the minimum functional density of the gas, similarly to tests in 4.2.1

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

4.2.3 Long Term Performance

To validate the long-term performance of electrical equipment in service the following test process is advised.

1. **Preliminary tests:**
   - measurement of the total pressure equivalent to 20 °C
   - partial discharge tests according to IEC 60270
   - dielectric tests in accordance with ENA TS 41-36, IEC 62271 and Section 4.11 of this document
   - tightness test according to IEC 60068-2-17
   - measurement of the resistance of the main circuit according to IEC 62271-1
2. **Short-time withstand current test**
3. **Making and breaking test**
   Making and breaking tests in accordance with ENA TS 41-36, IEC 62271 and Section 4.1.2 of this document
4. **Continuous current test**
   - Period operating at maximum rated current in continuous duty Ir. Where current value used is different this should be recorded;
   - Duration of operation to be recorded.
5. **Long term dielectric test**
   - To determine the ageing of the gas/gas mixture at ambient temperature or at a higher temperature while at rated voltage and no current for a determined period;
   - The duration and temperature of test should be recorded.
6. **Final tests:**
   - measurement of the total pressure at 20 °C,
   - dielectric withstand tests
   - permeability - tightness test
   - measurement of the resistance of the main circuit.
   - taking of gas samples for analysis.

Following these tests there should be no sign of noteworthy degradation in dielectric performance, tightness and resistance of the main circuit.

As well as assessing the practical performance of the gas over time, the characteristics of by products must also be assessed. This assessment should reflect the characteristics required in section 4.1 as well as the following;

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

4.2.4 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, considering their toxic nature is not necessarily linked to the gas itself but to the interaction with the conducting, supporting and insulating materials exposed to the arc and the humid air surrounding the electrical equipment.

Whatever the gases (pure or mixture) used as dielectric medium, it is necessary to check that the gas is not explosive in the configuration of operating (filling, temperature rise test, partial discharge, making of disconnector, internal arc fault test, leakage) especially when the gas contains oxygen atoms. In the case of a mixed gases, flammability should be checked at different temperatures given the relationship to pressure.

5 Conclusion

This document has outlined a methodology for testing pre-existing Ring Main Units, originally designed for use with SF_6, for containment of alternative gases used as an insulation medium. The information contained within has been sourced from existing industry regulation as well as leading sources of expertise in this field.

As the removal of SF_6, and its replacement with an alternative gas, establishes a fundamental change to the constitution of the Ring Main Unit it will be required that full type testing be undertaken in order for the equipment to regain certification for commercial use.

However, with the introduction of new gas insulating mediums comes reduced familiarity and the need for increased validation for their use. As such the additional guidance outlined in Section 4 of this document should be used in conjunction, if not before, type testing is performed on the modified Ring Main Unit. This information aims to specify the additional information and testing criteria required to ensure the performance of the electrical equipment throughout its service life while also familiarising the end user with the composition of the gas in use, from a Health, Safety and Environmental stand point.

It is to be noted that while this document outlines both methods of testing and practices to follow, these are written as guidance/recommendations only and consultation should be sought from the chosen test body/facility and equipment manufacturer, prior to testing being performed.

APPENDIX A

Table 1A – List of all required type tests in accordance with ENA TS 41-36 and supporting technical specifications and standards

Test Requirement	Technical Specifications and Standards
Dielectric - RME, including switch-disconnectors, circuit-breaker and earthing switches as appropriate. Tests to include VT and CTs when fitted. Partial discharge. Tests to be representative of two cable termination systems, in addition to switchgear manufacturer's own system if any.	IEC 62271-1. Sub-clause 6.2, IEC 62271-100. Sub-clause 6.2, IEC 62271-103.Sub-clause 6.2, IEC 62271-200. Sub-clause 6.2. Tables 1.1a and 1.1b of this TS IEC 62271-200. Sub-clause 6.2.9 and Annex BB ENA TS 41-18 Sub-clauses 1.5.103.1 and 1.6 of this TS
Voltage Withstand – Isolating Gap (provision for dielectric tests on cables).	IEC 62271-200. Sub-clauses 5.105 and 6.2.101. Sub-clause 1.4.2.2 of this TS.
d.c. Withstand Test on Test Devices, including all parts of the main circuit which cannot be disconnected from the test connections. X-ray emission test on open vacuum interrupters (for d.c. test with earthing switch closed) a.c. test on test connections/ devices	IEC 62271-200. Sub-clause 5.105. Sub-clause 1.5.201.1 of this TS. IEC 62271-1. Sub-clause 6.11 Sub-clause 1.5.19 of this TS. Sub-clause 1.6.3 of this TS.
Insulation level - electrically stressed gap due to movement of earthing switch contacts.	Sub-clause 1.5.6 of this TS
Measurement of the resistance of main circuit - RME, including switch -disconnectors and circuit-breaker as appropriate.	IEC 62271-1. Sub-clause 6.4, IEC 62271-100. Sub-clause 6.4., IEC 62271-103. Sub-clause 6.4, IEC 62271-200. Sub-clause 6.4
Temperature Rise - RME, including switch - disconnectors and circuit breaker as appropriate. Influence of solar radiation (outdoor only)	IEC 62271-1. Sub-clause 6.5, IEC 62271-100. Sub-clause 6.5 IEC 62271-103. Sub-clause 6.5, IEC 62271-200. Sub-clause 6.5 Sub-clause 1.6.201 of this TS.
Short-time withstand current and peak withstand current tests - Ring switch-disconnectors, busbar and connections.(3sec short time).	IEC 62271-1.Sub-clause 6.6, IEC 62271-103.Sub-clause 6.6, IEC 62271-200. Sub-clause 6.6.
Short-time withstand current and peak withstand current tests - Tee-off circuit-breaker. (3sec short time).	IEC 62271-1.Sub-clause 6.6, IEC 62271-100. Sub-clause 6.6, IEC 62271-200. Sub-clause 6.6.
Short-time withstand current and peak withstand current tests - Tee-off Earthing switch (3sec short time).	IEC 62271-1.Sub-clause 6.6, IEC 62271-102. Sub-clause 6.6, IEC 62271-200. Sub-clause 6.6.
" - Ring Earthing switches.	"
" - Single phase test of earth circuit. (sub-clause 1.4.5 of this TS)	IEC 62271-1.Sub-clause 6.6, IEC 62271-100. Sub-clause 6.6, IEC 62271-200. Sub-clause 6.6.
Verification of protection. - Verification of IP coding (indoor – IP4X minimum) (indoor – operational fascia IP3X) (Enclosure doors open IPXXB) (Partitions of HV compartment IP3XD) (Mechanism IP2X) Weatherproofing for outdoor equipment. (outdoor IP4XDW minimum) - Verification of IK coding (Mechanical impact. indoor – IK07 (2J), outdoor – IK10 (20J))	IEC 62271-1.Sub-clause 6.7 and annex C IEC 60529, IEC 62271-200. Sub-clause 6.7 Sub-clause 1.5.13.3 of this TS. IEC 62271-1Sub-clause 5.13.3. Sub-clause 1.5.13.3 of this TS
Tightness test.	IEC 62271-1.Sub-clause 6.8, IEC 62271-200. Sub-clause 6.8.
EMC tests.	IEC 62271-1.Sub-clause 6.9
Mechanical operations - Circuit-breaker. Non auto-reclosing circuit-breaker - class M1 - 2000 operating cycles. - 10% specified operating cycles with manual (production) handle - 50 manual operating cycles – emergency handle If used as earthing device -mechanical strength of kinematic chain between movable contacts and the position indicating device Force for manual operations (normal and emergency)	IEC 62271-100. Sub-clause 6.101.2. IEC 62271-200. Sub-clause 6.102 Sub-clause 2.4.110 of this TS Sub-clause 1.6 of this TS Sub-clause 1.6.202 of this TS IEC 62271-102 Sub-clause 6.105 and Annex A Sub-clause 1.6.202 of this TS
Mechanical operations - Ring switch-disconnector - 1 10% specified operating cycles with manual (production) handle 50 manual operating cycles – emergency handle (Including mechanical strength of kinematic chain between movable contacts and the position indicating device; Max. force for manual operation).	IEC 62271-103. Sub-clause 6.102.4, IEC 62271-200. Sub-clause 6.102 Sub-clause 1.6 of this TS Sub-clause 1.6.202 of this TS IEC 62271-102. Sub-clause 6.105 and Annex A IEC 62271-102. Sub-clause 5.102

Force for manual operations (normal and emergency)	Sub-clause 1.6.202 of this TS
Mechanical operations - Tee-off earthing switch. - 10% specified operating cycles with manual (production) handle - 50 manual operating cycles – emergency handle (Including mechanical strength of kinematic chain between movable contacts and the position indicating device; Max. force for manual operation). Force for manual operations (normal and emergency)	IEC 62271-102. Sub-clause 6.102 IEC 62271-200. Sub-clause 6.102 Sub-clause 1.6 of this TS Sub-clause 1.6.202 of this TS IEC 62271-102. Sub-clause 6.105 and Annex A IEC 62271-102. Sub-clause 5.102 Sub-clause 1.6.202 of this TS
Mechanical operations - Ring earthing switches. - 10% specified operating cycles with manual (production) handle - 50 manual operating cycles – emergency handle (Including mechanical strength of kinematic chain between movable contacts and the position indicating device; Max. force for manual operation). Force for manual operations (normal and emergency)	IEC 62271-102. Sub-clause 6.102 IEC 62271-200. Sub-clause 6.102 Sub-clause 1.6 of this TS Sub-clause 1.6.202 of this TS IEC 62271-102. Sub-clause 6.105 and Annex A IEC 62271-102. Sub-clause 5.102 Sub-clause 1.6.202 of this TS
Mechanical operations- switching devices and removable parts - 50 ops - interlocks - 50 ops(mechanical and electro-mechanical). (150% normal force against interlock–dependent manual) - 10 ops (in wrong direction)	IEC 62271-200. Sub-clause 6.102 Sub-clause 1.6.1 of this TS Sub-clause 1.6.202 of this TS
Low temperature tests.	IEC 62271-100. Sub-clause 6.101.3. IEC 62271-103 Sub-clause 6.102.3. IEC 62271-102. Sub-clause 6.104
High temperature tests	IEC 62271-100.Sub-clause 6.101.3. IEC 62271-103 Sub-clause 6.102.3. IEC 62271-102. Sub-clause 6.104
Short-circuit making and breaking tests - Circuit-breaker class E2. Non auto-reclosing circuit-breaker - tested in accordance with sub-clauses 6.112.1 and 6.106 of IEC 62271-100.	IEC 62271-100. Sub-clauses 6.102 to 6.106, and 6.112 IEC 62271-200. Sub-clause 6.101
Short-circuit making and breaking tests - Ring switch-disconnector (Switch-disconnector class E3 and Test duty TD_{ma} = 10 operations).	IEC 62271-103.Sub-clauses 6.101.1, (TD_{load}, TD_{loop}, TD_{cc}, TD_{lc}, & TD_{ma}, Table 3), IEC 62271-200. Sub-clause 6.101
Short-circuit making tests - Tee-off earthing switch (class E2) (Test duty TD_{ma} of IEC 62271-103 sub-clause 6.101.1.2 - 5 making operations) Earthing function performed by main switching device	IEC 62271-102. Sub-clause 6.101, IEC 62271-103. Sub-clause 6.101.1.2 IEC 62271-1 Sub-clause 6.2.11 Sub-clause 2.6 of this TS
Short-circuit making tests - Ring earth switch (class E2) (Test duty TD_{ma} of IEC 62271-103 sub-clause 6.101.1.2 - 5 making operations). Earthing function performed by main switching device	IEC 62271-102. Sub-clause 6.101, IEC 62271-103. Sub-clause 6.101.1.2 IEC 62271-1 Sub-clause 6.2.11 Sub-clause 2.6 of this TS
Out of phase making and breaking current – Circuit-breaker	IEC 62271-100. Sub-clause 6.110
Cable-charging breaking current tests - Ring switch- disconnectors.	IEC 62271-103. Sub-clause 6.101.7.3
Cable-charging breaking current tests - Circuit-breaker.	IEC 62271-100. Sub-clause6.111
Line-charging breaking current tests - Ring switch- disconnectors.	IEC 62271-103. Sub-clause 6.101.7.3
Line-charging breaking current tests - Circuit-breaker.	IEC 62271-100, Sub-clause 6.111
Internal Arc –C B Chamber, C T Chamber, BB Chamber, Cable box. (36kV cable-boxes using screened separate connectors – min 5kA)	IEC 62271-200. Sub-clause 6.106 and Annex A. Sub-clause 1.5.101 of this TS
Gas-filled Compartment Pressure Withstand.	IEC 62271-200. Sub-clause 6.103
Voltage presence indicating system (VPIS).	IEC 61958. Clause 6
Voltage detecting system (VDS)	IEC 61243-5. Clause 5
Operation at extremes of voltage of auxiliary and control circuits specified in sub-clause 1.4.8	IEC 62271-1 Sub-clause 6.10 Sub-clause 1.4.8 and 1.6 of this TS
Tests on auxiliary and control circuits/ equipment	
- Dielectric	IEC 62271-1 Sub-clause 6.10.6
- Measurement of resistance	IEC 62271-1 Sub-clause 6.4.2
- Temperature rise	IEC 62271-1 Sub-clause 6.5.5
- Functional	IEC 62271-1 Sub-clause 6.10.2
- Electrical continuity or earthed metallic parts	IEC 62271-1 Sub-clause 6.10.3
- Verification of operational characteristics (Auxiliary contacts)	IEC 62271-1 Sub-clause 6.10.4
- Environmental (Cold; Dry heat; Damp heat, steady state; Cyclic humidity; Vibration response & seismic; Final condition check)	IEC 62271-1 Sub-clause 6.10.5
Finish.	Performance to ENA TS 98-1
Process Control.	ISO 9001 ENA ER G79

APPENDIX B

An example submission of SF_6 Gas Characteristics to be used as guidance in requests for similar characteristics from SF_6 alternative gases

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 comments:	aquatic organisms, BCF = 89 product is present in air as inert form
Toxicological aspects	LC50 4h	NA
	NOAEL	NA
	TLV-TWA	1000 ppm
	CMR comments:	NA 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$0, O2, ...) present in the medium, the energy of electrical arcs, ... SOF2, SOF4, SF4, S2F10, SO2F2, SO2, HF, S2F10, S2OF10, S2O2F10, CF4, CO2, CO

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