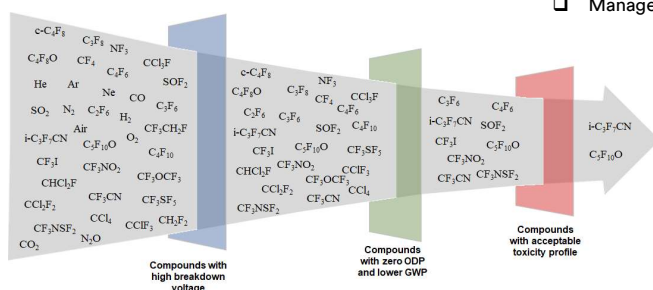


1

Decades of dedicated research to create sustainable alternatives to SF₆

Key Product Requirements:

- ☐ Nonflammable
- ☐ Low toxicity
- ☐ High dielectric strength
- ☐ Gas phase over temperature range
- ☐ Good heat transfer characteristics
- ☐ Long working life (good thermal/chemical stability)
- ☐ No corrosion or adverse effects on equipment
- ☐ Manageable decomposition products in switchgear



3M™ Novec™ 4710 Insulating Gas
C4 fluoronitrile, C4-FN

3M™ Novec™ 5110 Insulating Gas
C5 fluoroketone, C5-FK

Similar performance to SF₆ with
≥ 99% reduction of environmental impact

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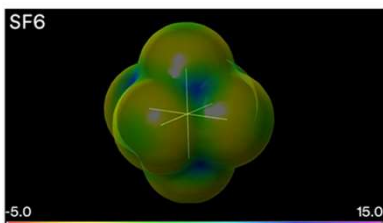


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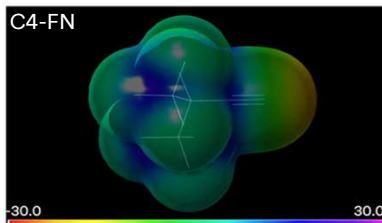
2

Physical characteristics of SF₆ alternatives

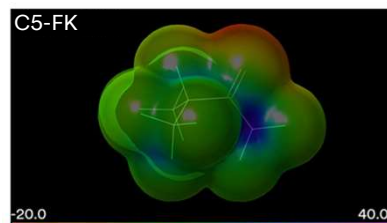
Positive surface area is an important factor impacting insulation characteristics



Positive surface area: 61.3 Å²



128.5 Å²



136.2 Å²

Larger positive surface area → Stronger electron adsorption → Higher insulation characteristics but lower vapor pressure so use in gas mixtures required.

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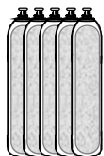
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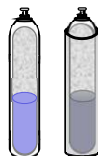
Generating Gas Mixtures

Pre-mixed
gas cylinders



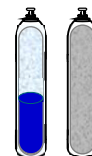
Simple Process that
maintains mix ratio but
multiple cylinders required

Pre-mixed
liquified gas cylinders



Fewer cylinders required but
must be heated above critical temp
(~40°C) to maintain mix ratio

Mixing on demand
from separate cylinders



Fewer cylinders required
but multiple different gases
handled to supply mixing system

Multiple methods available to produce insulating gas mixtures.

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Climate impact of alternative gas mixtures

Gas formulation	100% SF ₆	5% C5-FK in 95% air	5% C4-FN in 95% CO ₂
Pressure in GIS (bar absolute)	6	8	8
Gas density at 25°C (kg/m ³)	39.0	13.4	16.9
GWP of gas mixture	23,500	<1	396
Reduction in GHG emissions over 40-year life of the equipment*	—	>99.9%	>99.5%

*GHG emission reduction compared to SF₆ takes into account GWP, reduced density of the gas mixture and reduced accumulation of gas in the atmosphere due to shorter atmospheric lifetimes.

Reference: Owens, J.; Xiao, A.; Bonk, J.; DeLorme, M.; Zhang, A. Recent Development of Two Alternative Gases to SF₆ for High Voltage Electrical Power Applications. *Energies* 2021, 14, 5051.

Mixtures containing alternative insulating gases
enable significant reductions in GHG emissions compared to SF₆.

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Overview of regulatory requirements for new materials

- New chemicals brought to market are subject to regulation policies such as REACH in Europe, TSCA in US.
- Specific test requirements can be dependent on volume band and results of previous test results.
- Authorities have ability to place restrictions on use of chemicals or even ban their use if it is deemed the risks cannot be adequately managed.

Typical registration requirements	
acute inhalation toxicity	mutagenicity
repeated dose inhalation toxicity	reproductive/developmental toxicity
eye irritation	genotoxicity
skin irritation	chemical safety report

- Registered on global inventories: EU (REACH), US, CA, JP, KR, CN.
- Classified in lowest hazard categories under Classification and Labeling of Chemicals under the Global Harmonized System (GHS).
- Occupational exposure limits have been set to be protective of worker health.

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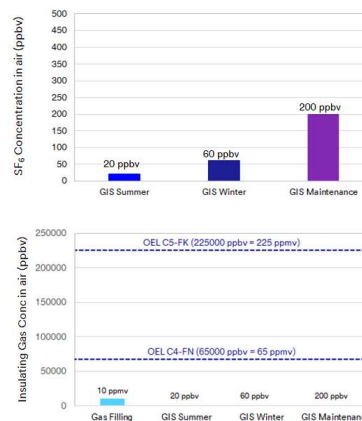
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Insulating Gas Worker Exposure Assessment

Occupation Exposure Limits (OELs) established by 3M Medical Department at 65 ppmv for Novec 4710 gas (C4-FN) and 225 ppmv for Novec 5110 gas (C5-FK)

Material	Common Use	OEL (ppmv, 8-hr TWA)
C4-FN	dielectric insulating gas	65 ppmv
ammonia	ingredient in glass cleaners	25 ppmv
acetic acid	active ingredient in vinegar	10 ppmv
C5-FK	dielectric insulating gas	225 ppmv
2-propanol	active ingredient in rubbing alcohol	200 ppmv
acetone	active ingredient in nail polish remover	250 ppmv



Alternative insulating gases have wide safety margins for workers when used as designed for intended applications in gas insulated electrical equipment.

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Typical degradation products

Arc interruption can create degradation products with higher toxicity compared to the original insulating gas:

Air: NO, NO₂, O₃ (CO)

SF₆: SF₄, S₂F₁₀, SO₂, SOF₂, SO₂F₂, SOF₄, HF

C5-FK: CO, HF, C₃F₆

C4-FN: CO, C_xF_yCN (x≤3), PFIB, HF

References: 1) Tsai, Journal of Fluorine Chemistry, (128) 1345-1352, 2007; 2) CIRED 2017 Paper 0230; 3) CIRED 2017 Paper 0795

All insulating gases can generate hazardous degradation products when exposed to arcing conditions.

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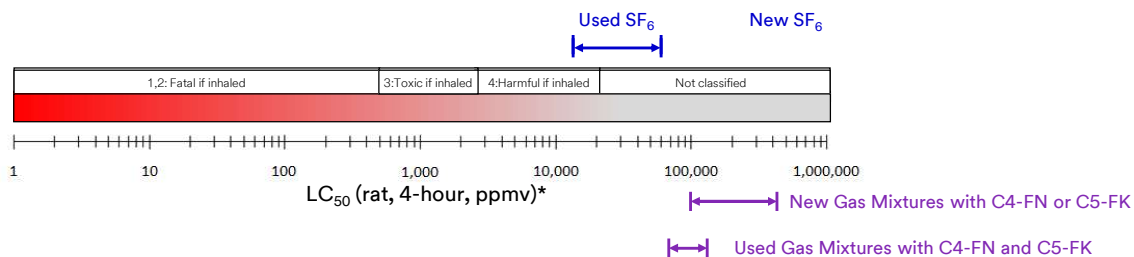
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Typical degradation products

Globally Harmonized System - Acute Inhalation Toxicity Classification



* Concentration lethal to 50% of test animals

Calculated for composite mixture of degradation products $LC_{50\text{mixture}} = \frac{1}{\sum_i \frac{c_i}{LC_{50i}}}$

Reference: CIRED 2021 paper 0268

Degraded alternative insulating gas mixtures
should be handled using procedures and PPE similar to those used with arced SF₆.

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Gas Handling and End of Life

- Gas Handling
 - › mixing to prepare new C4-FN and C5-FK gas mixtures
 - › recovery of gas mixtures from gas-insulated equipment
- Analysis of gas mixtures for composition
- Reprocessing of mixtures to reclaim C4-FN and C5-FK



Gas analysis, handling and recovery processes
have been developed for alternative insulating gas mixtures.

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Summary

- 3M™ Novec™ Insulating Gases (C4-FN, C5-FK) were developed specifically to have the required performance and safety properties for use as alternatives to SF₆ with significant and meaningful reduction of the environmental impact.
- The products are registered on chemical inventories for commercial use in switchgear applications within EU and other regions.
- Extensive toxicological testing to characterize any hazards and establish safe use
→ demonstrated wide margin of safety as dielectric medium in gas-insulated equipment.
- Gas handling and end-of-life processes have been established.

Additional Resources:

www.3m.com/3M/en_WW/sds-search-select-location/
www.3m.com/3M/en_US/novec-us/applications/insulating-gas/
<https://multimedia.3m.com/mws/media/1812234O/3m-novec-4710-health-safety-bulletin.pdf>
<https://multimedia.3m.com/mws/media/1812232O/3m-novec-5110-health-safety-bulletin.pdf>
<https://multimedia.3m.com/mws/media/1950512O/3m-novec-4710-insulating-gas-ramboll-cmr-self-classification-study.pdf>

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