Science. Applied to Life.™

3M™ Novec™ Dielectric Fluids
SF_6 Alternatives for Power Utilities
Workshop for SF_6 Emission Reduction Strategies

Dave Nyberg, Global Marketing Manager, 3M Company

January 2017

Agenda

- SF_6 background
- 3M™ Novec™ Dielectric Fluid Performance
- OEM R&D Activity
- Regulatory Environment
- Testing Equipment
- Safety

SF_6 (Sulfur Hexafluoride) facts

Excellent characteristics for arc quenching and electrical insulation

One of the best insulating media for medium and high voltage power equipment

- Circuit Breakers
- Switchgear
- Gas Insulated Lines

Inert, non-corrosive & thermally stable

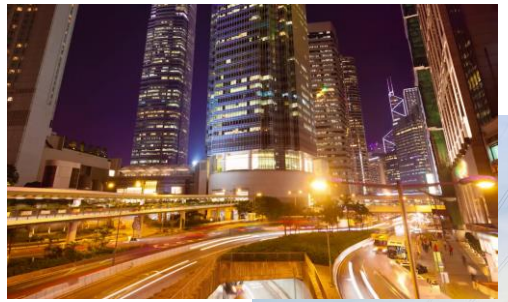
- Excellent arc extinction
- Breakdown products recombine
- Long in service life (decades in closed-system power infrastructure applications)

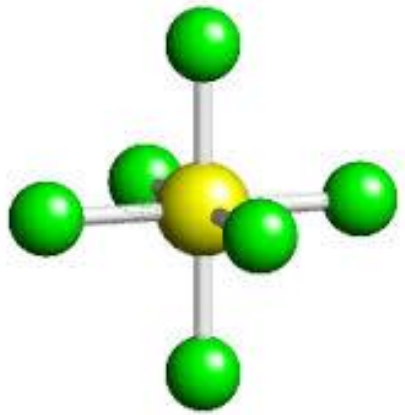
Resulting Byproducts

- S_2F_{10}
- HF
- SF_4 & others

Global Warming Potential **= 23,500**

- One of the highest known GWPs
- Atmospheric lifetime = **3,200 years**





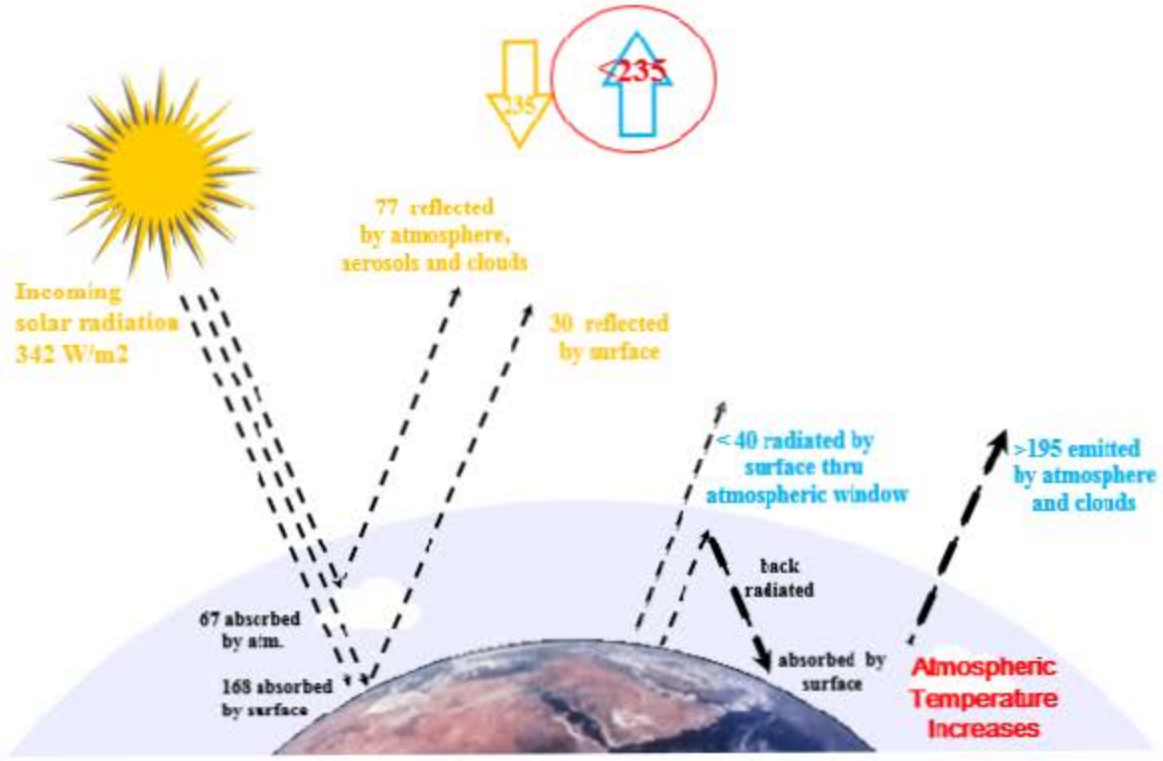
Concerns over SF_6 began in the early 1990s

Atmospheric Lifetimes of Long-Lived Halogenated Species

A. R. Ravishankara, S. Solomon, A. A. Turnipseed, R. F. Warren*

The atmospheric lifetimes of the fluorinated gases CF_4, C_2F_6, c-C_4F_8, $(CF_3)_2$c-C_4F_6, C_5F_{12}, C_6F_{14}, C_2F_5Cl, $C_2F_4Cl_2$, CF_3Cl, and SF_6 are of concern because of the effects that these long-lived compounds acting as greenhouse gases can have on global climate. The possible atmospheric loss processes of these gases were assessed by determining the rate coefficients for the reactions of these gases with $O(^1D)$, H, and OH and the absorption cross sections at 121.6 nanometers in the laboratory and using these data as input to a two-dimensional atmospheric model. The lifetimes of all the studied perfluoro compounds are >2000 years, and those of CF_3Cl, CF_3CF_2Cl, and CF_2ClCF_2Cl are >300 years. If released into the atmosphere, these molecules will accumulate and their effects will persist for centuries or millennia.

Most of the chemicals released into the atmosphere as a result of natural processes or human activities are converted to other forms or are completely removed from the atmosphere within a few years. This happens because most of these molecules react with the major oxidants in the atmosphere or are photolyzed at wavelengths greater than 190 nm. A few species, however, exhibit very low reactivities. We might ask: What happens to molecules that do not react with most of the oxidants in the stratosphere and the troposphere? The answer to this question is not only of fundamental interest but also of practical significance. If an industrially produced chemical



The challenge of finding a replacement for SF_6

ISH 2013
August 25–30, 2013 | Seoul, Korea
18th International Symposium on High Voltage Engineering

OE8-01

PREDICTING THE ELECTRIC STRENGTH OF PROPOSED SF6 REPLACEMENT GASES BY MEANS OF DENSITY FUNCTIONAL THEORY

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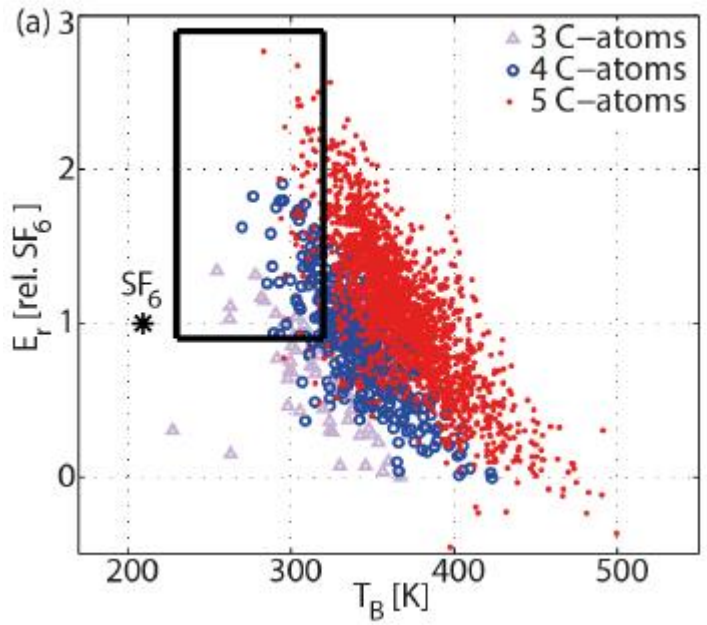
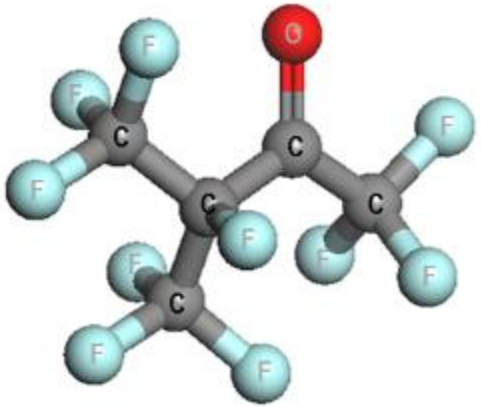


> 2000 compounds evaluated

- Significant challenges to meet the requirements of safety, performance, and reduced GWP
- Very few compounds meet all the requirements

3M™ Novec™ Dielectric Fluids as Alternatives to SF_6

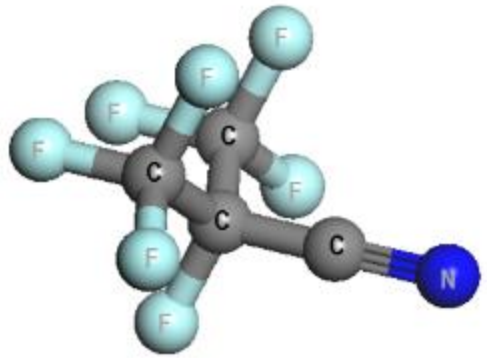


$(CF_3)_2CFC(O)CF_3$

Commercial name:

3M™ Novec™ 5110 Dielectric Fluid

- 1,1,1,3,4,4,4-heptafluoro-3-(trifluoromethyl)- 2-butanone
- CAS # 756-12-7
- C5 ketone



$(CF_3)_2CFCN$

Commercial name:

3M™ Novec™ 4710 Dielectric Fluid

- 2,3,3,3-tetrafluoro-2-(trifluoromethyl) propanenitrile
- CAS # 42532-60-5
- Fluoronitrile or Nitrile

3M™ Novec™ Dielectric Fluid properties versus SF_6

Significantly lower GWP and higher dielectric strength

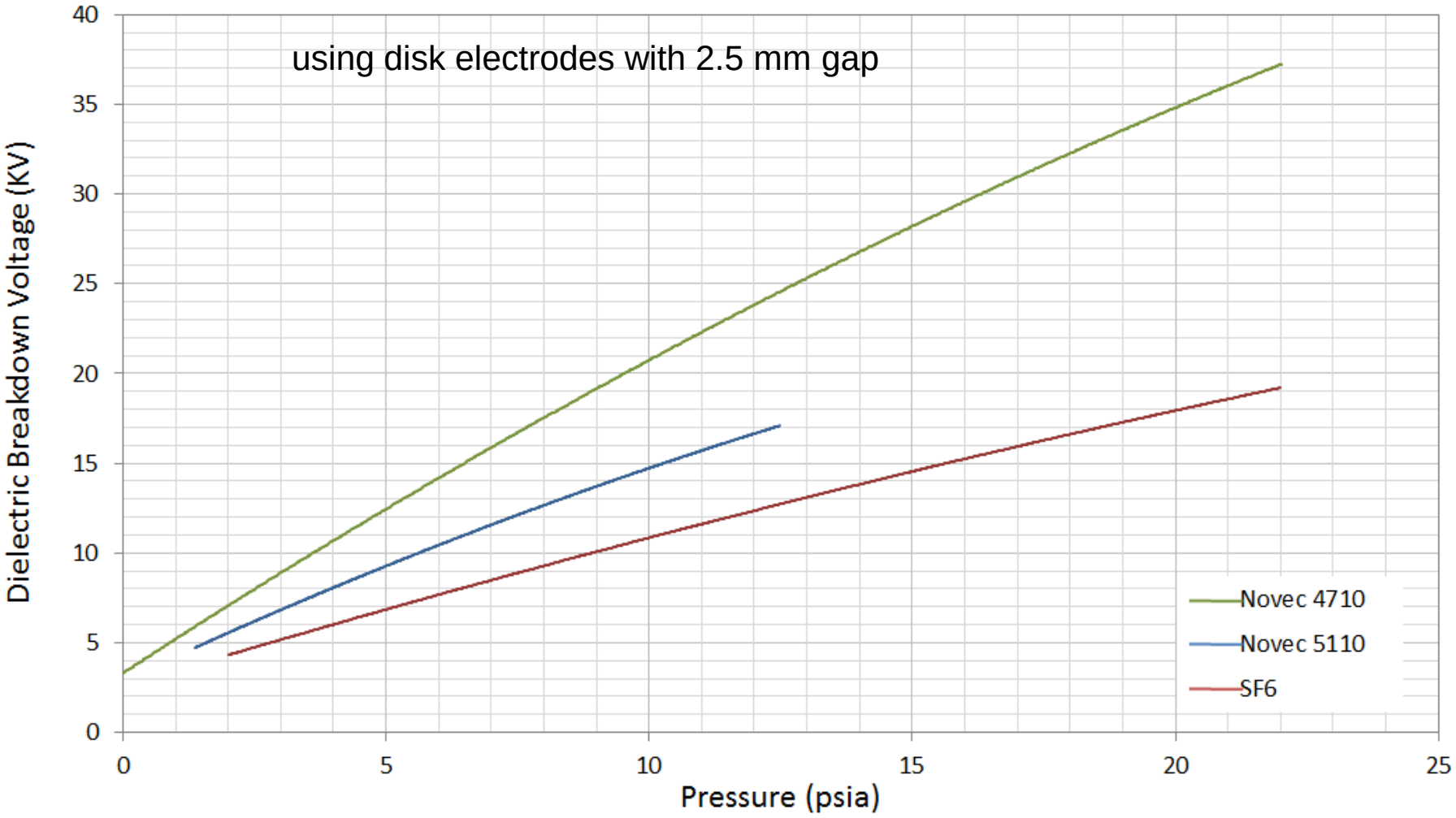
Property (at 25°C)	**Novec 5110**	**Novec 4710**	**SF_6**
Molecular Weight (g/mol)	266	195	146
Flash Point (°F)	nonflammable	nonflammable	nonflammable
Boiling Point (°F)	80.4	23.5	-90.9*
Freezing Point (°F)	-166	-180	-59.3
Gas Density at 14.5 psi (lb/ft^3)	0.67	0.49	0.37
Dielectric Strength at 14.5 psi (kV)	18.4 at sat'n	27.5	14.0
Vapor Pressure (psia)	13.6	36.5	312
Atmospheric Lifetime (years)	0.04	30	3200
Global Warming Potential (100-yr ITH, IPCC 2013 method)	< 1	2100	23500
Ozone Depletion Potential (CFC-11 = 1)	0	0	0

GWP calculated via IPCC 5th Assessment Report method

* sublimation point

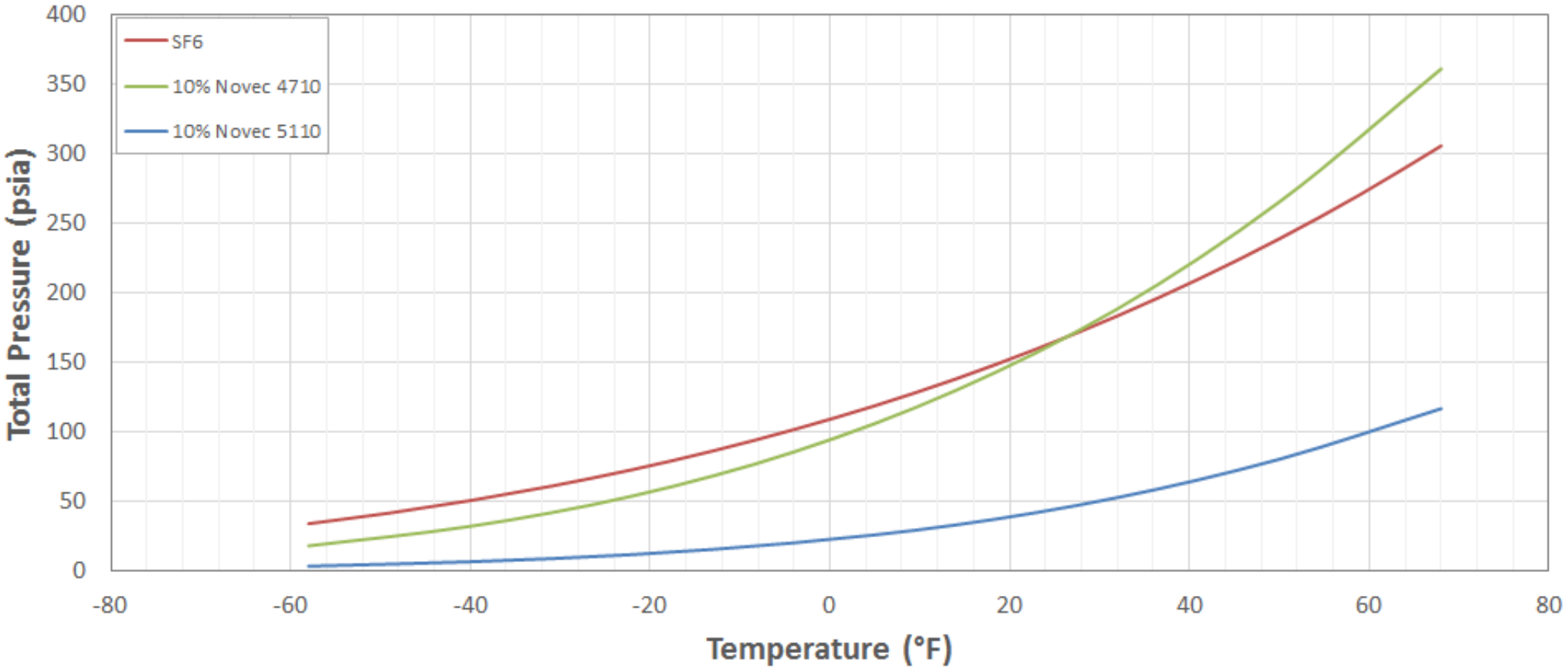
3M™ Novec™ Dielectric Fluid Breakdown Voltage

Dielectric strength exceeds SF_6



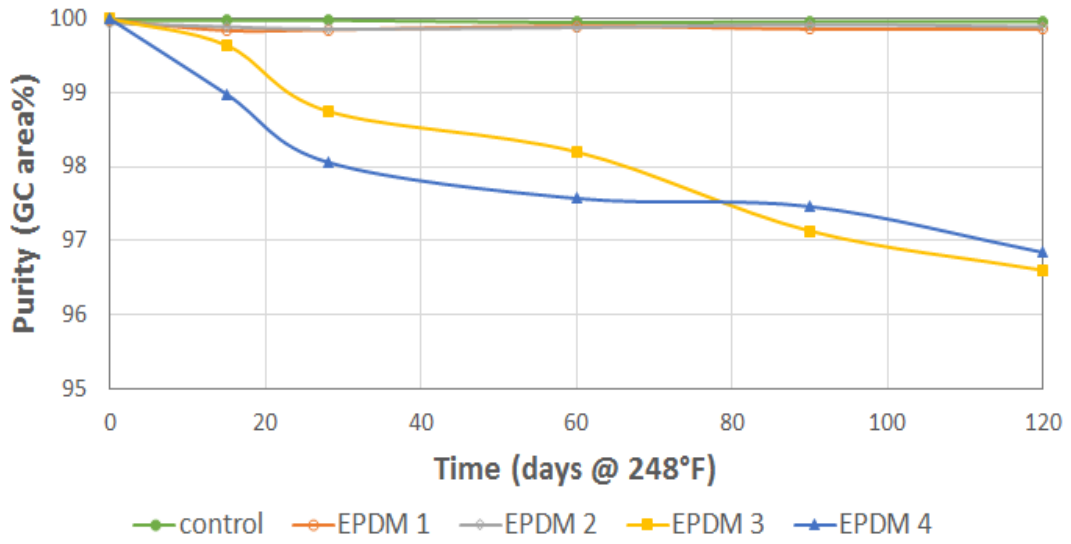
Condensation curves for gas mixtures containing 10 mole%

3M™ Novec™ Dielectric Fluids comparison to SF_6 vapor pressure



3M™ Novec™ Dielectric Fluid compatibility with power equipment materials and components

- Good compatibility with metals
- Compatible with most hard plastics
- Compatibility with elastomers depends upon specific formulation
  - Compounds that retain high moisture levels show reactivity
  - Formulations with basic (high pH) components can result in reactivity
    - Basic carbon black
    - Curatives
    - Acid acceptors
- Some lubricants/greases can contain reactive components, such as those with alcohol functionality
- The most compatible desiccants are 5A molecular sieves, $MgSO_4$ and $CaSO_4$



Global warming potential (GWP) comparisons

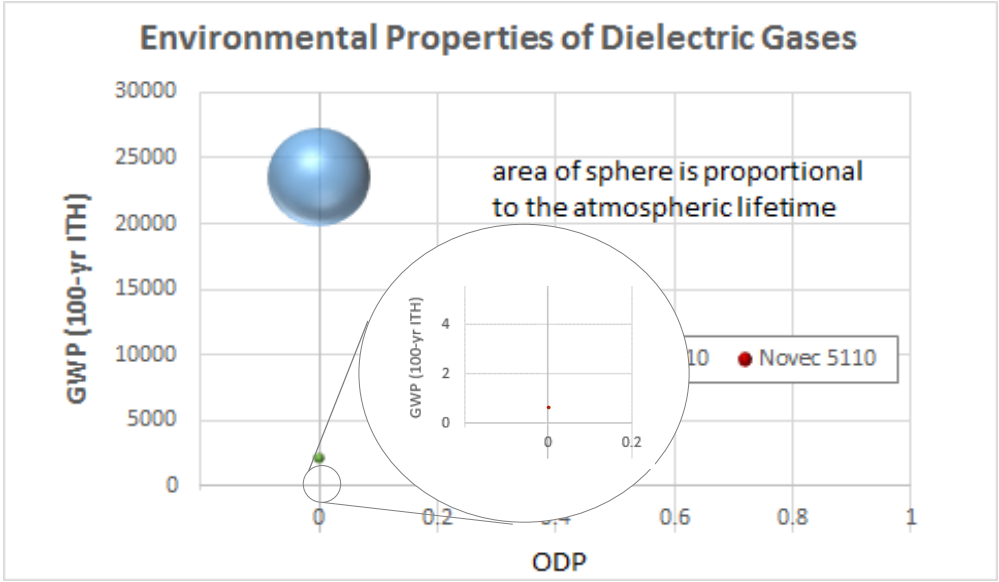
Both Novec™ Dielectric Fluid products offer superior GWP reductions

Property	Novec 5110	Novec 4710	SF_6
Atmospheric Lifetime (years)	0.04	30	3200
Global Warming Potential (100-yr ITH, IPCC 2013 method)	< 1	2100	23500
Ozone Depletion Potential (CFC-11 = 1)	0	0	0

Novec™ 5110 fluid: 99.99% reduction in GHG emissions at all concentrations

Novec™ 4710 fluid: Mixtures with air, N_2 or CO_2 achieve ≥ 98% reduction

Example: 10 mole% Novec 4710 fluid in CO_2 at 6 bar = 98.2% reduction in GHG vs 4 bar SF_6



OEM Innovations with 3M™ Novec™ Dielectric Fluids

The industry is investing in new equipment development

- Early adopter OEMs have equipment active on the grid in Europe
- Both Novec™ 4710 and Novec™ 5110 fluids are in use in Europe
- R&D effort continues around switchgear, breakers, and GIL

For the first time in decades, through the use of Novec™ Dielectric Fluids, a viable option exists to manufacture SF_6 free power equipment with a footprint and performance similar to current GIS equipment

United States Regulatory Activity

Massachusetts and California – early adopters of emission reduction programs

California Environmental Protection Agency
Air Resources Board

- On June 21, 2007, as part of the California Global Warming Solutions Act of 2006 (AB 32), the Air Resources Board (ARB) approved the reduction of sulfur hexafluoride (SF_6) emissions from electricity transmission and distribution equipment as an early action measure.

Maximum Annual SF_6 Emission Rate	
Calendar Year	**Maximum Allowable SF_6 Emission Rate**
2011	10.0%
2012	9.0%
2013	8.0%
2014	7.0%
2015	6.0%
2016	5.0%
2017	4.0%
2018	3.0%
2019	2.0%
2020, and each calendar year thereafter	1.0%

MassDEP
Commonwealth of Massachusetts
Department of Environmental Protection

- "Each federal reporting GIS owner shall ensure that the maximum annual SF6 emission rate for all of its active GIS equipment . . . shall not exceed the following":

Maximum Annual SF_6 Emission Rate	
Calendar Year	Maximum Allowable SF_6 Emission Rate
2015	3.5%
2016	3.0%
2017	2.5%
2018	2.0%
2019	1.5%
2020, and each calendar year thereafter	1.0%

F-gas regulation in Europe

No immediate impact on electrical equipment SF_6 use in Europe

- 517/2014 implemented to reduce the EU's F-gas emissions by two-thirds from 2014 levels by 2030
- Long term goal of reducing overall GHG emissions by at least 80% by 2050 against 1990 levels
- No phase out provisions of SF_6 in 517/2014
- The regulation does have a provision for reviewing the standards again in 2020
- Article 10 requires both switchgear manufacturers and users to train and be certified in all SF_6 handling operations from installation to decommissioning. Regulation 842/2006 required certification only for recovering old and unused SF_6
- Article 12 - manufacturers will need to modify the label content on all new equipment that contains fluorinated GHGs before commercialization
- Articles 4 and 5 waive leakage tests and detection systems of switchgear when the SF_6 it contains is below a certain level or if they are pressure- or density-monitored

Commission Regulation EU No. 517/2014

Lifecycle of power equipment gas

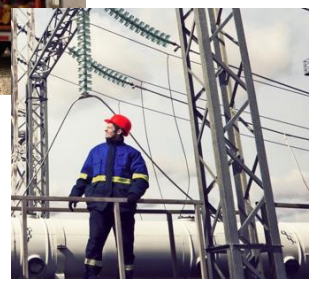
- **Process inputs**
  - Environmental regulations
  - Administrative costs to manage gas programs
  - Equipment innovations
  - GWP reduction initiatives
  - Projected lifecycle and maintenance of equipment

Supply

Commission

Maintenance

Decommission



Dispose

Equipment for mixing, gas handling, and monitoring

The industry is investing in solutions for SF_6 alternatives

DILO

- Service cart
- Gas detector
- Analyzer for gas quality
- Calibrated for g3 gas mixture using Novec™ 4710 Dielectric Fluid

WIKA

Equipment measures the gas composition - CO_2 and Novec™ Dielectric Fluid percentages

Multi-Zone

Multi-Zone Gas Leak Monitor

BACHARACH

H25-IR PRO

An industrial-grade gas leak analyzer

PGM-IR

Portable Leak Detector

21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

D1-305

CIGRE 2014

SF_6 ALTERNATIVE DEVELOPMENT FOR HIGH VOLTAGE SWITCHGEARS

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F. BIQUEZ, Ph. PONCHON

ALSTOM GRID, FRANCE

J. OWENS, M. COSTELLO,
M. BULINSKI, R. VAN SAN*,
K. WERNER

3M COMPANY, USA, (*) BELGIUM

d. Toxicity of the mixtures:

As mentioned above, the toxicity of the gas mixture was compared to ADR – European Agreement concerning the International Carriage of Dangerous Good by Road – where the toxicity of a gas mixture (LC_{50}) is calculated by taking into account the toxicity (LC_{50i}) and the mole fraction (f_i) of each substance (or volume fraction), LC_{50} (mixture) = $1/\sum f_i/LC_{50i}$.

CO_2 has an LC_{50} above 30%v (300000 ppm_v), then for the GIS mixture, the LC_{50} of the total gas would be equal to roughly 120000 ppm_v (12%v) which is a value close to the LC_{50} of SF_6 (above 100000 ppm_v). Additional toxicity measurements made after current interruption test demonstrates that the gas is less toxic than SF_6.

23rd International Conference on Electricity Distribution Lyon, 15-18 June 2015

Paper 0587

ALTERNATIVE GAS INSULATION IN MEDIUM-VOLTAGE SWITCHGEAR

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Safety of personnel is most important in the unlikely event of an internal arc. Personnel should not enter the switchgear room without intensive ventilation of the room following the internal arcing event. This procedure is well known for SF_6 insulated switchgear, but also for air-insulated switchgear. The same procedure is applicable to switchgears with C5 FK/air gas mixtures.

Conclusion for eco-efficient GIS

The investigations and tests have shown that it is feasible to modify existing SF_6 GIS designs allowing the usage of an alternative insulation gas based on a mixture of C5 FK and technical air. The required modifications of the switchgear intended for circuit-breaker applications are limited and the cost impact are in balance with the ecological improvement.

Based on the results of the study, ABB decided to perform type tests for selected variants of a slightly modified ZX2 targeting a technology pilot installation to gain field experience in this new technology.

Thank you

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