3M™ Novec™ Dielectric Fluids
SF₆ Alternatives for Power Utilities
Workshop for SF₆ Emission Reduction Strategies

Dave Nyberg, Global Marketing Manager, 3M Company

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Agenda

• SF₆ 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
The challenge of finding a replacement for SF$_6$

> 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 SF₆

3M™ Novec™ 5110 Dielectric Fluid

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

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 SF₆

Significantly lower GWP and higher dielectric strength

<table>
<thead>
<tr>
<th>Property (at 25°C)</th>
<th>Novec 5110</th>
<th>Novec 4710</th>
<th>SF₆</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Weight (g/mol)</td>
<td>266</td>
<td>195</td>
<td>146</td>
</tr>
<tr>
<td>Flash Point (°F)</td>
<td>nonflammable</td>
<td>nonflammable</td>
<td>nonflammable</td>
</tr>
<tr>
<td>Boiling Point (°F)</td>
<td>80.4</td>
<td>23.5</td>
<td>-90.9*</td>
</tr>
<tr>
<td>Freezing Point (°F)</td>
<td>-166</td>
<td>-180</td>
<td>-59.3</td>
</tr>
<tr>
<td>Gas Density at 14.5 psi (lb/ft³)</td>
<td>0.67</td>
<td>0.49</td>
<td>0.37</td>
</tr>
<tr>
<td>Dielectric Strength at 14.5 psi (kV)</td>
<td>18.4 at sat’n</td>
<td>27.5</td>
<td>14.0</td>
</tr>
<tr>
<td>Vapor Pressure (psia)</td>
<td>13.6</td>
<td>36.5</td>
<td>312</td>
</tr>
<tr>
<td>Atmospheric Lifetime (years)</td>
<td>0.04</td>
<td>30</td>
<td>3200</td>
</tr>
<tr>
<td>Global Warming Potential (100-yr ITH, IPCC 2013 method)</td>
<td>&lt; 1</td>
<td>2100</td>
<td>23500</td>
</tr>
<tr>
<td>Ozone Depletion Potential (CFC-11 = 1)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

GWP calculated via IPCC 5th Assessment Report method

* sublimation point
3M™ Novec™ Dielectric Fluid Breakdown Voltage
Dielectric strength exceeds SF₆

- Using disk electrodes with 2.5 mm gap
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

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**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 SF₆ 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

- 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 (SF₆) emissions from electricity transmission and distribution equipment as an early action measure.

- “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”:

<table>
<thead>
<tr>
<th>Calendar Year</th>
<th>Maximum Allowable SF₆ Emission Rate</th>
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<tbody>
<tr>
<td>2011</td>
<td>10.0%</td>
</tr>
<tr>
<td>2012</td>
<td>9.0%</td>
</tr>
<tr>
<td>2013</td>
<td>8.0%</td>
</tr>
<tr>
<td>2014</td>
<td>7.0%</td>
</tr>
<tr>
<td>2015</td>
<td>6.0%</td>
</tr>
<tr>
<td>2016</td>
<td>5.0%</td>
</tr>
<tr>
<td>2017</td>
<td>4.0%</td>
</tr>
<tr>
<td>2018</td>
<td>3.0%</td>
</tr>
<tr>
<td>2019</td>
<td>2.0%</td>
</tr>
<tr>
<td>2020, and each calendar year thereafter</td>
<td>1.0%</td>
</tr>
</tbody>
</table>
F-gas regulation in Europe

No immediate impact on electrical equipment SF₆ 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 SF₆ 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 SF₆ handling operations from installation to decommissioning. Regulation 842/2006 required certification only for recovering old and unused SF₆
- 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 SF₆ it contains is below a certain level or if they are pressure- or density-monitored
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

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**Dispose**

**Supply**

**Decommission**

**Commission**

**Maintenance**
Equipment for mixing, gas handling, and monitoring

The industry is investing in solutions for SF$_6$ alternatives

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

Equipment measures the gas composition - CO$_2$ and Novec™ Dielectric Fluid percentages
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 (LC50) is calculated by taking into account the toxicity (LC50i) and the mole fraction (fi) of each substance (or volume fraction), LC50 (mixture) = 1/\sum f_i/LC_{50i}.

CO₂ has an LC50 above 30%v (300000 ppmv), then for the GIS mixture, the LC50 of the total gas would be equal to roughly 120000 ppmv (12%v) which is a value close to the LC50 of SF₆ (above 100000 ppmv). Additional toxicity measurements made after current interruption test demonstrates that the gas is less toxic than SF₆.
ALTERNATIVE GAS INSULATION IN MEDIUM-VOLTAGE SWITCHGEAR

Maik HYRENBACH  
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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 SF₆ 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 SF₆ 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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