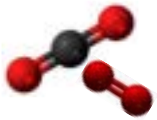
7TH ANNUAL SF_6 GAS MANAGEMENT SEMINAR 2022

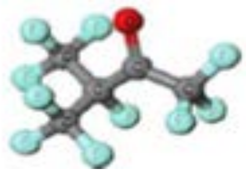
Insulating Fluid Alternatives to SF_6 Gas
Status and Strategy Considerations

SF_6

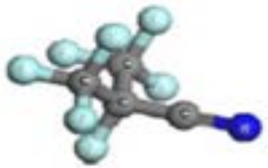
$N_2 + O_2$



$CO_2 + O_2$



C5 - Fluoroketone



C4 - Fluoronitrile

Presented by: George Becker, P.E.

Principal Substation Engineer

POWER ENGINEERS

Agenda

- Provide a high-level description of Gas Insulated Switchgear.

- Discuss the drivers behind the search for SF_6 alternatives.

- Discuss the status and strategy considerations associated with the use of SF_6 alternatives for high voltage switchgear.

GIS Design Features

General Ratings

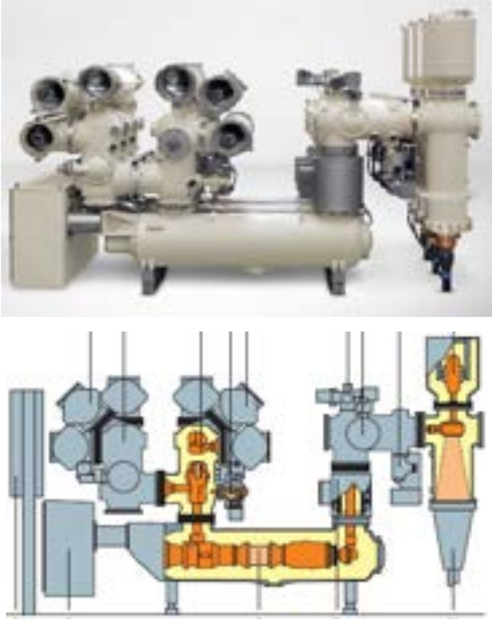
- Max Voltage 1kV to 800kV (up to 1100kV China)
- Rated Current up to 5000A
- Short Circuit Breaking Currents up to 80kA (90kA on the table)
- Switching Impulse Withstand up to 1500kV
- Lightning Impulse Withstand up to 2100kV
- Interrupting times 2 and 3 cycles

Alternatives to SF_6 continue to be developed!

Design Features

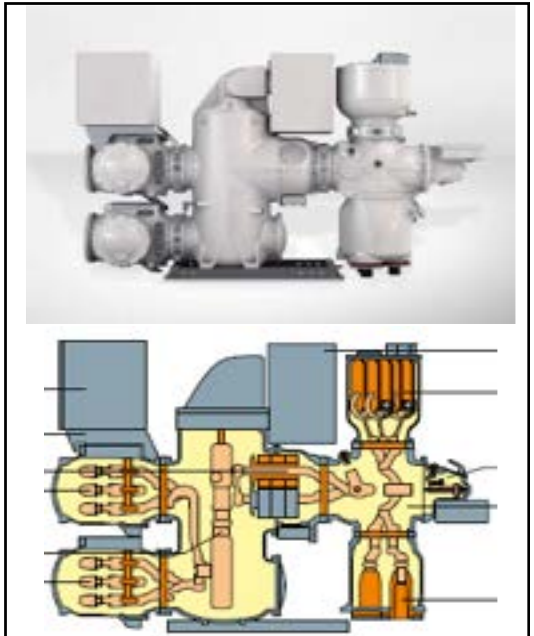
- Modular design, factory pre-assembled and tested units
- Space requirement up to 20 % of comparable AIS
- High Safety (enclosed energized components)
- Protected against aggressive environmental conditions
- Continuous monitoring of SF6 density
- High seismic resistance
- Sealed for operating life > 50 years
- Major inspection: not before 25 years

High-Level Description of GIS



Single-phase encapsulated
245kV to 800kV, 5000A, 63kA

High-Level Description of GIS



Three-phase encapsulated
72.5kV to 170kV, 4000A, 63kA

High-Level Description of GIS

Single-phase encapsulated
5kV to 40.5kV, 2500A, 40kA

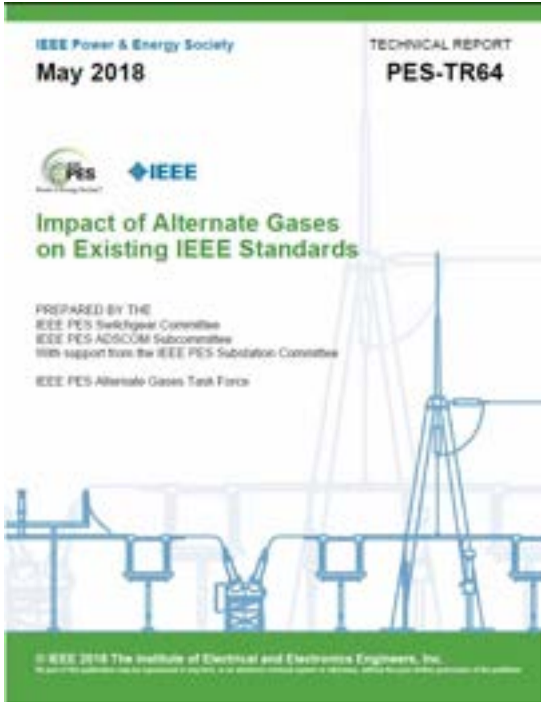
High-Level Description of GIS

Introduction

- SF_6 has a proven track record in the power industry since the 1960s.
- SF_6 advantages are well understood and documented both in industry and academia.
  - Excellent dielectric.
  - Excellent heat transfer.
  - Arc quenching properties contributed to making switchgear smaller, lighter, more cost-effective and more reliable.
  - Nontoxic (in a pure state), nonflammable, noncorrosive properties allow for ease of installation and ease of handling.
  - Chemically inert
- Extremely high Global Warming Potential (GWP)—namely, its long lifetime and high absorption potential.

Industry Activities

- New gases and gas mixtures have emerged and have potential for replacing SF_6.
- IEC, CIGRE and Current Zero Club are continually investigating and have published papers and studies and embarked on pilot projects.
- IEEE Joint Task Force published Technical Report TR64, Impact of Alternate Gases on Existing IEEE Standards – 2018.



Industry Standards and Brochures

- IEEE Switchgear Working Group C37.100.7 - Performance Evaluation of SF_6 Alternatives - 2021
- IEEE Substation Working Group C37.122.10 - Guide for Handling Non-Sulphur Hexafluoride (SF_6) Gas Mixtures for High Voltage Equipment – 2022
- IEC 62271-4 High-voltage switchgear and controlgear - Part 4: Handling procedures for gases for insulation and/or switching - 2022
- CIGRE - A3.41 Interruption and switching performance with SF_6 free switching equipment - 2021
- CIGRE - D1.67 Dielectric performance of non-SF_6 gases and gas mixtures for gas insulated systems - 2020
- CIGRE - B3.45 Application of non-SF_6 gases or gas mixtures in MV and HV gas-insulated switchgear – 2020
- CIGRE – Joint A3/B3.60 User Guide for Non-SF_6 Gases and Gas Mixtures in Substations - 2023

Regulatory Drivers

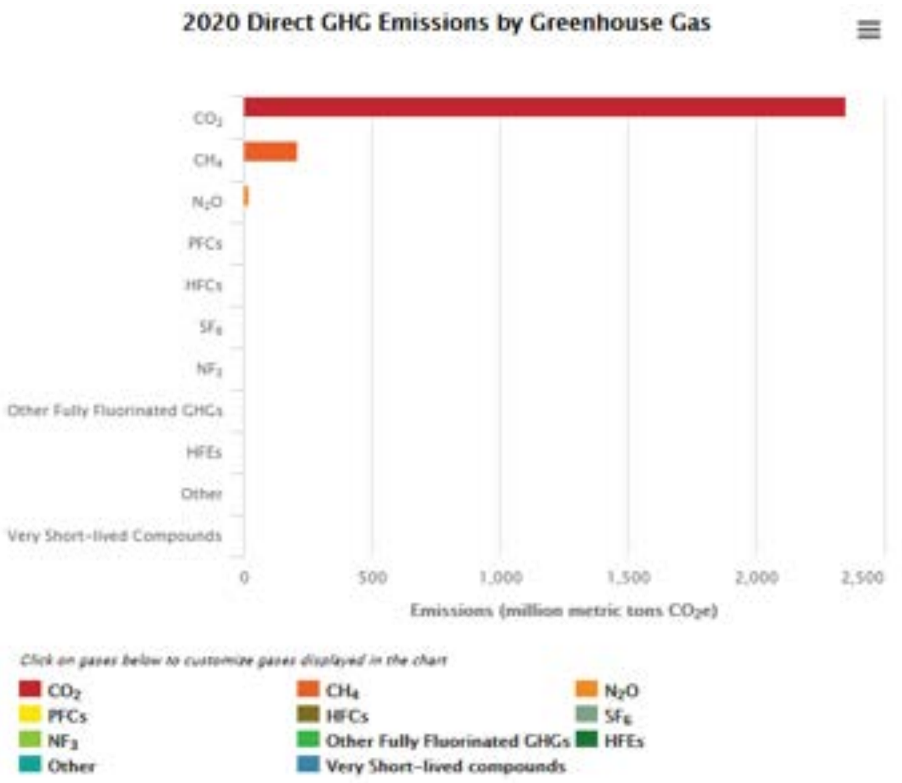
- SF_6 is classified as a greenhouse gas.
- SF_6 is subject to all regulations related to the reduction of greenhouse gas emissions.
- Mandatory greenhouse gas (GHG) emissions reporting through the SF_6 Emission Reduction Partnership for Electric Power Systems required by the EPA began in 2010.

Emissions Facts

For reporting year (RY) 2020, over 8,000 facilities and suppliers reported to the Greenhouse Gas Reporting Program (GHGRP). Among these reporters,

7,634 facilities in nine industry sectors reported direct emissions;

Reported direct emissions totaled 2.60 billion metric tons carbon dioxide equivalent (CO_2e);



Emissions Facts

- In 2020, the total CO_2e (carbon dioxide equivalent) reported direct emissions subject to mandatory reporting to the EPA from all sources was 2.60 billion metric tons CO_2e.
- SF6 emissions from the electric utility industry and electrical equipment manufacturers in 2020 accounted for approximately 2.3 million metric tons CO2e, or less than 0.1% of all sources reporting CO2e emissions to the EPA.

The emissions trend for SF_6 (i.e., CO_2e) has been declining. SF_6 emissions trends have been significantly declining for the members of the SF_6 Emission Reduction Partnership, in a collaborative, voluntary effort between EPA and the electric power industry.

Emissions Facts

- SF_6 emissions from the electric utility industry and electrical equipment manufacturers in 2020 accounted for approximately 2.3 million metric tons CO_2e, or less than 0.1% of all sources reporting CO_2e emissions to the EPA.

Number of reporters and emissions in the electrical equipment production and use sector (as of 8/7/2021)

Electrical Equipment Sector - Greenhouse Gas Emissions Reported to the GHGRP

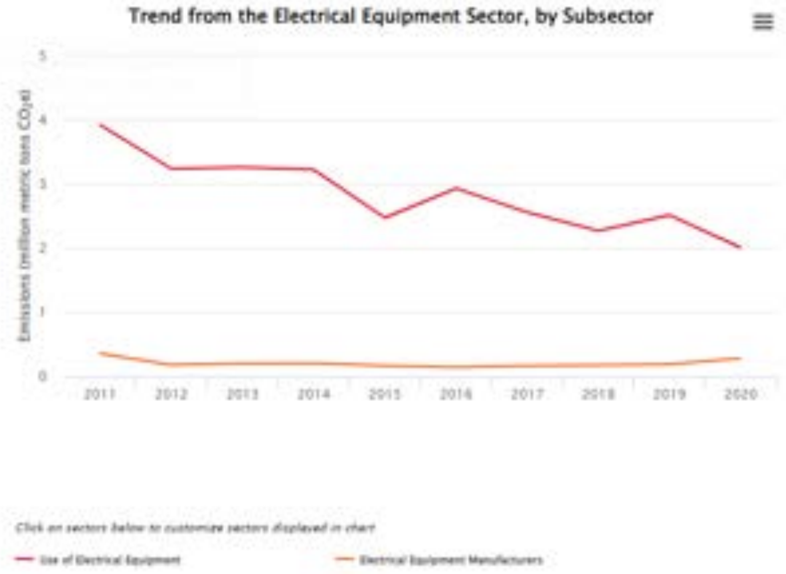
(all emissions values presented in million metric tons CO_2e)

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Number of facilities:	127	128	127	125	112	95	83	90	91	94
Total emissions (CO_2e):	4.3	3.4	3.5	3.4	2.6	3.1	2.7	2.4	[illegible]	2.3
Emissions by greenhouse gas (CO_2e)										
• Carbon dioxide (CO_2):	**	**	**	**	**	**	**	**	**	**
• Methane (CH_4):	**	**	**	**	**	**	**	**	**	**
• Nitrous oxide (N_2O):	**	**	**	**	**	**	**	**	**	**
• Perfluorocarbons (PFCs):	**	**	**	**	**	**	**	**	**	**
• Sulfur hexafluoride (SF_6):	4.3	3.4	3.4	3.4	2.6	3.1	2.7	2.4	[illegible]	2.3

Number of reporters and 2020 emissions (CO_2e) per electrical equipment industry subsector

Industry Sector	2020 Number of Reporters	2020 Emissions (million metric tons CO_2e)
Use of Electrical Equipment	89	2.0
Electrical Equipment Manufacturers	5	0.3

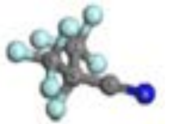
Trend of Annual Reported GHG Emissions by Subsector (as of 8/7/2021)

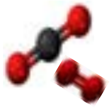


Gas Mixture “Frontrunners”

- Several potential gas mixtures using gas circuit breaker interrupter technology and vacuum circuit breaker interrupter technology have emerged:
  - Fluoroketone (C5), carbon dioxide (CO_2) and oxygen (O_2). Chemical compound: $C_5F_{10}O+CO_2+O_2$
  - Fluoronitrile (C4), carbon dioxide (CO_2) and oxygen (O_2). Chemical compound: $C_4F_7N+CO_2$
  - Carbon dioxide and oxygen. Chemical compound: 70% CO_2 and 30% O_2
  - Technical grade (synthetic) air. Chemical compound: 80% N_2 and 20% O_2


C5 - Fluoroketone


C4 - Fluoronitrile

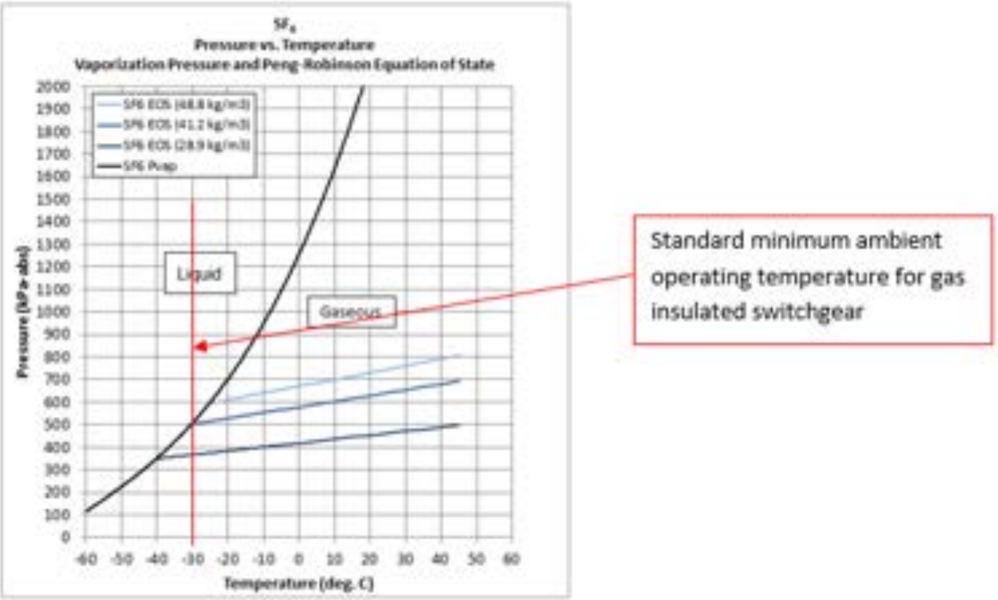

$CO_2 + O_2$


$N_2 + O_2$

Facts About Emerging Gas Mixtures

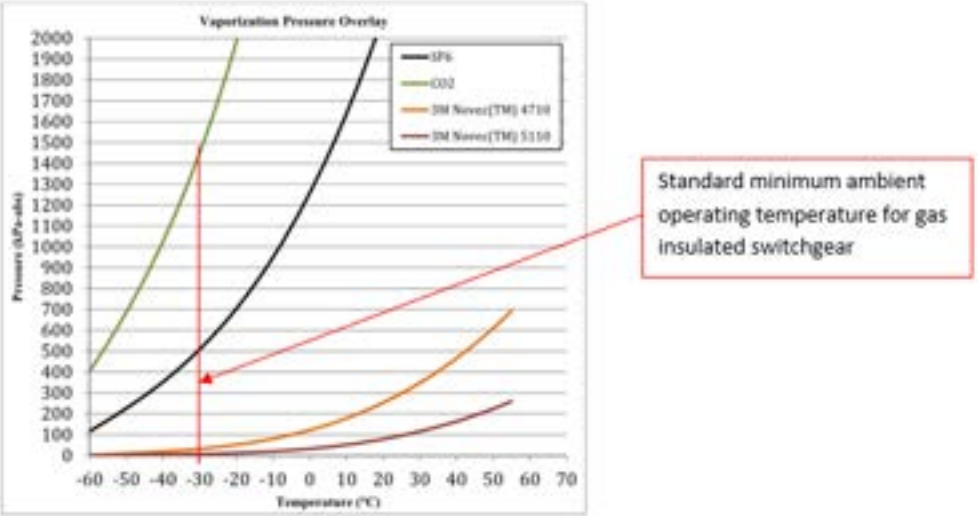
			Natural Origin Gas Mixtures (NOGs)		Fluorinated Gas Mixtures	
		Sulfur-hexafluoride	Clean-Air	Carbon Dioxide and Oxygen	C4-Fluoronitrile	C5-Fluroketone
Base Gas	Chemical Formula	SF_6	80% N_2 + 20% O_2	70% CO_2 + 30% O_2	$(CF_3)_2CFCN$	$(CF_3)_2CFC(O)CF_3$
	$CO2_e$(GWP)	23,500	0	<1	2,210	1
	Boiling Point	-64°C	<-183°C	-50C	-5°C	+27°C
	Dielectric Strength	1.00	0.43	0.77	2.20	1.70
Gas Mixture	Background (gases)	Pure or with N_2 or CF_4	80% N_2 + 20% O_2	70% CO_2 + 30% O_2	~90% CO_2	~90% O_2 With N_2 or CO_2
	$CO2_e$(GWP)	23,500	0	<1	~380	<1
	Lowest Operating Temperature	-30°C *	-50°C	-50C	-30°C	0°C to +5°C -20°C possible
Internal Arc Reaction	Decomposition Products	HF, S_xF_y, SOF_x, F_2, SO_x, CF_4	If applicable: O_3, NO_x	CO, O_3	CO, HF, C_nF_{2n+2}, other Fluorinated Compounds	CO, HF, COF_2, C_xF_y, other Fluorinated Compounds
	Toxicity of Decomposition Products	Slightly toxic (Hodge-Sterner)	Typically None	Relatively harmless (Hodge-Sterner)	Practically non-toxic (Hodge-Sterner)	

Vapor Pressure of SF_6



- SF_6 has been used successfully for many years as a single-component gas in high- voltage switchgear.
- Most switchgear is required to operate at minimum ambient temperature of -30°C.
- SF_6 will be 100% gas only at vapor pressure of 500 kPa-abs or lower at -30°C.

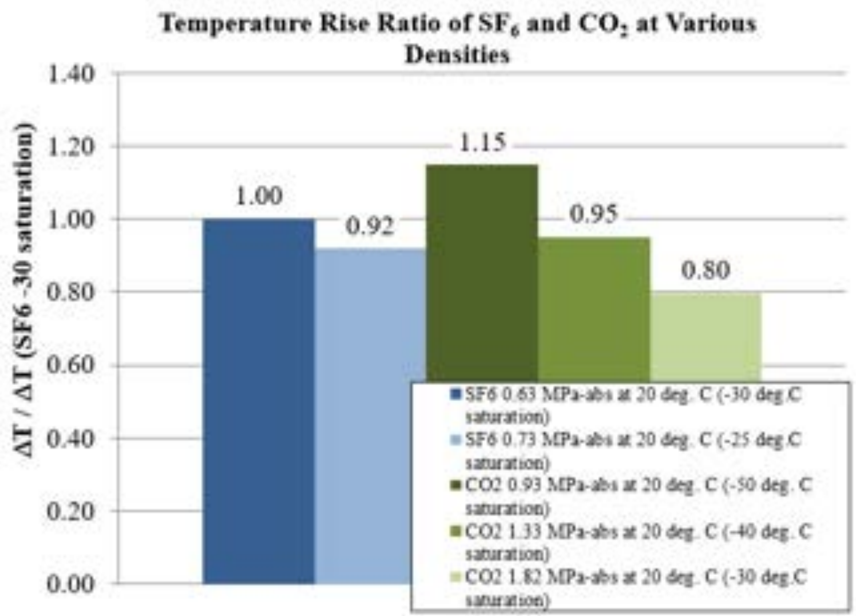
Vapor Pressures of C4 and C5



- When condensation occurs, gas density drops rapidly along with dielectric performance.
- For CO_2, C4 (Novec™ 4710) and C5 (Novec™ 5110), the vapor pressures at -30°C are 1430, 31.4 and 6.7 kPa-abs, respectively.
- This explains the need for additional diluent CO_2 in the case of the alternative gases.
- Their vapor pressures are low compared to SF_6, and they will condense at much lower pressures than SF_6 especially at a minimum operating temperature of -30°C.

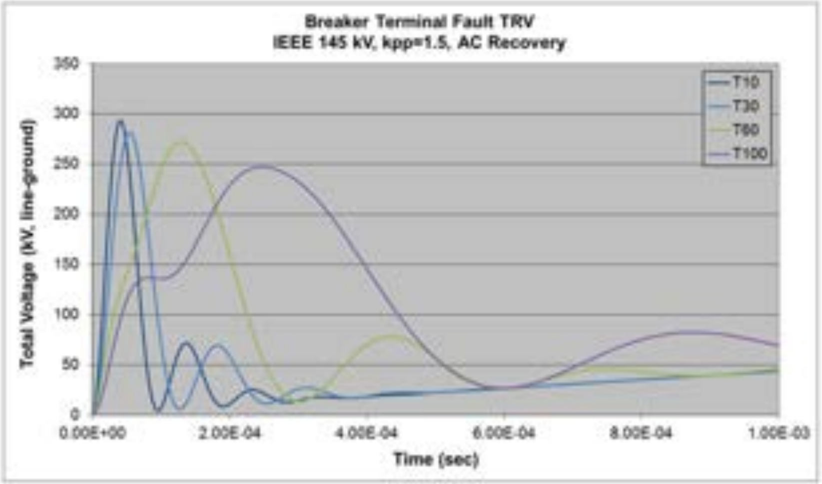
Heat Transfer in All Gas Mixtures

- Only CO_2 is compared with SF_6 because CO_2 dominates the molar fraction of the mixtures.
- In mixtures using CO_2, C5-Fluoroketones and C4-Fluoronitriles, the dielectric gases other than CO_2 have low molar fractions and therefore do not dominate the heat transfer behavior.
- It is possible to fall short of, meet or exceed the thermal behavior of SF_6 with CO_2 or mixtures dominated by CO_2.



Circuit Interruption and Switching

- The core function of transmission and distribution switchgear is to clear faults within the designated time to minimize their impact and ensure system stability and performance.



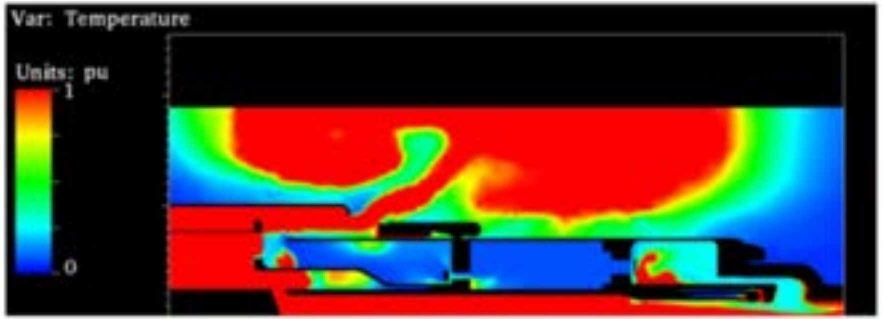
TRV's for 145 kV breaker; first pole to clear factor of 1.5

Terminal faults T10 and T30 will provide the greatest stress, testing the hot dielectric recovery capability of the arc-quenching gas or gas mixture.

Circuit Interruption and Switching

- Successful terminal fault performance includes management of hot exhaust gases.
- Long arcing times are the most severe condition for the exhaust gasses in an interrupter.
- Long arcing times supply the most arc energy to the interruption process.
- Hot dielectric strength of pure SF_6 is well understood.
- The same level of understanding is possible for each SF_6 alternative and requires investments in Computational Fluid Dynamics simulations as well as validation power tests.

HIGH-PRESSURE GAS INTERRUPTERS USING FLUORINATED AND NATURAL ORIGIN GAS MIXTURES

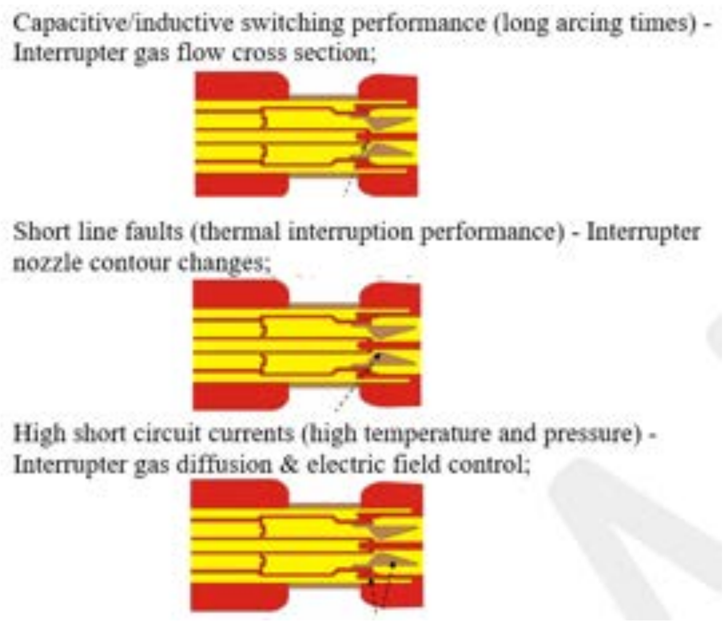


Axisymmetric CFD simulation showing hot gas exiting the interrupter

Circuit Interruption and Switching

- The standard short line fault (SLF) duty is particularly stressful for the thermal recovery of the gas gap in a gas interrupter.
- This is because of the minimal time delay and high rate of rise of recovery voltage (RRRV).
- The ability of SF_6 breakers to interrupt the short line fault duty without additional external capacitance (no intentional delay) has become a highly competitive goal for manufacturers.
- SF_6 alternatives will reset this activity, and manufacturers will again be competing to develop product that can fulfill the SLF requirement at 40, 50 and 63 kA without additional capacitance.

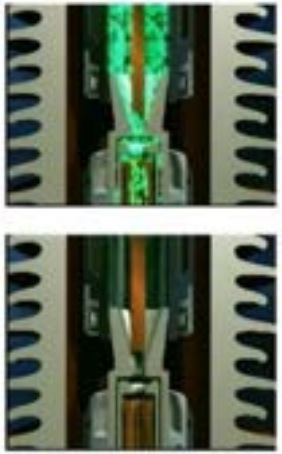
HIGH-PRESSURE GAS INTERRUPTERS USING FLUORINATED AND NATURAL ORIGIN GAS MIXTURES



Circuit Interruption and Switching

- Pure SF_6 mostly recombines after arcing and dissociation.
- Partial decomposition of C5-Fluoroketones, C4-Fluoronotriles and NOGs, do not fully recombine after high current arcing and dissociation.
- For SF_6 alternatives, in addition to contact and nozzle wear, there is degradation of the gas and long-term effects on the performance of the equipment.
- Reconsideration of the service capability tests should be made considering the possibility for permanent gas decomposition.

HIGH-PRESSURE GAS INTERRUPTERS USING FLUORINATED AND NATURAL ORIGIN GAS MIXTURES

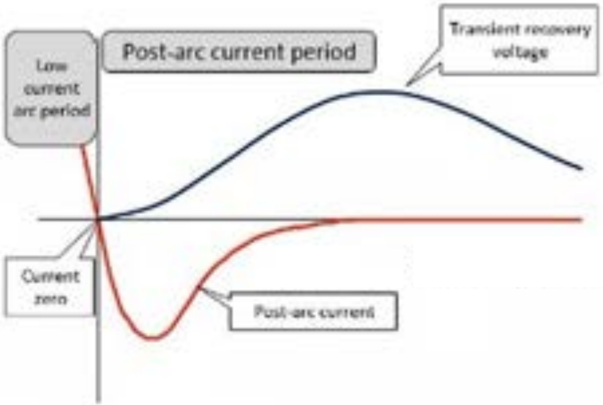


Limitation 145 kV class, 3150 A continuous current rating, 50 kA interrupting rating

Circuit Interruption and Switching

- C5-Fluoroketones, C4-Fluoronotriles and NOGs have a higher post arc current and higher transient pressure peaks.
- Capacitive switching capability is equivalent to SF_6.
- Low short circuit duties (T10 & T30) require slightly higher blow pressure compared to SF_6.
- High short circuit duties (T100) are similar, but the exhaust cooling system needs to be adapted.
- Short-line fault duties (L75 & L90) performance are 20% lower then SF_6.

HIGH-PRESSURE GAS INTERRUPTERS USING FLUORINATED AND NATURAL ORIGIN GAS MIXTURES



Circuit Interruption and Switching

HIGH-PRESSURE GAS INTERRUPTERS USING FLUORINATED AND NATURAL ORIGIN GAS MIXTURES

	CO_2 + Fluoroketone
Fault interruption (dielectric phase)	Derating 245 kV, 50 kA, 50 Hz to 170 kV, 40 kA, 50 Hz gives equal performance to SF_6. O-CO sequence and condition check successful. T10 results indicate that ITRV may be achievable.
Fault interruption (thermal phase)	~20% reduction compared to SF_6 SF_6 60 Hz design is reduced to 50 Hz
Low Current GCB Switching	Derating 245 kV, 50 kA, 50 Hz to 170 kV, 40 kA, 50 Hz gives adequate performance as indicated by dynamic cold characteristic tests. Cold dielectric strength approximately 5% reduction compared to SF_6 at 0.45 MPa-abs (-40 deg. C). Implies approximately 50% reduction compared to SF_6 at 0.7 MPa-abs (-30 deg. C) (see fig. 12)
Practical Experience	GIS 8 bays - 170 kV, 40 kA indoor GIS installed at EWZ in Zurich (2015)

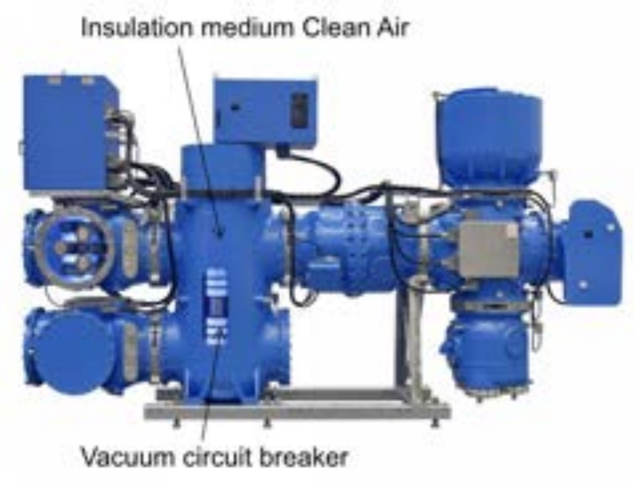
	CO_2 + Fluoronitrile
Fault interruption (dielectric phase)	145 kV, 40 kA, 50 Hz successful for T10, T30, T100a and OP2
Fault interruption (thermal phase)	145 kV, 40 kA, 50 Hz SLF successful after adaptation to the physical characteristics of CO_2. In [5] the authors describe the size of the chamber as, "comparable with existing SF_6 self-blast chambers".
Low Current GCB Switching	145 kV, 40 kA, 50 Hz capacitive switching test was successful but the specific rating is not disclosed. See fig. 13
GIS Switching	145 kV, 40 kA, 50 Hz Disconnect Switch and High Speed Grounding Switch 1600 A bus transfer current successful with behavior similar to SF_6. Bus-charging is not required but successfully completed. Induced current tests of the grounding switch successful with behavior similar to SF_6. 420 kV, 50 Hz Disconnect Switch Total test pressure 0.55 MPa-abs (0.51 MPa CO_2 + 0.04 MPa C_4F_7N) Successful 1600 A, 20 V bus transfer test with stable arcing time and contact wear similar to SF_6.
Practical Experience	420 kV GIL at National Grid (2016)

Circuit Interruption and Switching

- For equipment using "technical grade air" and vacuum interrupters, the issues associated with gas decomposition, gas recombination and hot dielectric recovery are not applicable.
- The "technical grade air" that insulates the vacuum interrupter, bus bars and any other devices must be at a high pressure, particle free and free of humidity to ensure that the breakdown strength is enough for the required voltage rating.

Limitation 145 kV class, 3150 A continuous current rating, 40 kA interrupting rating

VACUUM INTERRUPTERS INSULATED WITH NATURAL ORIGIN GAS MIXTURES



Circuit Interruption and Switching

	N2 + O2 Technical Grade Air		
Fault interruption (dielectric phase)	145kV, 40kA, 50/60 Hz successful for T10, T30, T100		
Fault interruption (thermal phase)	145kV, 40kA, 50/60 Hz SLF successful		
Low Current GCB Switching	145kV, 40kA, 50/60 Hz capacitive switching test successful		
GIS Switching	Rated voltage	up to	145 kV
	Rated frequency		50/60 Hz
	Rated short-duration power-frequency withstand voltage (1 min)	up to	275 kV
	Rated lightning impulse withstand voltage (1.2 / 50 µs)	up to	650 kV
	Rated normal current – busbar	up to	3150 A
	Rated normal current – feeder	up to	3150 A
	Rated short-circuit breaking current	up to	40 kA
	Rated peak withstand current	up to	108 kA
	Rated short-time withstand current (up to 3 s)	up to	40 kA
Practical Experience	72.5kV live tank circuit breaker installed in Germany (2010) 145kV live tank circuit breaker installed in Germany (2016) 145kV voltage transformers installed in Germany (2016) 72.5kV GIS installed in Denmark offshore wind (2017)		

VACUUM INTERRUPTERS INSULATED WITH GAS MIXTURES

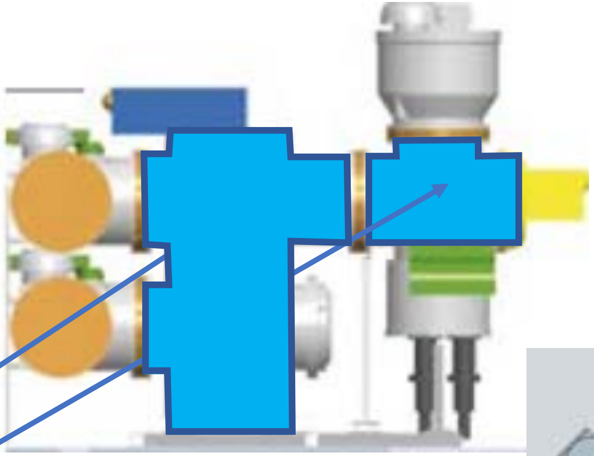
- Vacuum interrupter design must be capable of the required basic insulation level (BIL), continuous current carrying capability and interrupting capability at the rated voltage.

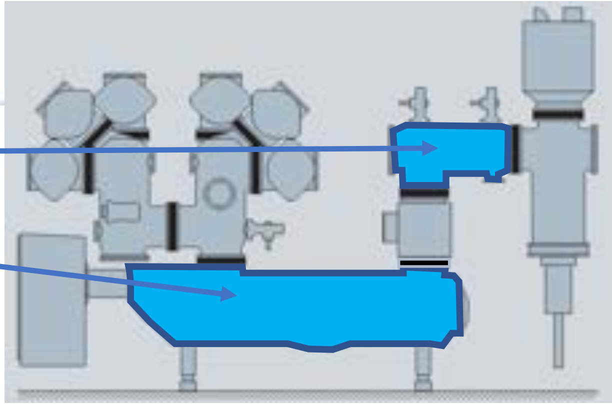
Additional Practical Experience:

- 72.5 kV GIS installed Europe/Asia offshore wind (2018)
- 145 kV Live tank circuit breakers Europe/USA (2020)
- 145 kV Dead tank circuit breakers USA (2021)
- 145 kV GIS installed Europe (2020)/USA (2022)

Circuit Interruption and Switching

SHORT-TERM DESIGN SOLUTIONS TO CIRCUIT INTERRUPTION AND SWITCHING DEFCIENCIES





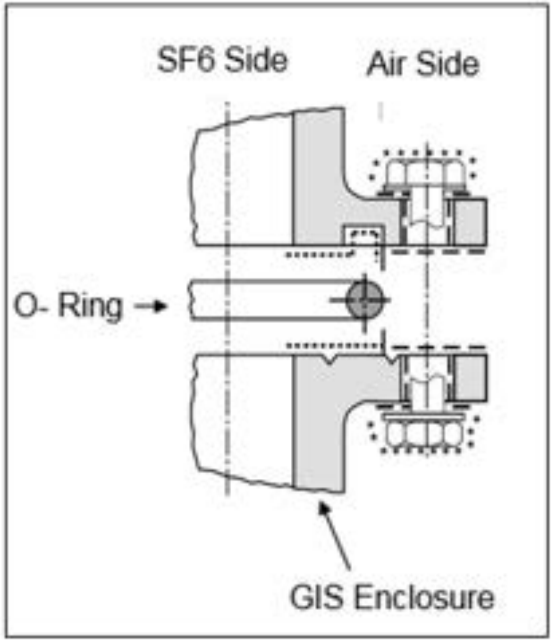
- Use of SF_6 alternative gas mixtures in all components of the switchgear except the circuit breaker and high-speed grounding switches where ratings greater than 145 kV, 50 kA interrupting/fault closing are required.

Gas Mixture Stability

- Gas mixture homogeneity
  - If liquefaction of one component occurs due to low temperature, then some time is required before homogeneity (and full dielectric capability) is restored.
- Extensive testing must continue, to assess the gases and gas mixtures:
  - To ensure that they retain their useful properties in the presence of different environments and other substances.
  - To ensure that they are compatible with all materials used to construct the HV switchgear over the life of the equipment.
  - To ensure that partial discharges do not induce reactions decomposing the gas mixtures into other chemical compounds, especially potentially harmful chemical compounds.

Gas Tightness of the Switchgear

- The permeation rates of alternative gases and carrier gases are different.
- Carrier gases such as CO_2 and all the leading alternative gases used in the gas mixtures must be tested individually for switchgear enclosure permeability.
- The permeability factor of CO_2 is up to 5 times higher than that of SF_6.
- The flange sealing systems must be able to mitigate against changes the partial pressure makeup of the gas mixture, which would jeopardize the dielectric/insulation properties of the gas mixture.



Separation-Aging-Decomposition

- Gas mixtures remain homogeneous over long periods of time even if the temperature cools down to minimum temperature, if the saturated vapor pressure of the gas is not reached, and no liquefaction happens.
- For the C5+CO_2+O_2 and C4+CO_2+O_2 gas mixtures, aging tests showed no detectable decrease in the purity of the base gases.
- With SF_6 gas during switching, arc-quenching resonance capture of free electrons occurs and there is SF_6 gas decomposition.
- However, after switching is completed and arc quenching has ended, then dissociative attachment occurs and there is recombination of the SF_6 gas.
- C5-Fluoroketones and C4-Fluoronitriles <u>do not</u> fully recombine after disassociation because of high temperature arcs and partial decomposition.

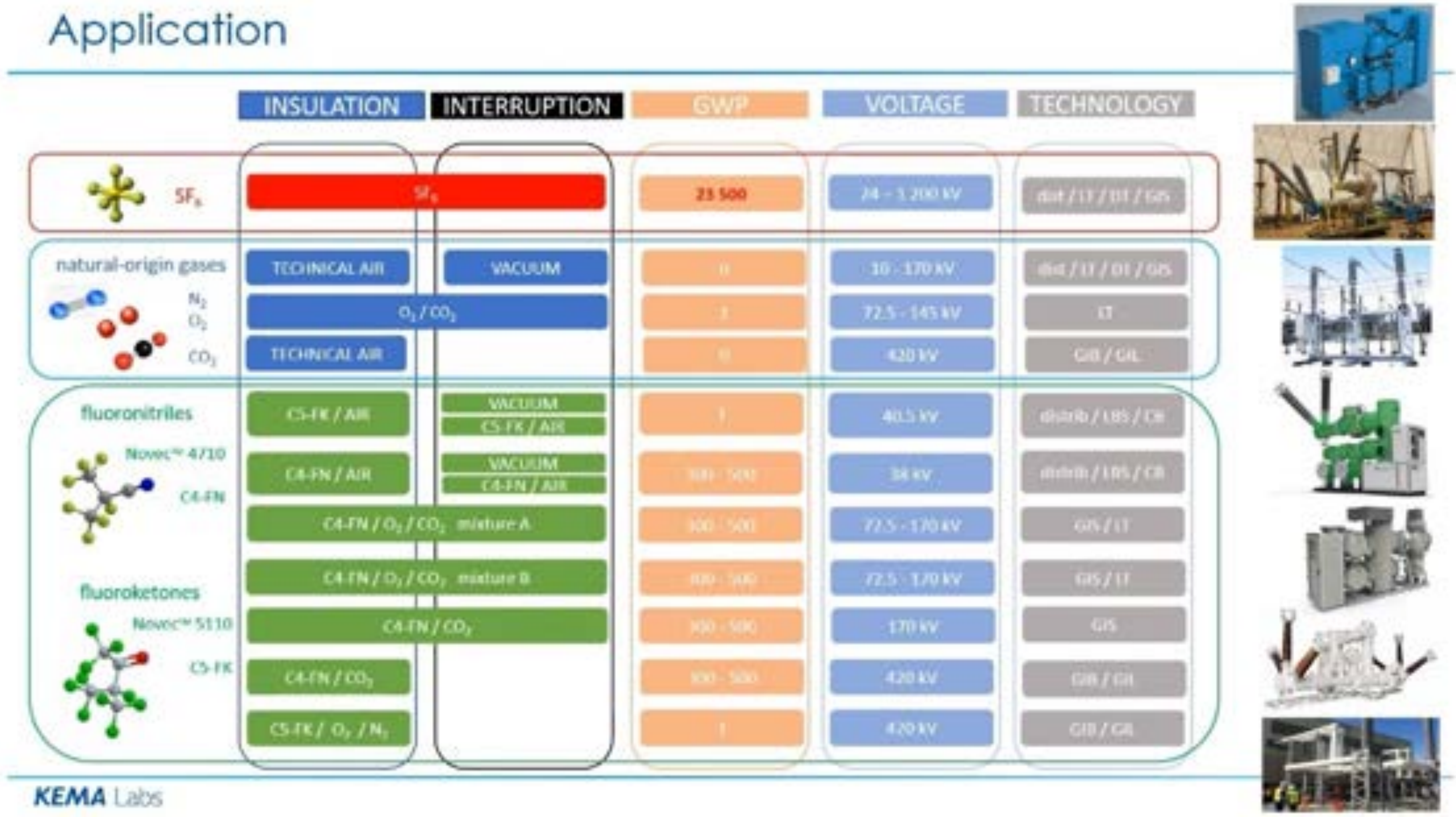
Gas Mixture Handling

- The use of multiple gas mixtures in equipment produced by different manufacturers presents an increased complexity in how users must handle these gas mixtures.
- The following are some operating concerns of users:
  - Multiple variations of filling equipment types
  - Homogeneity of gas mixtures
  - Multiple procedures for gas processing
  - Multiple types of labeling criteria
  - The need for multiple failsafe connections (different valves for different mixtures and identification)
  - Multiple gas handling standards and guides
  - Multiple MDS sheets
  - Base gas toxicity
  - Varied arcing decomposition by-products and how to handle them
  - Multiple gas detection equipment variations
  - Unequal gas leakage due to molecular size variations
  - Multiple gas mixture testing scenarios

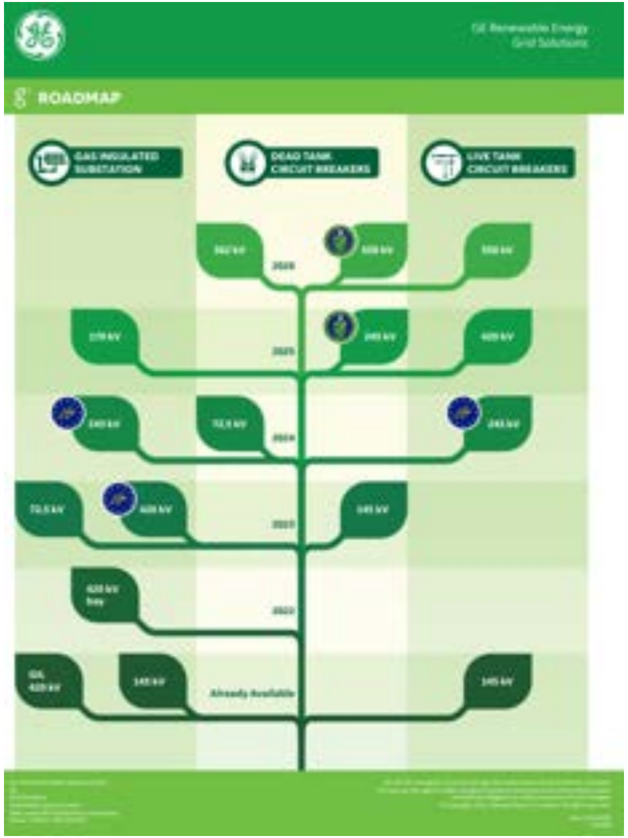
Developments Back in 2020

- A Korean company has succeeded in developing 170 kV eco-friendly GIS for the first time in the world.
- The world's first 170 kV, 50 kA GIS in the field of ultra-high-pressure GIS.
- GIS uses GE/3M Novec g3 gas [Fluoronitrile (C4), carbon dioxide (CO_2) and oxygen (O_2); chemical compound: $C_4F_7N+CO_2$], after technical cooperation with GE.
- The 170 kV GIS performance tests were completed at KERI, an internationally recognized test institute.
- GWP = 300-500
- Operating temperature, low range is -25°C.
- Operating pressure, Over 100 psi.

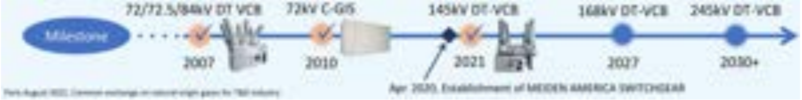
Where We Were End of 2021



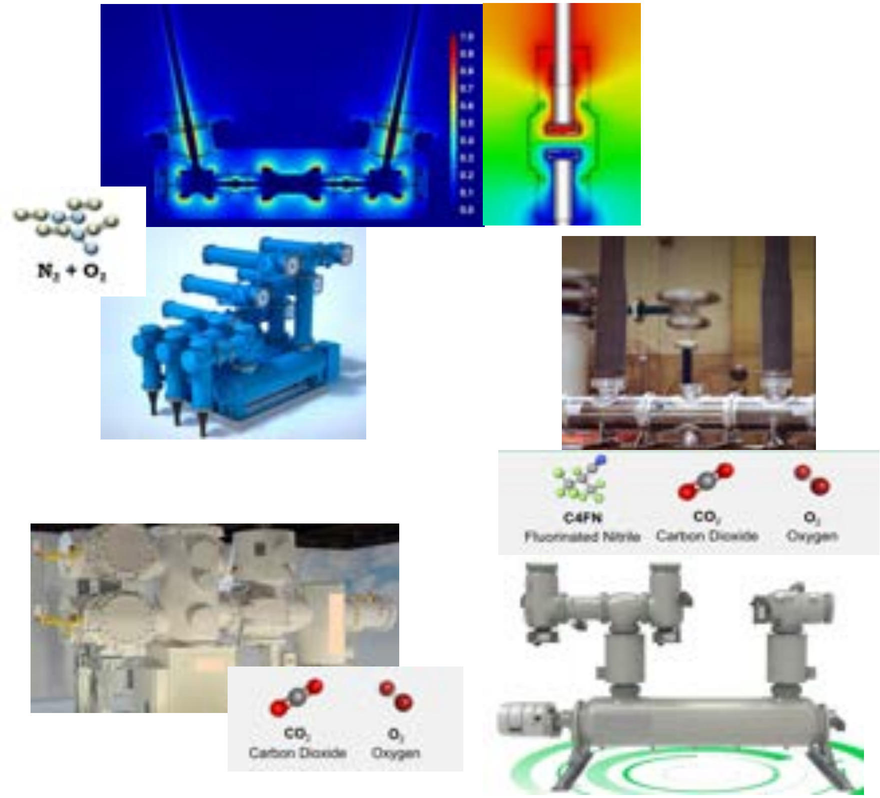
Fluoronitrile Gas Mixtures 2022



Natural Origin Gas Mixtures 2022



Moving Forward



The big question……….??

Are we reaching a technology ceiling? Probably not.

With respect to insulation, there is GIL and GIB in operation at 420kV.

With respect to switching and fault interruption, there is gas insulated equipment approaching the 420kV voltage level.

Other big questions ??

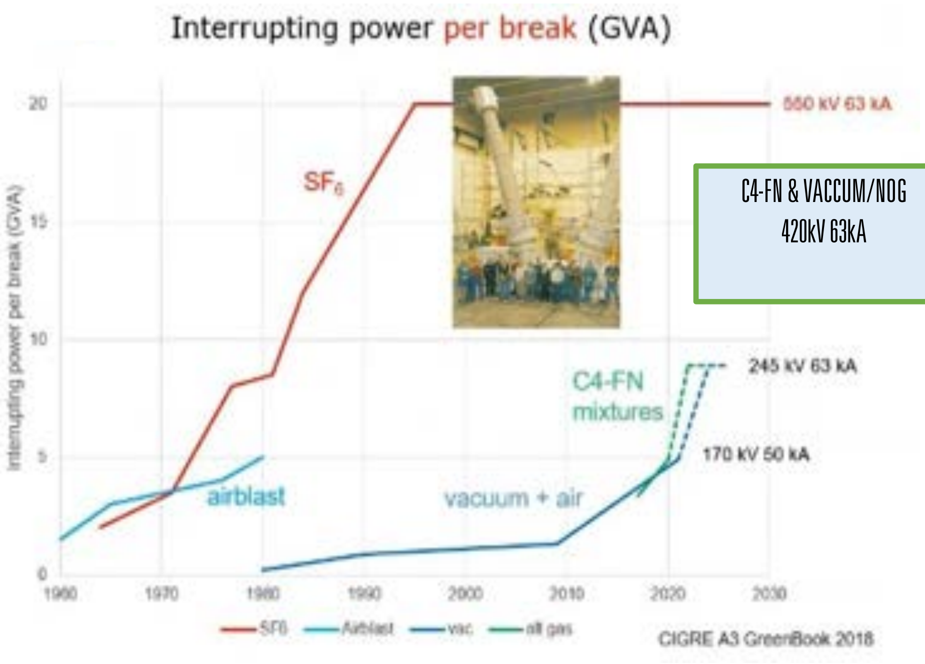
When will alternative fully match the capabilities of SF$_6$?

What about multi-break interrupter technologies?

Moving Forward

Factors affecting progress:

- Regulators restricting GWP.
- Life cycle assessment of alternative technologies.
- Considerations on health and safety.
- Convergence of technology to one gas mixture.
- Convergence of technology to natural-origin gases with vacuum interrupter technology advancement.
- Scalability and single break technology at higher voltages.
- Research and manufacturing costs not recoverable based on population served.



C4-FN & VACCUM/NOG
420kV 63kA

Strategy Considerations

- Global Warming Potential (GWP) of gases and substances is the major non-technical driver to explore SF_6 alternatives.
- Except for reduced GWP, the relevant physical and electrical performance characteristics of existing and practical SF_6 alternatives, in their mixed form, are inferior in most respects to SF_6 —especially at maximum operating voltages greater than 145 kV.
- Extension of the basic electrical ratings demonstrated by alternative gases will require continued and extensive research and development.
- The base gases of C5 and C4 alternative mixtures do not fully recombine after disassociation because of high temperature arcs. This will need to be overcome.

Strategy Considerations

- There is no measurable improvement in safety related to the handling of SF_6 alternatives as compared to pure SF_6.
- New gas mixtures generate new arc byproducts, and some compatibility testing with existing switchgear materials has led to acceptable solutions.
- Toxicity of both the base gas and arc byproducts must be considered, and evaluation of these compounds for health and safety is paramount.
- The interrupting capability of switchgear using SF_6 alternatives is largely based upon CO_2 gas mixtures. CO_2 is orders of magnitude more permeable than SF_6, and the sealing technologies of switchgear will be challenged.

Strategy Considerations

- SF_6 alternative equipment using "technical grade air" and vacuum interrupters operates at a significantly higher pressure than SF_6 equipment.
- Vacuum interrupters in equipment using "technical grade air" are presently limited to maximum operating voltages of 145 kV and below and interrupting ratings of 40 kA.
- High-pressure gas interrupters using gas mixtures are presently limited to maximum operating voltages of 145 kV and below and interrupting ratings of 50 kA.
- The design, manufacture and test of reliable pressure vessels will continue to be an important consideration no matter what gas or gas mixture is employed.

Strategy Considerations

- The existing SF_6 density switches can be recalibrated to perform the same functions with the SF_6 alternative mixtures.
- All the new gas mixtures operate at higher pressures as compared to SF_6. This presents two challenges: first, the design of pressure vessels that can operate safely and reliably for long periods of time; and second, customer acceptance of switchgear with higher operating pressures. Higher gas pressures can also mean higher leakage rates.
- New gases, gas mixtures and pressure schemes will require the development of multiple new gas handling systems.
- The market potential for SF_6 alternatives is relatively small for gas- insulated equipment above 145 kV, as compared to the research and development capital outlay required to develop designs for both high-pressure gas interrupters using gas mixtures or vacuum interrupters using “technical grade air.”

Thank you for your attention

7TH ANNUAL SF_6 GAS MANAGEMENT SEMINAR 2022

Questions & Discussion

POWER ENGINEERS