KEMA Labs 3M

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High-voltage switchgear: The road towards SF_6 alternatives

CESI

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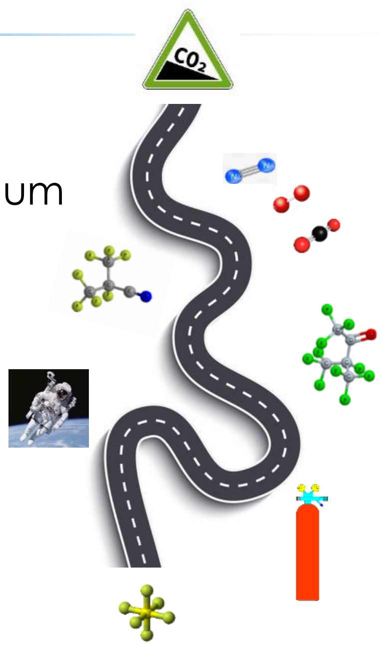
Content of today's roadtrip



1. Introduction
2. Switchgear technology – Gas and Vacuum
3. Use of media and products developed
4. HSE aspects of F-gases
5. Short quiz
6. F-gases in switchgear
7. Roadmaps and outlook
8. Testing and international activities
9. Q&A

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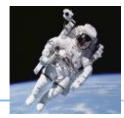
SF_6 in the world

- SF_6 is extreme greenhouse gas: GWP 23 500 (25 200: IPCC AR6 2021)
  - 1 kg SF_6 equals 5 times around the world with a gasoline car
  - SF_6 emission equivalent to 0.3 - 0.6% of global CO_2 emission
- EU SF_6 leakage 70 - 140 t/yr
- EU is reviewing F-gas regulation (SF_6 ban possible)
- Utilities pay/will pay penalties for SF_6 losses
  - Denmark, Spain
- NGC (UK) stops procurement of SF_6 275 - 400 kV switchgear ≥ 2024
- California: phase-out towards GWP ≤ 1, otherwise reporting required
- Japan: Reduced SF_6 leakage -> 0.1%/yr
  - Defined 7 requirements for SF_6 alternatives
- EU is funding to develop 420 kV SF_6-free gas circuit breaker
- Pilots are going on, though many with reduced stresses
- Korea: KEPCO supports development SF_6-free 170 kV 50 kA
- Two tracks: gas based and vacuum + air



- **Eliminate all SF6 gas from our assets by 2050.** Technology and solutions are not yet available to achieve this. Therefore, we will work with partners from across the sector to identify, develop and implement SF6-free solutions at the earliest opportunity.

NGC 2020

Voltage (kV)	Short-circuit Current (kA)	CARB Phase out Date
≤ 145	< 63	1/1/2025
	≥ 63	1/1/2025
≤ 245	All	1/1/2029
> 245	All	1/1/2031

California Clean Air Resources Board 2020

EU LifeGrid

KEPCO 2019

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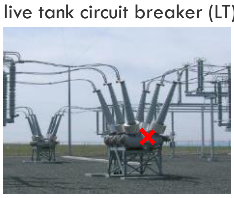
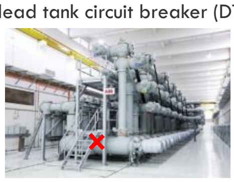
Gas circuit breakers: What does the gas do?

Technologies

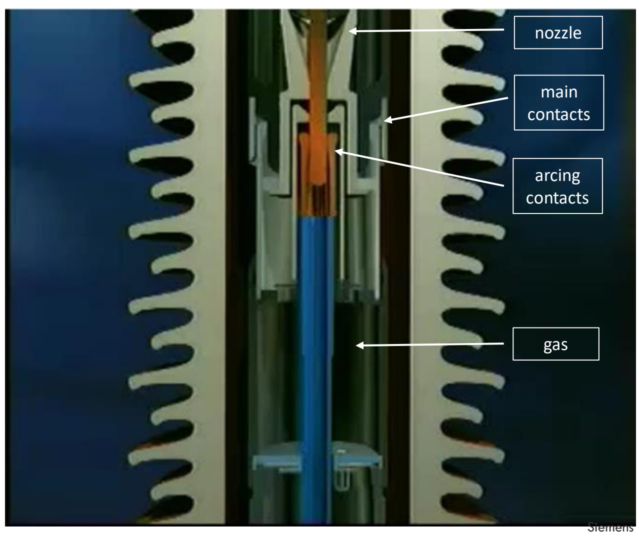
live tank circuit breaker (LT)



dead tank circuit breaker (DT)



GIS circuit breaker



Siemens

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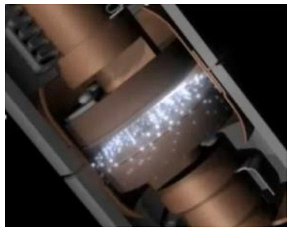
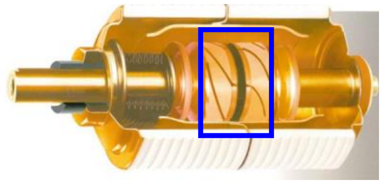
Vacuum + compressed air

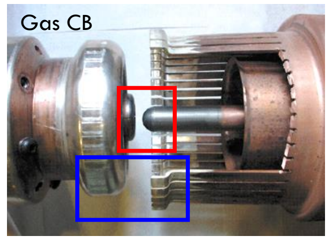
- Switching in vacuum
  - Well-proven in medium voltage
  - Very simple contact system
- A single contact system must:
  - Conduct current
  - Interrupt current (incl. fault)
  - Insulate



Eaton

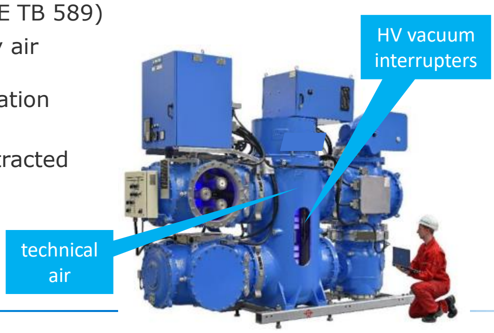


One contact set does it all

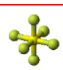
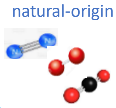
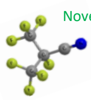
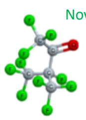


main contacts + arcing contacts

- Traditional designs for HV vacuum breakers have SF_6 as insulation
  - Over 10 000 in Japan (CIGRE TB 589)
- New designs use technical/dry air
  - Need higher pressure
  - Very low temperature application
- Over 1800 units installed/contracted
  - mainly 72.5 kV
  - US market



Application

	INSULATION	INTERRUPTION	GWP	VOLTAGE	TECHNOLOGY
 SF_6	SF_6	SF_6	23 500	24 – 1 200 kV	dist / LT / DT / GIS
natural-origin gases  N_2, O_2, CO_2	TECHNICAL AIR	VACUUM	0	10 - 170 kV	dist / LT / DT / GIS
	O_2 / CO_2	O_2 / CO_2	1	72.5 - 145 kV	LT
	TECHNICAL AIR		0	420 kV	GIB / GIL
fluoronitriles  Novec™ 4710 C4-FN	C5-FK / AIR	VACUUM C5-FK / AIR	1	40.5 kV	distrib / LBS / CB
	C4-FN / AIR	VACUUM C4-FN / AIR	300 - 500	38 kV	distrib / LBS / CB
	C4-FN / O_2 / CO_2 mixture A	C4-FN / O_2 / CO_2 mixture A	300 - 500	72.5 - 170 kV	GIS / LT
	C4-FN / O_2 / CO_2 mixture B	C4-FN / O_2 / CO_2 mixture B	300 - 500	72.5 - 170 kV	GIS / LT
fluoroketones  Novec™ 5110 C5-FK	C4-FN / CO_2	C4-FN / CO_2	300 - 500	170 kV	GIS
	C4-FN / CO_2		300 - 500	420 kV	GIB / GIL
	C5-FK / O_2 / N_2		1	420 kV	GIB / GIL

SF_6-free distribution switchgear 12 – 40.5 kV (examples)

	ABB	SIEMENS	Schneider Electric	nuventura	DRIESCHER WEGBERG	efacec	EATON	G&W	S&C	MITSUBISHI ELECTRIC Changes for the Better	TOSHIBA	(China)
												
Function	Primary	Secondary	Secondary	Primary	Secondary	Secondary	Secondary	Secondary pole mounted	Under-ground	Secondary	Secondary	Secondary pole mounted
Insulation	C5-FK mix	Air	Air	Dry air	C4-FN mix	Solid + air	Solid + air	Solid	C4-FN mix + solid	Dry air	Solid	C4-FN mix
Switching	Vacuum	Vacuum	Vacuum	Vacuum	C4-FN mix	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum
Rated voltage (kV)	40.5	24	24	36	24	24	24	29.3	38	12	24	12
Current (A)	2000	1250	630	1250	630	630	1250	630	630	630	1250	630
Short-circuit curr (kA)	31.5	25	20	31.5	20	20	25	12.5	25	25	25	25

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SF_6-free transmission switchgear 72.5 – 170 kV (examples)

	LS IS	GE	HITACHI ABB	HITACHI ABB	HYUNDAI	ILJIN	SIEMENS energy	MITSUBISHI ELECTRIC Changes for the Better	PINGGAO GROUP	MEIDEN	TOSHIBA
											
Design	GIS	GIS / LT	GIS	Live tank	GIS	GIS	GIS / LT	Dead tank	GIS	Dead tank	C-GIS
Insulation	C4-FN mix	C4-FN mix	C5-FK mix -> C4-FN mix	Dry air	C4-FN mix O_2-free	Dry air	Techn. air	Techn. air	CO_2	Dry air	Solid
Switching	C4-FN mix	C4-FN mix	C5-FK mix -> C4-FN mix	O_2 / CO_2	C4-FN mix O_2-free	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum
Rated voltage (kV)	170	145	170	145	170	170	145	72/84	126	145	72/84
Current (A)	3150	3150	1250	3150		4000	3150	1200	2500	3150	1200
Short-circuit current (kA)	50	40	50	40	50	50	40	31.5	40	40	31.5
Fill. Press. (MPa)abs	0.8	0.85	0.83	1.2	0.85		0.8		0.8	1.0	-

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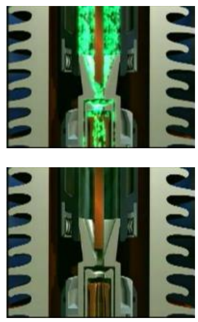
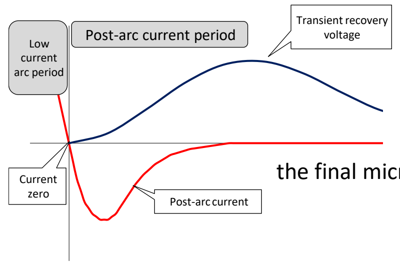
Interruption performance of gas mixtures

- High current
  - Partial decomposition of C4-FN, C5-FK
- Arc voltage
  - Arc energy
- Arc conductivity
  - Interruption capability
- Transient pressure
  - Higher pressure peaks
- Thermal recovery
  - Higher post-arc current
- Dielectric recovery
  - Breakdown voltage
- New breaker design necessary
  - Type testing must demonstrate performance



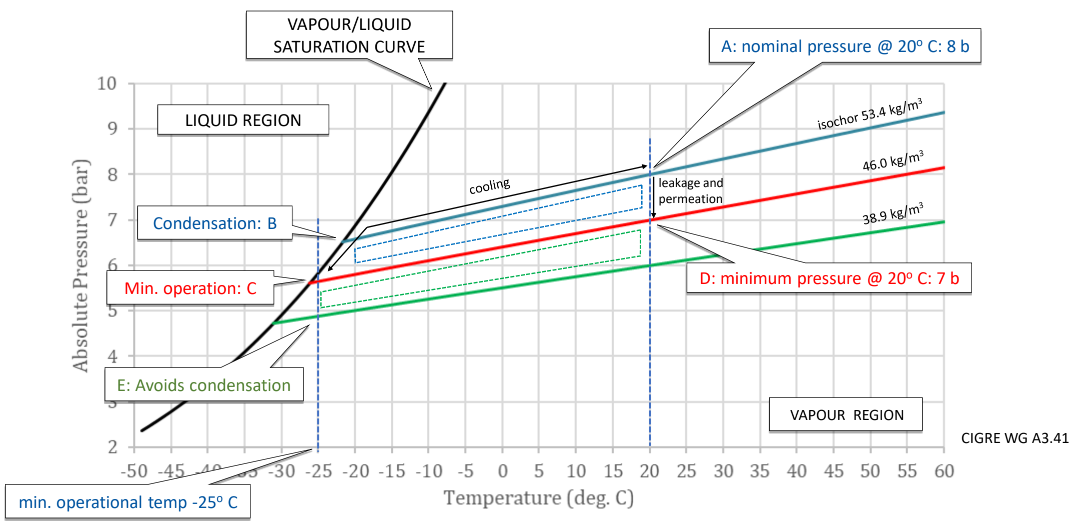


the final microsecond

Manufacturer's statements:

- Capacitive switching 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, exhaust cooling system has to be adapted
- Short-line fault duties (L75, L90) performance around 20% lower than SF_6

Operation characteristic SF_6 circuit breaker

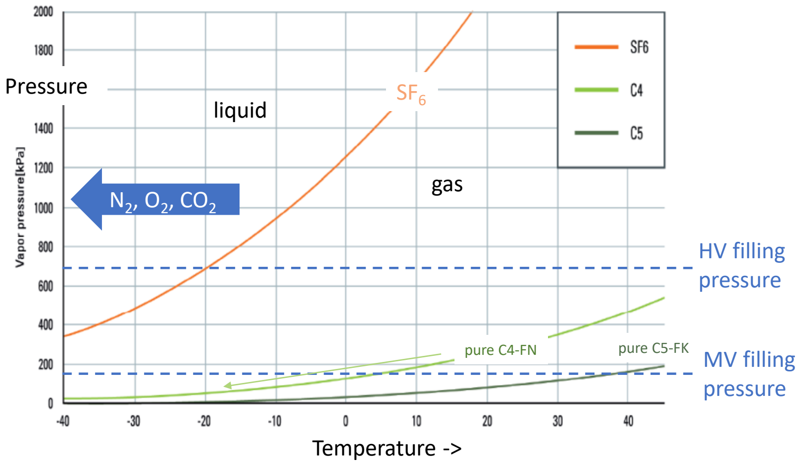


- Blue design ABCD: condensation, higher pressures, higher dielectrical withstand
- Green design DCEF: no condensation, lower pressure, lower dielectrical withstand

Vapour curves of insulating gases

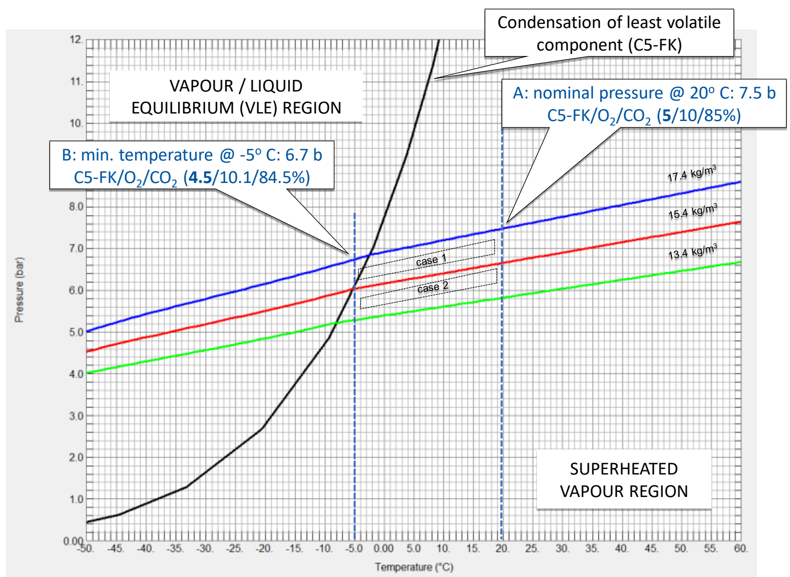
- Pure F-gas (C4-FN / C5-FK) cannot be used in switchgear
- Condensation at room temperature
- Small fraction (5-12%) - lower partial pressure

- HV applications have smaller alt gas content
- MV can have higher alt gas content
- C5-FK better compatible with MV applications than with HV



Operation characteristic alt. gas mixture circuit breaker

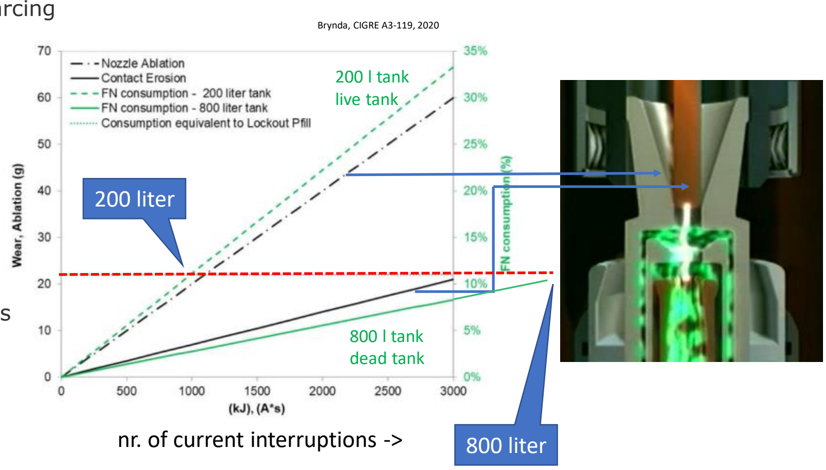
- Thermodynamics very complicated
- Low content of F-gas will decrease the minimum operational temperature
- Low content of F-gas will reduce dielectrical withstand
- Trade-off has to be found



CIGRE WG A3.41

F-gas consumption

- C4-FN and C5-FK is consumed by arcing
  - 0.3 - 0.5 mol/MJ
- This is new with respect to SF_6
- The gradual loss of the effective gas is a new wear mechanism
  - contact erosion
  - nozzle ablation
  - F-gas decomposition
- Small volume breakers reach gas wear limit faster than large ones
- Testing shall be focused to the smallest volume
- Small reduction of F-gas will affect dielectric performance marginally
- Voltage condition check essential
- Operational limits need to be observed



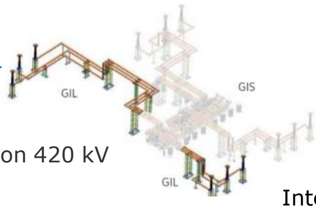
HV technology road maps

- Roadmaps of SF_6-free technologies show 550 kV switchgear by 2030

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
550				GIS						
									LT/ DT	GIS
420		GIS	LT							
						LT	GIS			
362			DT							
						DT				
245		GIS?		LT / DT	GIS					
				DT	LT			GIS		
					DT	GIS				
170	GIS									
	GIS									
			DT	GIS						
145	LT / GIS	DT								
	LT/DT/GIS									
	LT									

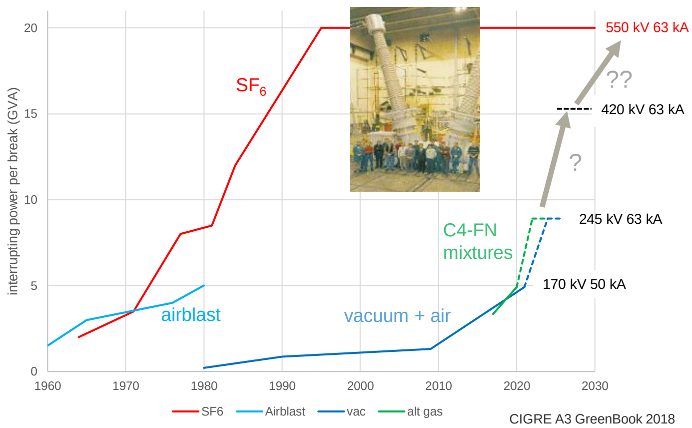
C4-FN mixture switching and insulation
Vacuum switching, technical air insulation
Natural-origin gas switching and insulation

Outlook



- Insulation
  - GIL / GIB already in operation 420 kV
  - switchgear still SF_6 based
- Interruption
  - upto 170 kV to approach SF_6
  - (when) can alternatives fully match SF_6?
  - multi-break technology?
- Deciding factor(s):
  - Regulator restricting GWP?
  - Life Cycle Assessment?
  - Health, safety and environment?
  - Size / Pressure / costs / temperature?
  - TRL? Convergence of technology?
  - One gas fits all?
  - Natural-origin gases for switching + insulation?
  - Long term behaviour?
  - Scalability? Single break 550 kV?

Interrupting power per break (GVA)

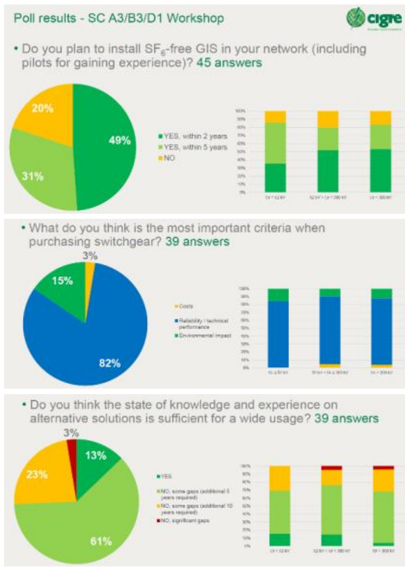


CIGRE A3 GreenBook 2018

System operators embraces the change?

Results from poll at CIGRE SF_6-free switchgear workshop Aug. 2021

- When planning to install SF_6-free GIS?
  80% says "within 5 years" (49% within 2 years)
- When do you stop buying SF_6 equipment?
  74% says "yes within 10 years" (22% within 5 years)
- Higher price allowed?
  63% says "yes"
- Decided already on a certain technology?
  72% says "not yet"
- State of knowledge and experience enough for wide use?
  87% says "not yet" (13% thinks needs another 10 years)
- Most important criterion to decide on "new" switchgear?
  82% says "reliability" (only 3% says "costs")
- No uncertainty about the willingness to get rid of SF_6
- Uncertainty about the technology readiness level of the alternatives?



Testing in quality assurance / design verification

- Switchgear is newly designed
- A variety of technologies on the market
  - Thermo-electrically complicated
- Independent type test certificate (not from country of origin) gives maximum performance assurance
- Critical test duties
  - L90 -> L75-> LXX?
  - Extremes of the composition?
- Pre-qualification for lifetime
  - Electrical endurance?
  - Gas consumption?

Test experience @ KEMA High-Power Labs

- Switchgear from 15 different manufacturing sites
- Up to 145/170 kV @ 50 kA three-phase synthetic
- Mostly R&D tests, no type-test certificate issued
- Short-circuit (all duties), capacitive, shunt reactor, bus transfer, MV internal arc


Hitachi ABB @ KEMA Labs

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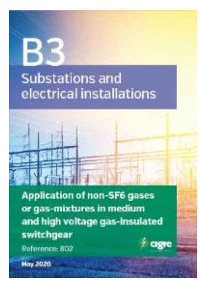
Independent industry activities

- **IEEE PES TR64** “Impact of Alternate Gases on Existing IEEE Standards” 2018 (Uzelac)
- **CIGRE WG B3.45** “Application of non-SF6 gases or gas mixtures in medium voltage and high voltage gas-insulated switchgear. TB 802, 2020 (Knol)
- **T&D Europe** “Technical report on alternative to SF6 gas in medium voltage & high voltage electrical equipment” (2020)
- **CIGRE WG D1.67** **“**Dielectric performance of new non-SF6 gases and gas mixtures for gas-insulated systems” -> 2021 (Franck)
- **IEEE C37.100.7** “Guide for the Performance Characteristics of Alternative Gases” -> 2021 (Schiffbauer)
- **CIGRE WG A3.41** “Interruption and switching performance with SF6 free switching equipment” -> 2021 (Smeets)
- **IEC 62271-4 ED-2** “Handling procedures for gases and gas mixtures for interruption and insulation” -> 2022 (in draft)
- **CIGRE WG B3/A3.60** “User guide for non-SF_6 gases and gas mixtures in substations“ -> 2023 (Knol)



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Thank you for your kind attention!

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