Presentation Submission Information:

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- Presentation ID#: 5.4
- Presentation Title: Dielectric Replacement Gas Testing for Sulfur Hexafluoride (SF6) in Substation Equipment (5.4)
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- Organization(s): Idaho National Laboratory

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Dielectric Replacement Gas Testing for SF_6 in Substation Equipment (5.4)

DOE OE TRAC Peer Review 2026

Battelle Energy Alliance manages INL for the
U.S. Department of Energy's Office of Nuclear Energy

Idaho National Laboratory

Dielectric replacement gas testing project overview

Project Description:

- This project investigates candidate gas mixtures as direct drop-in replacements for SF_6, a potent air pollutant, in existing high-voltage switchgear and circuit breakers. The objective is to develop and validate a replacement gas capable of reducing billions of tons of CO_2-equivalent emissions while avoiding billions of dollars in equipment replacement costs across the approximately 80,000 U.S. substations that rely on SF_6-based equipment.

Alignment/Supports strategic pathway:

- **Stabilize —** Reduces the need for premature replacement of critical transmission assets and supports reliable operation of existing breakers while addressing environmental concerns
- **Optimize —** Extend the value of existing transmission assets by enabling direct gas replacement instead of costly equipment replacement, improving lifecycle cost and asset utilization
- **Grow —** Advance U.S. innovation in next-generation switchgear technology to support transmission expansion and future electricity demand

- **Period of Performance:** Oct. 1, 2026 to Sept. 30 2026
- **Award Amount:** $300k
- **Prime Awardee:** Idaho National Laboratory
- **Partners:** GE Vernova
- **Technology Area:** Advanced Transformers
- Transformer Materials
- DC Circuit Breakers
- Busbars, and Dielectric Materials

Team members

- **Program Manager (PM)**
  - Krystal Pratt (Krystal.Pratt@inl.gov)
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- **INL Laboratory Program Manager (LPM), Relationship Manager (RM)**
  - Jake P. Gentle (Jake.Gentle@inl.gov)

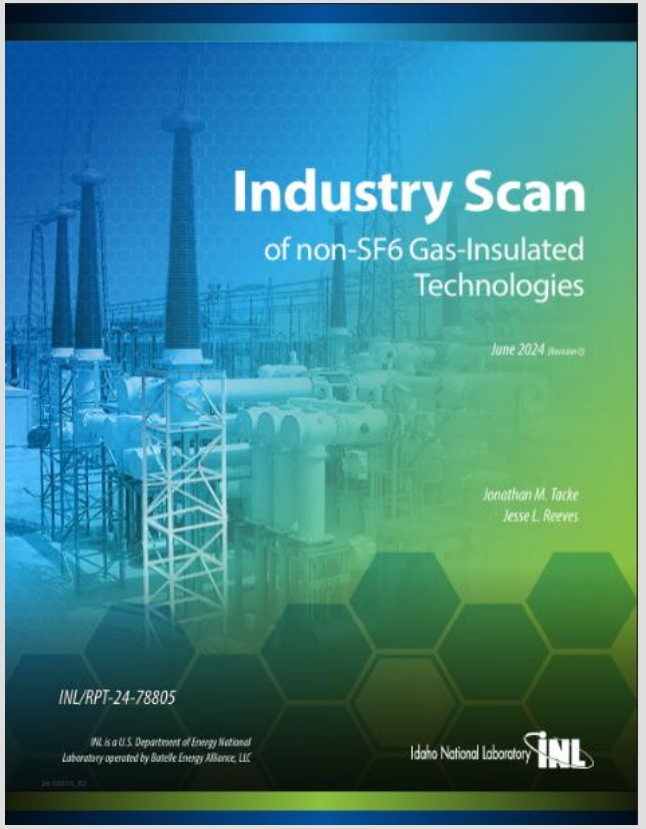
Problem statement

- SF_6 is the industry-standard insulating gas for high-voltage equipment, but its significant environmental impact and the lack of a direct replacement compatible with existing breakers create a critical need for modeling and testing of reliable alternatives.



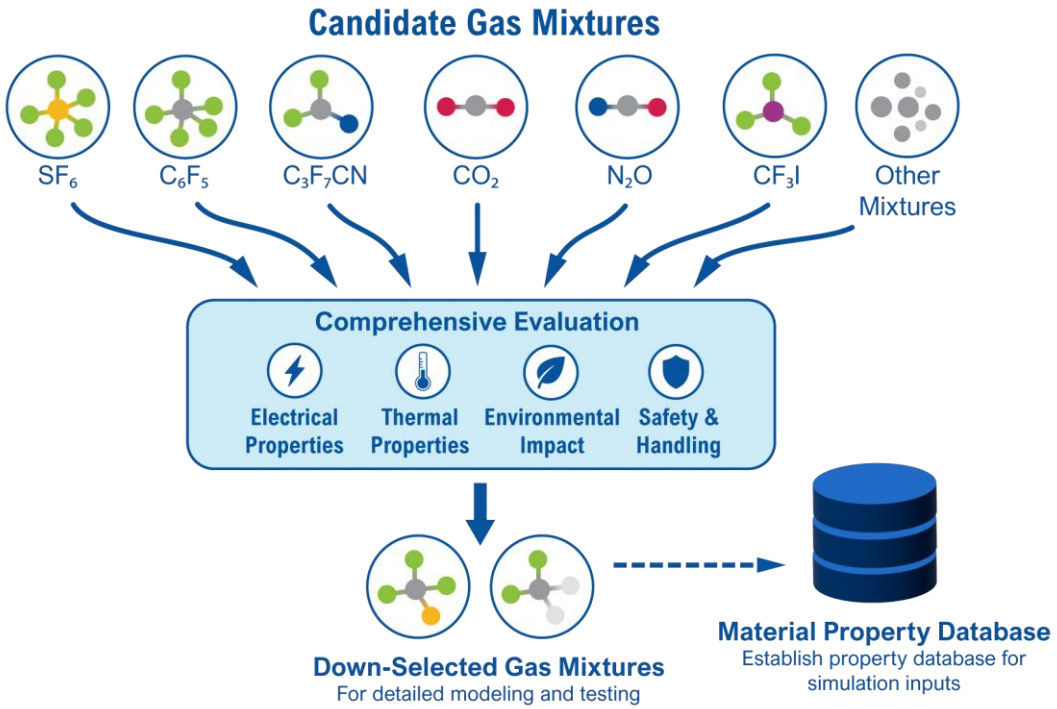
Literature review

- Review peer-reviewed research and currently available SF_6 replacement technologies
- Compile an extensive summary of candidate gases, gas mixtures, and reported performance
- Identify key findings, limitations, and remaining technical gaps in the existing literature
- Develop an initial list of candidate gas mixtures for further analysis, modeling, and testing



Gas analysis and down selection

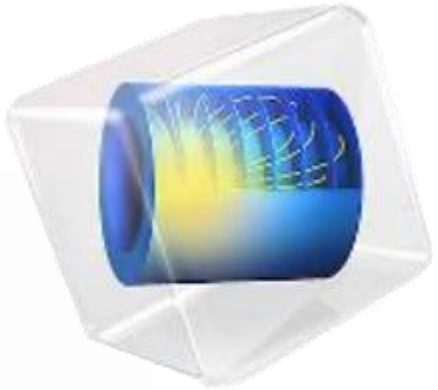
- Develop a database of material and performance properties for candidate gas mixtures identified in the literature
- Evaluate electrical, thermal, environmental, and safety properties
- Down-select promising gas mixtures for detailed modeling and testing
  - Mix and very the gas(es) -
    - Identification and quantification of C_2F_6, fluoronitrile, and CF_3I.
    - Identify for trace SF_6 and N_2O.
    - Fourier Transform Infrared with a gas cell for rapid, simultaneous measurement—especially when concentrations are in the ppm-to-percent range.
    - Certified multicomponent gas standards for quantitative calibration to validate.



Multiphysics modeling

- Develop thermal, fluid flow, and electric field models
- Simulate gas behavior within high-voltage breaker geometry
- Compare candidate gas performance against SF_6 baseline
- Support test planning through virtual evaluation of gas mixtures

COMSOL MULTIPHYSICS®



Test plan



- Define the critical gas properties and performance metrics to be evaluated
- Develop methods for comparing candidate gas mixtures directly against SF_6
- Identify required equipment, instrumentation, safety controls, and data collection methods
- Prioritize arc-quenching testing while evaluating the feasibility of additional measurements including dielectric strength, thermal behavior, gas flow, and pressure response
- Produce a completed test plan to guide laboratory-scale validation

SF_6 alternative options

- Ongoing testing to confirm alternatives will be available once down select is completed

Test plan: compare gas candidates at service conditions

Sulfur hexafluoride (SF_6) is the baseline. Candidates include fluoronitrile (C_4F_7N), trifluoroiodomethane (CF_3I), hexafluoroethane (C_2F_6), fluoroketone ($C_5F_{10}O$), hydrofluoroolefin (HFO), carbon dioxide (CO_2), nitrogen (N_2), and oxygen (O_2).

1

Electrical insulation

- Critical reduced electric field (E/N)
- Effective ionization and attachment
- Streamer / leader inception
- Impulse and surface-flashover sensitivity

2

Arc and recovery

- Thermal recovery rate
- Post-arc conductance
- Transient recovery voltage (TRV) withstand
- Pressure and mass-flow response

3

Feasibility envelope

- Vapor–liquid equilibrium (VLE)
- Pressure–volume–temperature (PVT) behavior
- Global warming potential (GWP)
- Materials, byproducts, and supply

SF_6 alternatives

Indicators are relative to sulfur hexafluoride (SF_6), not equipment ratings; pressure is shown in megapascal (MPa).

Candidate mixture	Dielectric indicator relative to SF_6	Evidence level	Primary limitation	Recommended program use
C_4F_7N/CO_2 20/80	1.06 screening proxy	Full-scale passive gas-insulated-line test	Phase and GWP screens fail at the default point; per- and polyfluoroalkyl substances (PFAS) and supply review	Calibration and upper-bound benchmark
C_4F_7N/CO_2 15/85	**0.90** **screening proxy**	Experimental literature plus calibrated electron-swarm proxy	Negative phase margin at −30 °C and 0.6 MPa; breaker arc response unknown	Lead conditional window: test 12–16%
C_4F_7N/N_2 12/88	≈1.00 screening proxy	Measured electron-swarm evidence	Phase and GWP screens fail; oxygen-free carbon-deposition concern	Alternate carrier only
HFO-1336mzz(E)/CO_2 30/70	Up to 0.90 in a weakly uniform field	Experimental medium-voltage insulation at 0.15–0.20 MPa	Gap-, field-, and pressure-specific; arc interruption unproven	Medium-voltage insulation branch
CF_3I/N_2 20/80	0.56 screening proxy	Experimental high-pressure impulse evidence	Cold-phase margin; iodine-containing products and materials; breaker evidence sparse	Bounded alternate branch

Fluoronitrile is the strongest lead, but the useful concentration is set by phase behavior—not dielectric strength alone.

Alternative chemistries add learning value—not a clear drop-in winner

The comparison separates promising research branches from useful controls and environmentally unacceptable benchmarks.

Candidate and role	Dielectric indicator relative to SF_6	What helps	Decisive limitation	Recommended disposition
C_2F_6/CO_2 20/80 Calculated benchmark	0.43–0.49 linear proxy	High molecular mass; likely adequate phase margin at low partial pressure	Mixture GWP ≈5,540; pure C_2F_6 GWP ≈12,600 and atmospheric lifetime ≈10,000 years	Benchmark only; stop at environmental gate
$C_5F_{10}O/CO_2$ 2.86/97.14 Fluoroketone	0.38 screening proxy	Low mixture GWP; strong pure-molecule electron attachment	Cold-phase failure and incomplete post-arc recovery evidence	Hold for warmer or medium-voltage envelope
HFO-1234ze(E)/N_2 5–10% Low-GWP branch	0.42–0.45 screening proxy	Phase and GWP screens pass at low additive loading	Large dielectric shortfall; mixture flammability and decomposition uncertain	Bounded carbon-dioxide / oxygen co-buffer optimization
CO_2/O_2 80/20 Non-fluorinated control	0.36 screening proxy	Phase, safety, and GWP screens pass; scalable	Likely requires higher pressure or interrupter redesign	Maintain as the PFAS-free control
Synthetic air: N_2/O_2 80/20 Technology control	0.39 screening proxy	Safe, available, and cold-temperature robust	Insufficient gas interruption at fixed legacy geometry	Insulation / vacuum-interrupter benchmark

Recommendation: do not spend experimental down-selection resources on C_2F_6; its climate burden defeats the replacement objective.

Ambient properties reveal large flow and pressure mismatches

Calculated at 293.15 kelvin (K) and 0.6 megapascal (MPa) absolute.
These cold-gas properties inform chamber flow, not arc interruption.

Candidate mixture	Density kg/m³	Volumetric heat capacity kJ/m³·K	Viscosity µPa·s	Thermal conductivity / sound speed
Sulfur hexafluoride (SF_6) Baseline	39.15	26.00	15.30	13.00 mW/m·K 135 m/s
C_4F_7N/CO_2 15/85 Lead	**17.32**	12.90	14.70	15.85 mW/m·K 210 m/s
CF_3I/N_2 20/80 Alternate	15.39	9.26	17.28	18.76 mW/m·K 226 m/s
C_2F_6/CO_2 20/80 Calculated benchmark	16.14	13.12	15.12	14.48 mW/m·K 215 m/s
$C_5F_{10}O/CO_2$ 2.86/97.14 Secondary	12.90	10.34	14.85	15.93 mW/m·K 247 m/s

Key mismatch: alternatives provide only 36–50% of SF_6 volumetric heat capacity and have 55–83% higher sound speed.

Thermal recovery speed does not equal dielectric strength

One-dimensional (1D) arc-model indices are normalized to SF_6 = 1.00. They support screening only, not breaker qualification.

Candidate mixture	Average recovery rate relative to SF_6	Average recovery strength relative to SF_6	Practical caveat	Program implication
C_4F_7N/CO_2 10/90	**0.397**	0.668	More phase-practical than high-additive blends, but both recovery indices remain below SF_6	Lead mixture still needs geometry-specific magnetohydrodynamic modeling
$C_4F_7N/N_2/O_2$ 10/45/45	0.610	0.639	High oxygen fraction is a screening case—not a proposed fill composition	Use to isolate carrier-gas and oxygen effects
$C_5F_{10}O/N_2/O_2$ 10/45/45	0.953	0.565	Fast modeled recovery rate coexists with weaker recovery strength and phase constraints	Maintain separate thermal and dielectric gates
CF_3I mixtures	Not reported in the common index	Not reported	Arc products have been studied, but matched current-zero recovery data are sparse	Measure post-arc conductance and TRV withstand
C_2F_6 mixtures	Not reported in the common index	Not reported	High-temperature transport data exist; environmental gate already fails	Use only to test property and plasma models

Decision rule: never advance on thermal recovery alone—rapid cooling can coexist with inadequate post-arc dielectric recovery.

Advance a portfolio by evidence tier—not by one composite score

The portfolio retains one lead, two learning-rich branches, one secondary chemistry, and one benchmark-only gas.

Candidate family	Decision	Why it remains valuable	Hard limitation	Next decisive evidence
$C_4F_7N/CO_2/O_2$ Fluoronitrile lead	**CONDITIONAL ADVANCE**	Strongest dielectric evidence and most mature high-voltage insulation basis	Cold-phase margin; PFAS / supply; carbon and fluorinated arc products; breaker recovery	Measured VLE, validated swarm data, and reduced-scale interruption across 12–16%
$CF_3I/CO_2/N_2$ Iodinated alternate	CONDITIONAL HOLD	Strong pure-gas attachment and impulse-insulation evidence	Condensation, iodine-containing products, occupational exposure, and materials compatibility	Phase map, impulse testing, decomposition yields, and post-arc conductance
HFO-1336mzz(E)/CO_2 Insulation branch	BOUNDED EXPLORE	Experimental medium-voltage dielectric performance up to about 0.90 of SF_6	Condition-specific short-gap evidence; phase, flammability, and interruption data incomplete	Mixture safety, phase envelope, and reduced-scale interruption
$C_5F_{10}O/CO_2/O_2$ Secondary	HOLD	Low mixture GWP and useful modeled arc-recovery behavior	Cold-temperature phase limit and incomplete post-arc dielectric evidence	VLE plus paired thermal- and dielectric-recovery measurements
C_2F_6/CO_2 Benchmark only	STOP ENVIRONMENTAL	Useful dielectric and high-temperature transport datasets for model validation	Extreme GWP and atmospheric persistence defeat the replacement objective	No formulation testing after model calibration

Maintain $CO_2/O_2/N_2$ as the non-fluorinated control; it is not the leading gas-interrupter replacement at fixed geometry.

Results

- Literature review completed, establishing the technical basis for candidate gas evaluation, breaker modeling, and future testing
- Candidate gas mixtures down-selected to approximately ten promising alternatives, emphasizing compatibility with SF_6 dielectric, thermal, and arc-quenching performance
- Material property database initiated by compiling key electrical, thermal, environmental, and safety characteristics from published literature
- Procurement of test equipment initiated, including evaluation of commercially available arc-quenching test systems and supporting laboratory instrumentation
- Foundation established for Year 2 activities, including COMSOL platform modeling, molecular dynamics simulations, and laboratory validation of selected gas mixtures.

Next Steps

- Continue procurement and development of the laboratory-scale arc-quench test setup
  - Evaluate dielectric strength, thermal behavior, pressure response, and gas flow where feasible
  - Compare candidate gas mixtures directly against SF_6
- Refine the leading mixture through additional testing, if needed
- Progress successful candidate mixtures toward full-scale breaker validation performed at INL's Critical Infrastructure Test Range Complex (CITRC) and Modular Power Systems (MPS) Testbed.

Acknowledgements

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