INL/CON-24-80528-Revision-0

Seismic Resilience of Large Power Transformer Bushings & Non-SF6 Industrial Base Scan Review

September 2024

Bjorn C Vaagensmith, Jonathan Michael Tacke, Jesse L Reeves

Changing the World's Energy Future

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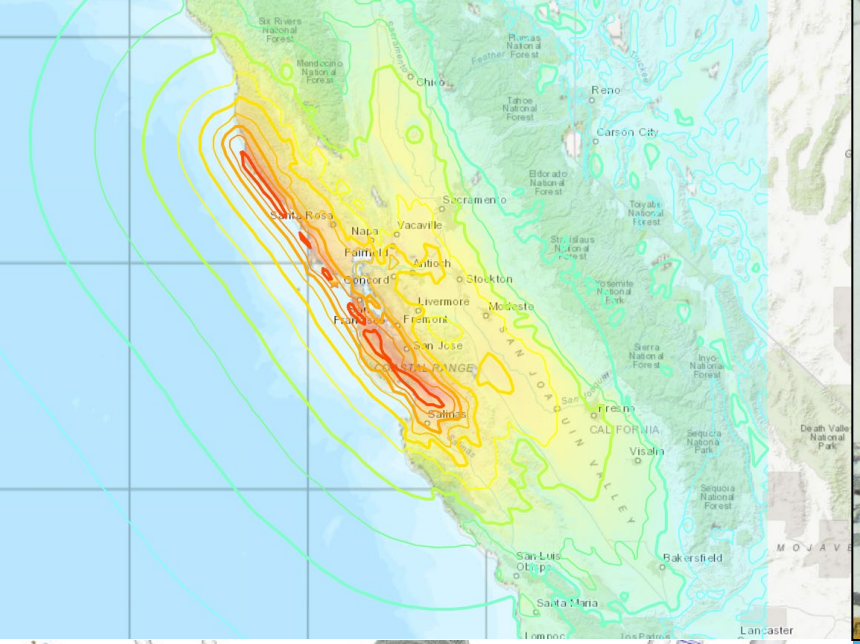
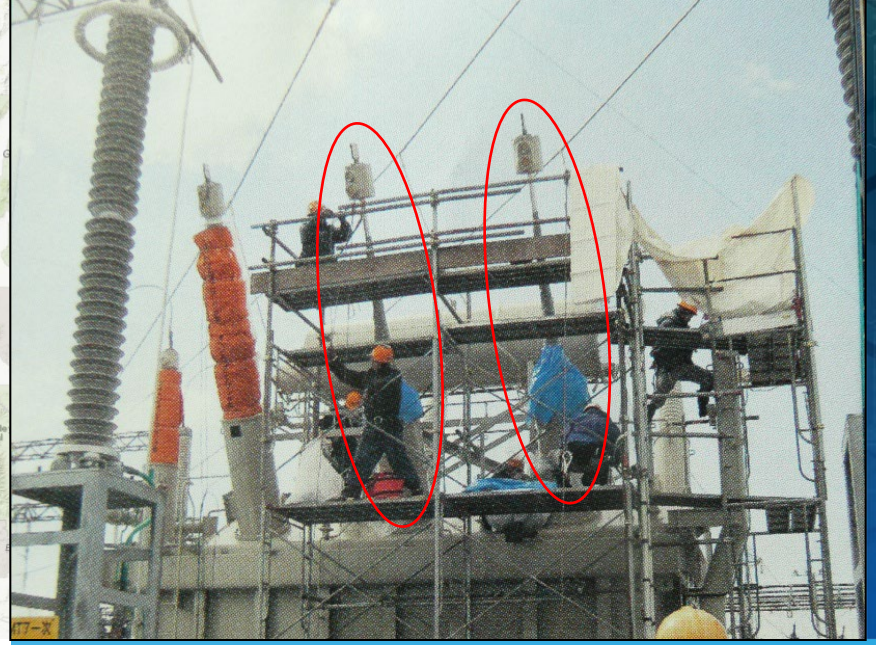
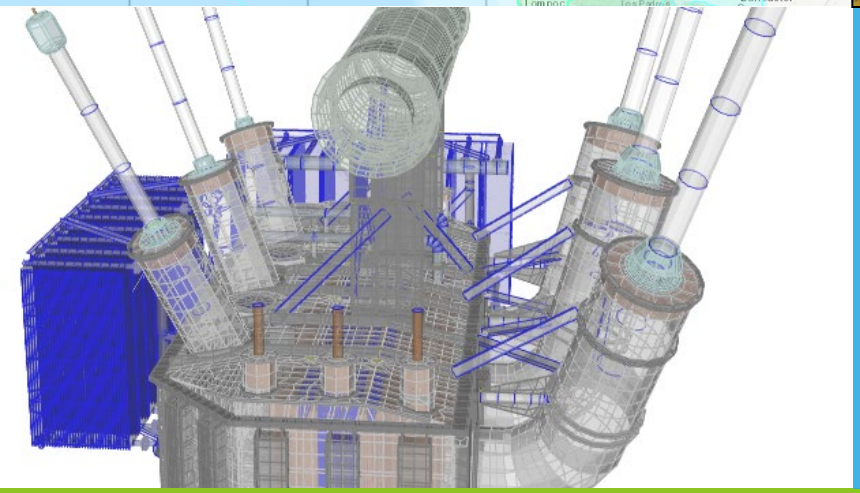
http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517, DE-AC07-05ID14517, DE-AC07-05ID14517







August 29, 2024

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Seismic Resilience of Large Power Transformer Bushings

DOE-OE Briefing: Year 1 project Overview

Battelle Energy Alliance manages INL for the
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INL Idaho National Laboratory

Recent Post-Seismic Bushing Failures

Chile M8.8 Feb. 27th 2010

Equipment	500 kV	220 kV	154 kV	110 kV	66 kV
Transformer Bushing Failures	9		20		

Japan M9.0 March. 11th 2011

Damage	3/11	4/7	4/11 & 4/12
Substations (Total Sub. 612, KV 500-275-145)	57	19	4
Transformers (Bushings and Other Components)	70	19	4

2010 Mexico Earthquake
Affected One US Substation (adjacent to border)

- **500kV: 2 transformers had failed bushings**
- **230kV: 4 transformers had failed bushing**

Peak ground acceleration (PGA) ~0.3g. All bushings were qualified to IEEE 693 for 1.0g PGA

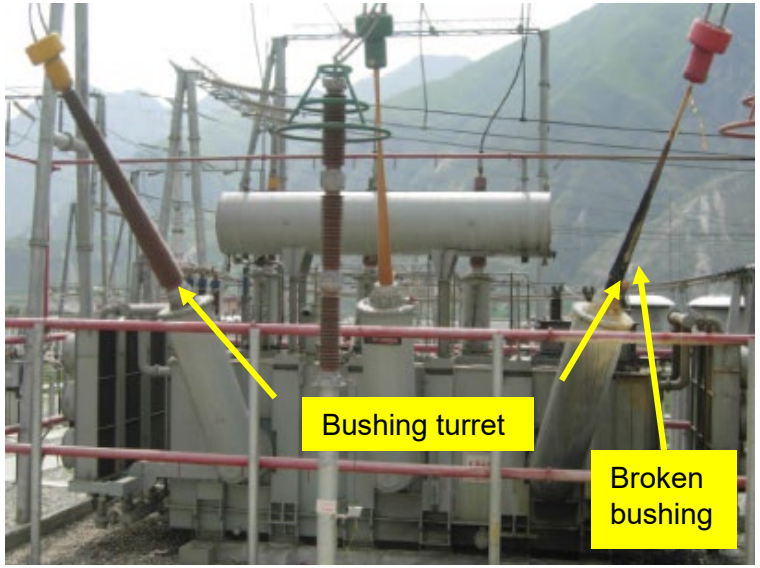
Northridge Earthquake (M6.7, 1/17/1994) - twenty-five 230kV bushing failures

Additional Earthquake Bushing Failures:

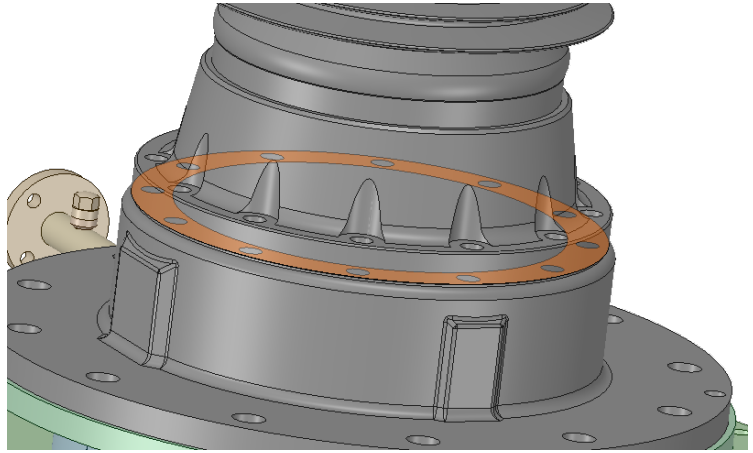
- **New Zealand 2011**
- **Wenchuan, China 2008**
- **Haiti, 2010**

Significance and Impact

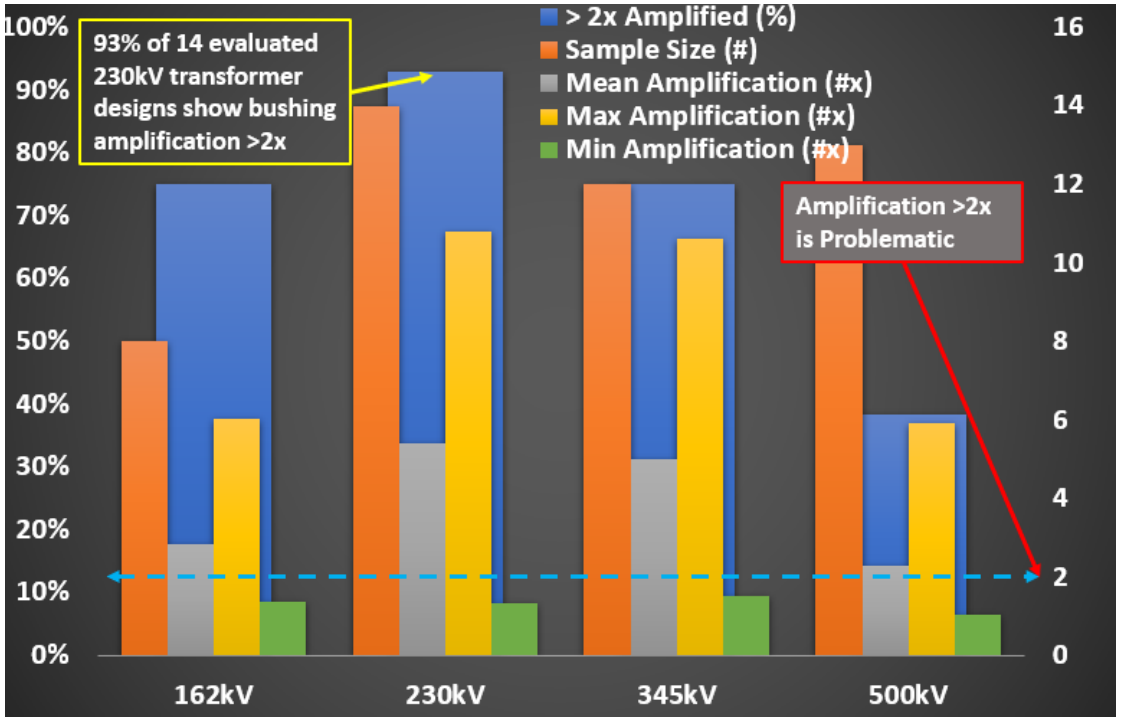
- **The Problem:** power transformers are a **critical component** to the united states power grid and have **known vulnerabilities** to seismic events [1] [2]
  - Dynamic coupling of bushings with tank
  - Short circuiting in the core
  - Oil leak reducing cooling ability

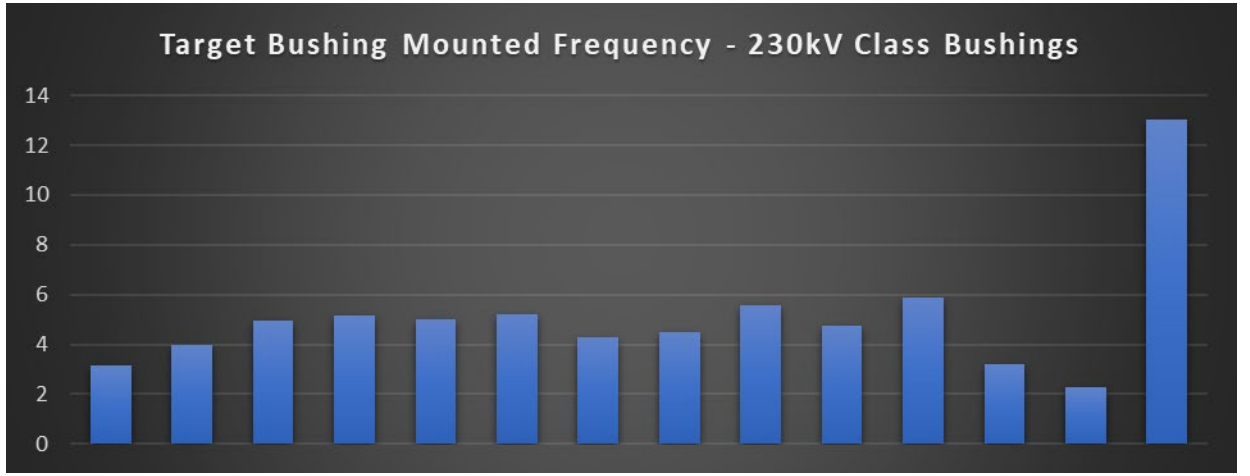


- **Current solutions** are also inadequate
- Industry standards may be insufficient [3][4]
- Spare transformers are redundantly vulnerable
- Stiffening bushing support structures can exacerbate the problem [3]
- Base isolation is unproven and expensive, but promising
- **Proposed solution:** Bushing mount decoupler
  - Cost effective
  - Retrofit flexibility
  - Fits wide range of transformer designs



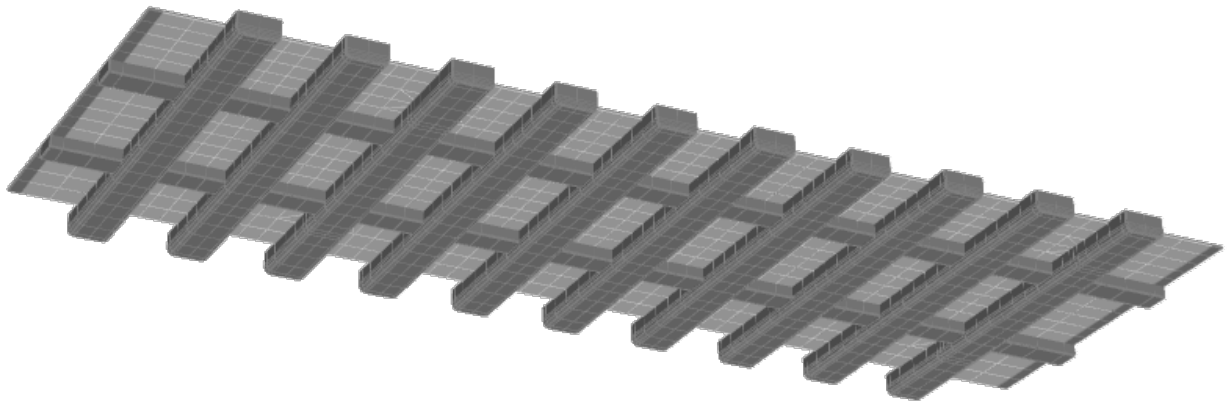
Progress to Date / Targe bushing mounted frequencies

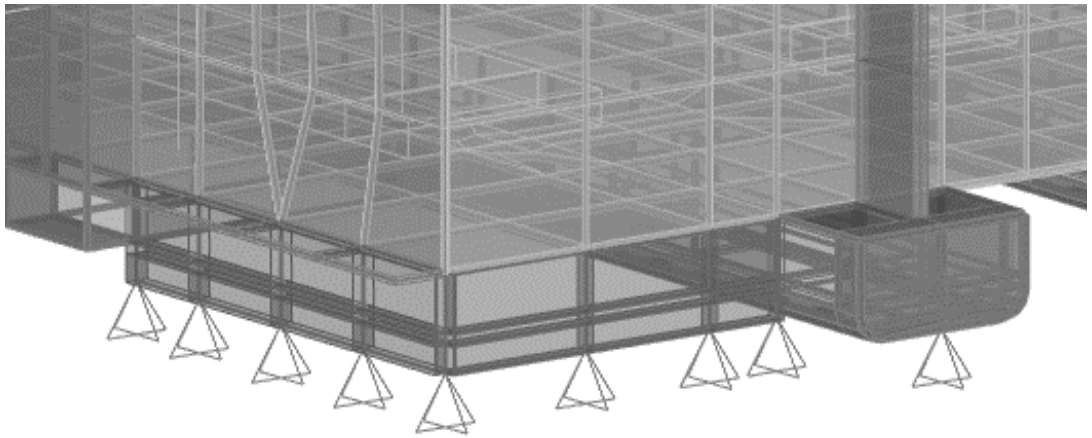




- (Left) Transformer application vs voltage class (6-15 samples per voltage class)
  - Indicates 230 kV class is particularly vulnerable
- (Right) Bushing resonance frequency reductions required to reduce amplification below 2x
  - Target frequency is 4 Hz (covers 79% of cases)
  - Stretch goal of 3 Hz (covers 93% of cases)

Progress to Date / Skid mounting impact on amplification

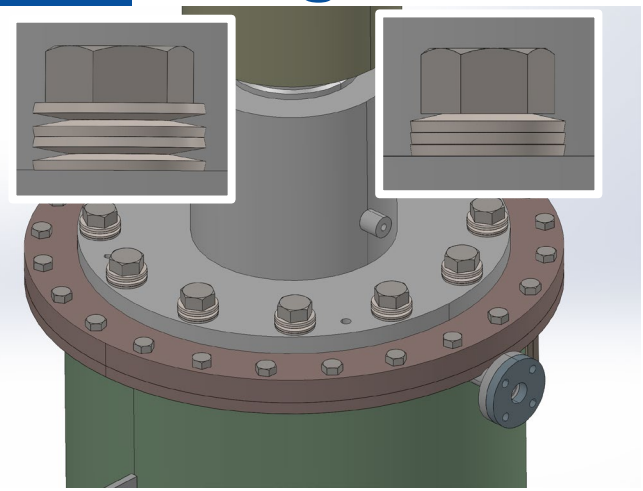


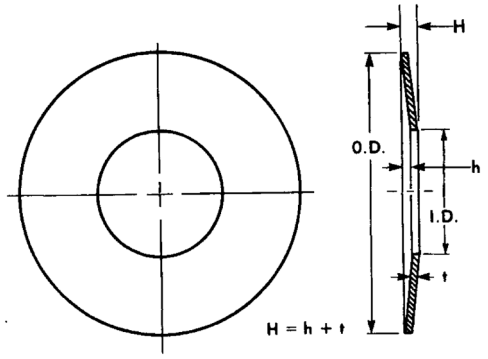


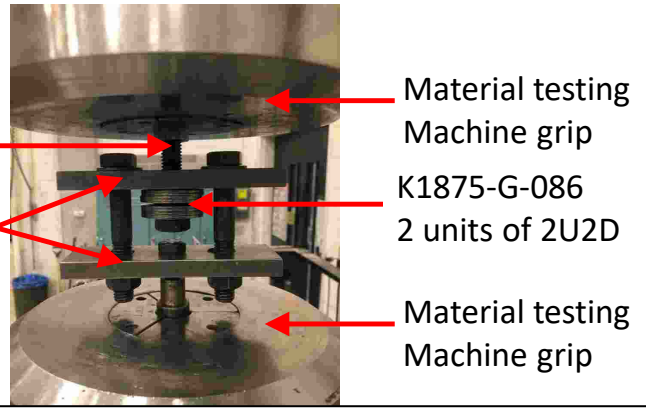
- Transformer are placed on skids
  - Blocking out the transformer corners can reduce amplification up to 76%
- Blocking out corners reduced amplification to within IEEE 693 standards for one case
- Increases catchment for 4Hz target frequency of decoupler
- Average amplification reduction of 37% ± 24%
  - Each design is unique

Case	kV Class	Weight (kip)	Max Bushing Amplification	
			As Installed	Blocked Corners
1	345	971	7.78	5.67
2	345	930	7.71	1.88
3	345	397	6.17	3.65
4	230	720	7.27	7.17
5	230	511	9.35	3.40
6	230	288	6.28	3.83
7	230	526	6.17	5.57
8	230	325	10.79	5.60
9	500	1152	3.92	2.70

Progress to Date / Disk spring solutions

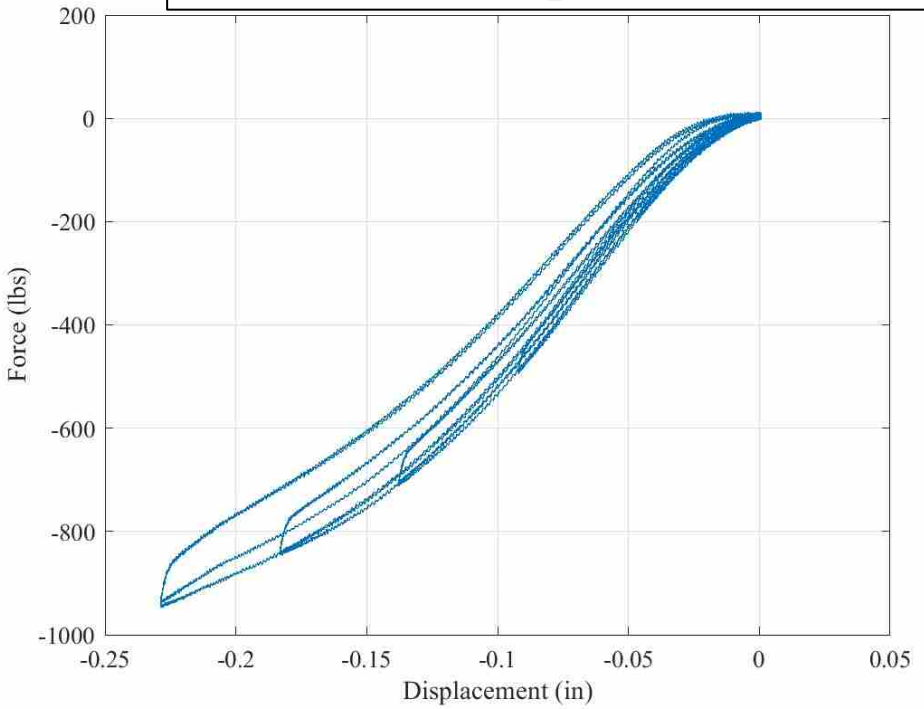






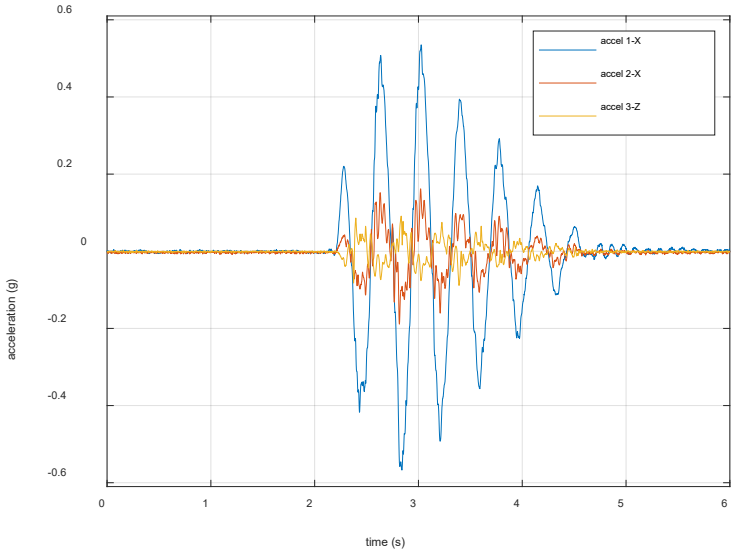
$$F = \frac{4E}{1-\mu^2} \cdot \frac{t'^4}{K_1 \cdot D_e^2} K_4^2 \cdot \frac{s}{t'} \left[K_4^2 \left(\frac{h'_0}{t'} - \frac{s}{t'} \right) \left(\frac{h'_0}{t'} - \frac{s}{2t'} \right) + 1 \right]$$

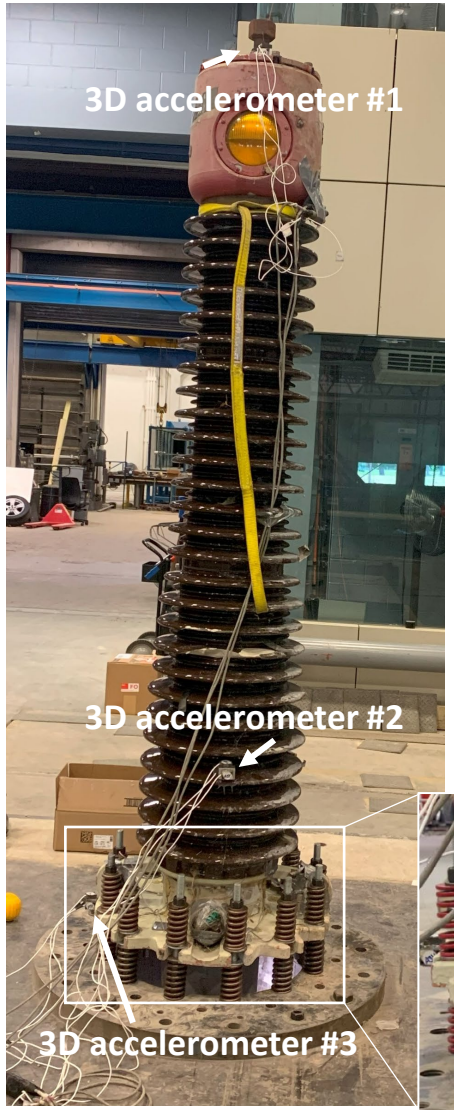
- Disk springs could be placed under the bushing mounting bolts
  - Tunes the resonant frequency response
- Performed small scale response tests on spring disks
  - Showed dynamic dampening response
  - Need to model and predict spring disk behavior



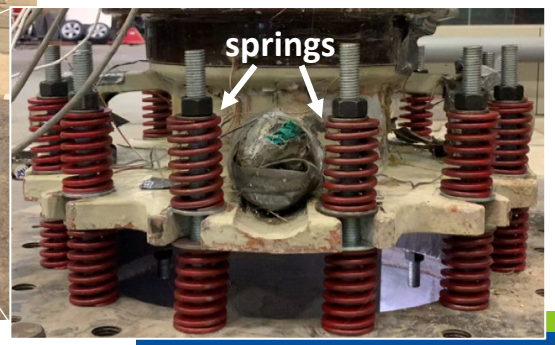
Progress to Date / Disk springs tested on a bushing

- 6 axis experimentation with full bushing
  - Stiff fitting
  - Springs
    - 787 lb/in
    - 1500 lb/in
- Predict behavior with and with/out springs
- Predict behavior with disk springs





Above ground

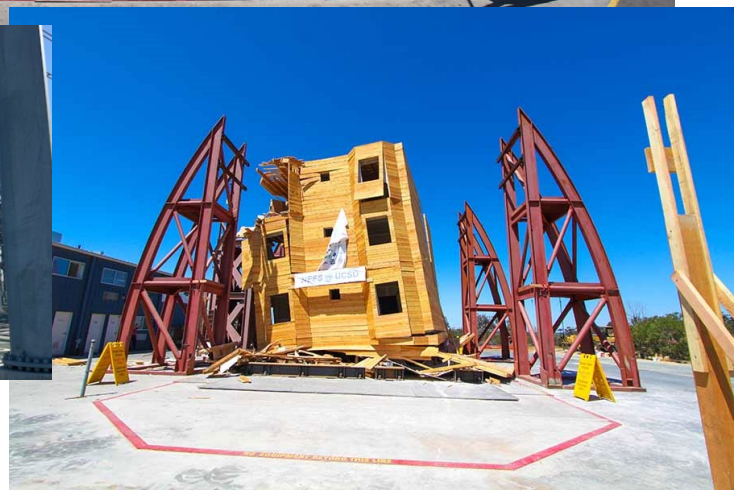


Below ground

Entire Bushing

Progress to Date / Next Steps

- **Major Accomplishments**
  - Industry Engagement:
    - Transformer working group
    - Inner utility working groups
    - IEEE PES GM panel
  - Contract sent to UCSD for shake table in 2026
  - Identified a transformer close by the table
- **Approach for the next year or to the end of project**
  - Complete subcontract with UCSD shake table
    - Currently penciled into schedule
  - Solidify power transformer availability for shake table test
  - Beta testing of spring washers
  - Full scale (**first of a kind!**) shake table test with fully dressed power transformer

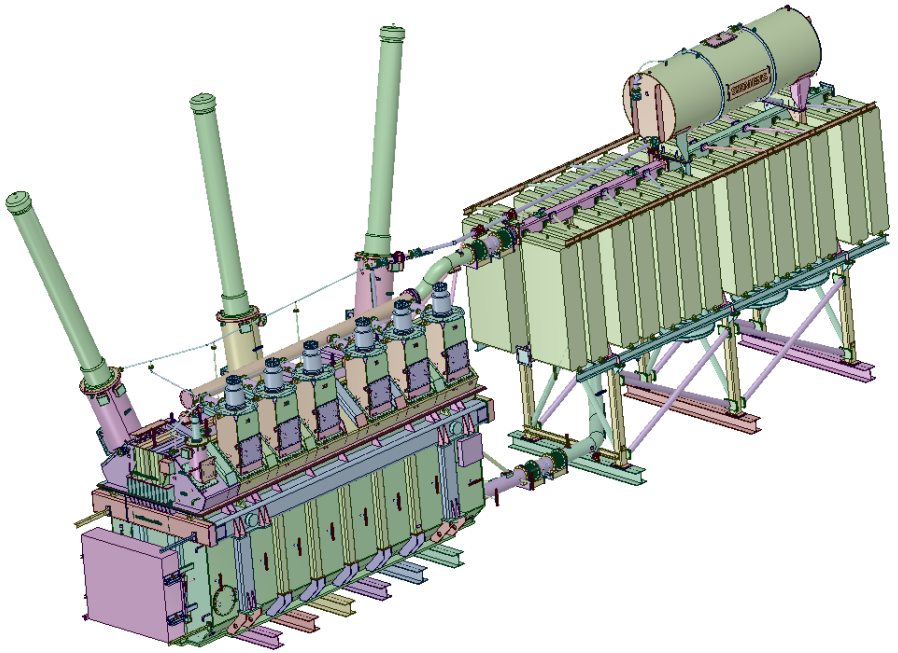


Industry outreach indicates massive interest in this first ever shake table test!!!

- Various suggestions and addons (e.g. place accelerometers on the transformer core) to the shake table test

Future efforts

- Transferability from large shake table to smaller scale tests
- Filling gaps in experimental seismic data of substation equipment, HVDC, offshore wind



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Aug 29, 2024

Dr. Bjorn Vaagensmith Electrical Engineering Researcher
Dr. Jesse Reeves Research Engineer
Johnathan Tacke Graduate Fellow

Non-SF_6 Industrial Base Scan Review

DOE-OE Briefing: Year 1 project Overview

Idaho National Laboratory

Executive Summary

- SF_6 and the Environment
  - 22-25k times GWV of CO_2 and a 3.2k year atmospheric dwell time
- SF_6 GIE
  - High-voltage gas-insulated switchgear (GIS)
  - Gas circuit-breakers (GCB)
  - Live tank breakers (LTB) and dead tank breakers (DTB)
  - Gas-insulated lines (GIL)
- Non- SF_6 technology options
  - Clean Air
  - Vacuum
  - Flouronitrile Gas
- Long lead times (2-3 yr) to procure Non- SF_6 technology options
- Industry Scan
  - U.S. Utilities adoption
  - Supply Chain bottlenecks
  - U.S. Manufacturing capacity

SF_6 High Impact Gas

Greenhouse Gas	Global Warming Potential
SF_6	22,800-25,200 times more potent than CO_2 (note 23,500 is commonly accepted and academically reported)

1 unit of CO_2

1 unit of SF_6

Picture comparison: DOE Office of Environmental Compliance and ES&H Reporting

Common Utility Class Equipment

- **High-voltage gas-insulated switchgear (GIS)**

A switchgear is a device that contains all of the equipment necessary to isolate a circuit from the power grid. The use of an insulating gas makes GIS much smaller and less expensive than other designs

- **Gas circuit-breakers (GCB)**

A circuit breaker is a device which interrupts the flow of electrical current and is often contained within a switchgear. Again, the use of an insulating gas allows the devices to smaller and less expensive in high voltage applications

- **Live tank breakers (LTB) and Dead tank breakers (DTB)**

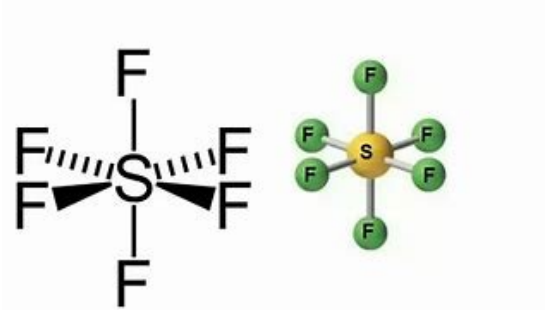
LTBs and DTBs are types of circuit breakers where the mechanisms are fully enclosed in a “tank” to isolate them from the environment. DTBs are grounded, allowing for circuit transformers to be used on the connections, while LTBs are not, making them generally less expensive. Both use insulating gas to reduce size.

- **Gas-insulated lines (GIL)**

GILs are typically short segments of transmission line used to connect components within a substation or in otherwise densely populated areas. The use of the insulating gas reduces stray electromagnetic fields that can adversely impact equipment and personnel.

SF_6 Growth and Demand

- North America growth rate for SF_6 from 2024 to 2030 is projected to be 6.5%.
  - Asia Pacific is projected to have the highest growth rate in the SF_6 market.
- The expected growth rate for the North American non-SF_6 market until 2030 is anticipated ~7%.
- SF_6 GIS accounted for 60% of the market for indoor circuit breakers.
- Demand is being driven by
  - Demand for electricity
  - Rising global urbanization
  - High renewable energy capacity additions



Sulfur Hexafluoride Industry Statistics • Gitnux

- Different environmental accounting methods generate very divergent timelines for SF_6 equivalency
  - At point of manufacturing (including deployed): 2035
  - At point of environmental release: after many decades

SF_6 Alternatives

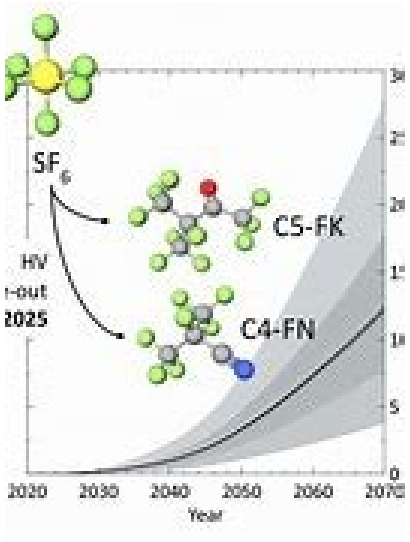
- 3M Novec Dielectric
  - GE
  - Hitachi
  - ABB
- Vacuum/clean Air
  - Siemens
- Synthetic Air
  - Mitsubishi
- Dry Air
  - MEIDEN
  - Mitsubishi
- Retrofit
  - Replace gas in existing equipment with new gas
  - In testing phase

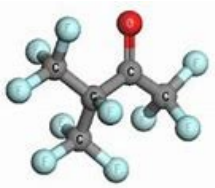
	C_{ad} [1]	p_{min}/ MPa [2]	T_{min}/°C [3]	GWP	D.S. [4]	Toxicity LC50 ppmv
SF_6	-	0.43…0.6	-41…-31	23500	0.86…1	-
CO_2	-	0.6…1	≤ -48 [6]	1	0.4…0.7	>3e5
CO_2/C5-PFK/O_2 (HV)	≈6/12	0.7	-5...+5	1	≈0.86	>2e5
CO_2/C4-PFN (HV)						
Air/C5-PFK (MV)						
N2/C4-PFN (MV)						

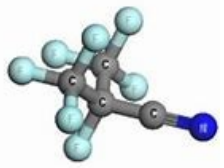
	CAS number	Boiling point/°C	GWP	ODP	Flammability	Toxicity LC50 (4h) ppmv	Toxicity TWA[1] ppmv	Dielectric strength/pu at 0.1 MPa
SF_6	2551-62-4	-64 [2]	23500	0	No	-	1000	1
CO_2	124-38-9							
C5-PFK	756-12-7							
C4-PFN	42532-60-5							

	Operating pressure [MPa]	Dielectric strength/pu	SLF performance compared to SF_6 /pu [1]	Dielectric recovery speed/pu
SF_6	0.6	1	1	1
CO_2	0.8…1	0.5		
CO_2+C5-PFK/O2	0.7…0.8	clo		
CO_2/C4-PFN	0.67…0.82	clo		

Medium	SF_6	CO_2	C5-PFK	C4-PFN	HFO1234zee
CAS Number	2551-62-4	124-38-9	756-12-7	42532-60-5	1645-83-6
Boiling Point (°C)	-64	-78.5	26.5	-4.7	-19
GWP	23900	1	< 1	2100	6
ODP	None	None	None	None	None
Flammability	None	None	None	None	Yes
Dielectric Strength (relative to SF_6)	1	0.3	1.4	2	0.8-0.9
Toxicity (ppm)	1000	5000	225	65	800
Potential Insulator	-	✓	✓	✓	✓
Potential Interrupter	-	✓	✗	✓	✗
TRL	9	8-9	7	6	3



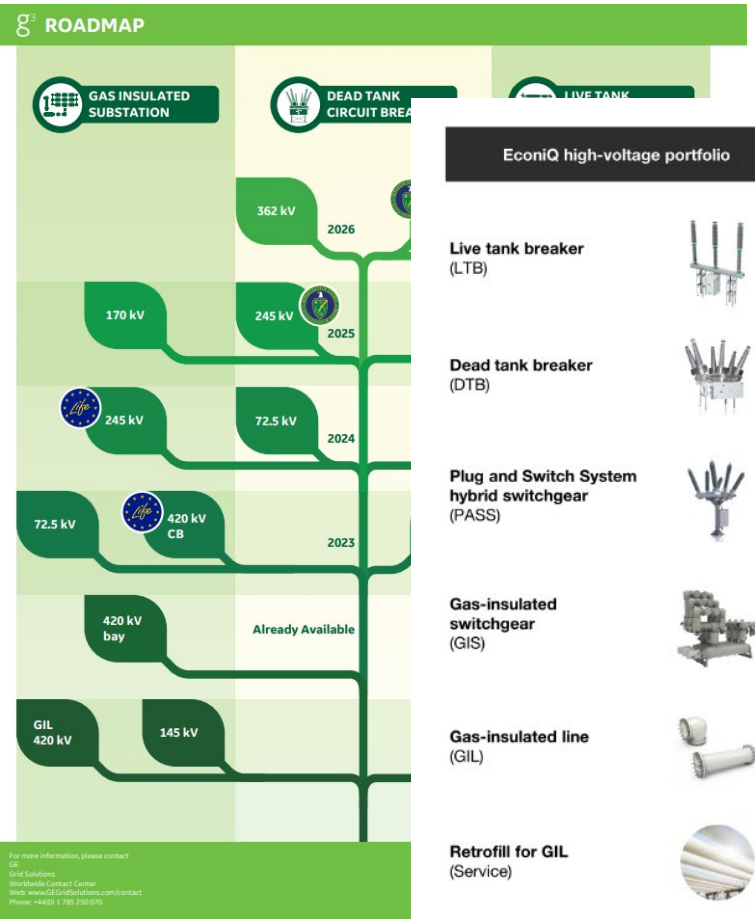

Novec 5110

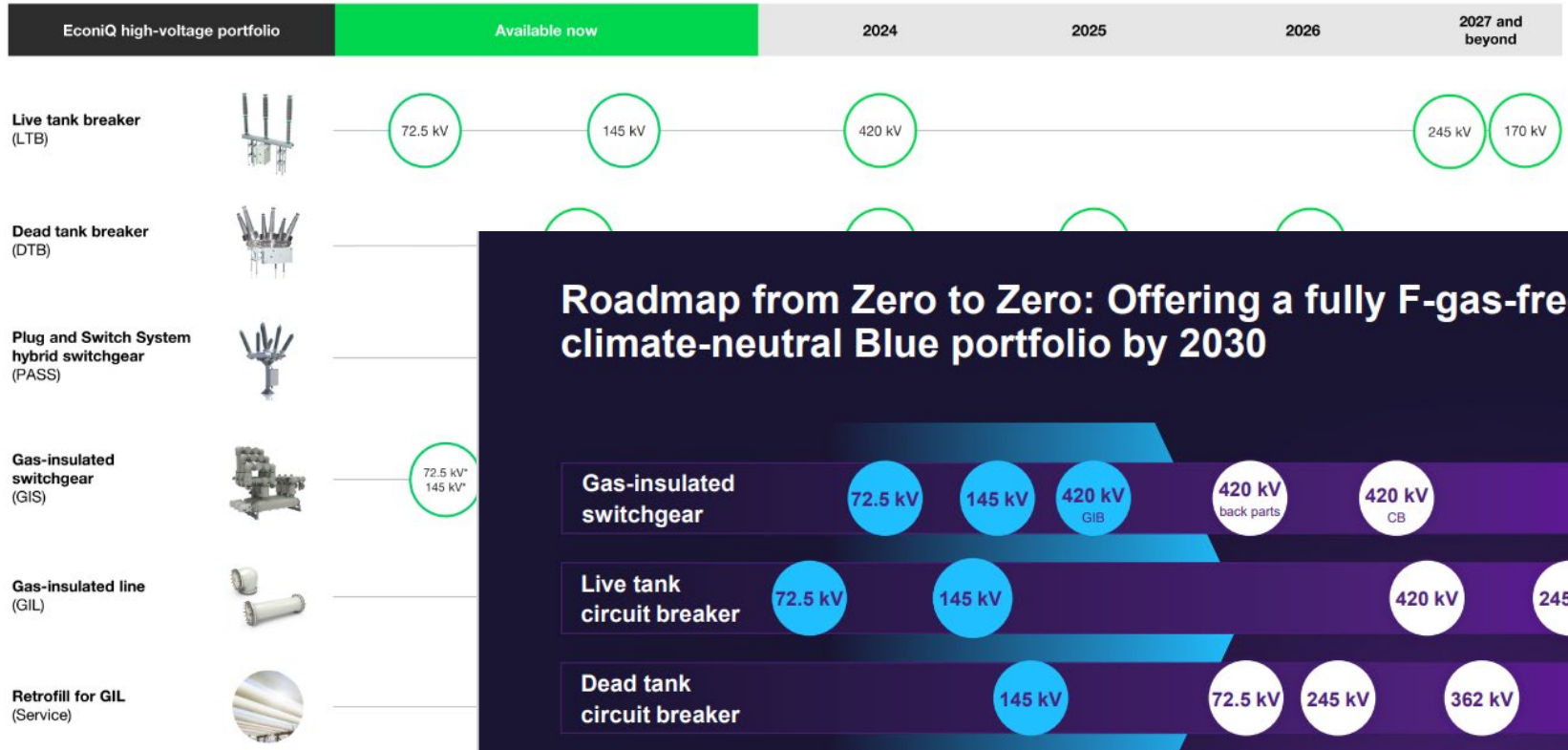

Novec 4710

Recent development of SF_6 alternative gases for switching applications
•L. Falkingham
•Published 2017
•Engineering, Materials Science

Development SF_6 Alternative Gases in Switchgears - Switchgear Content

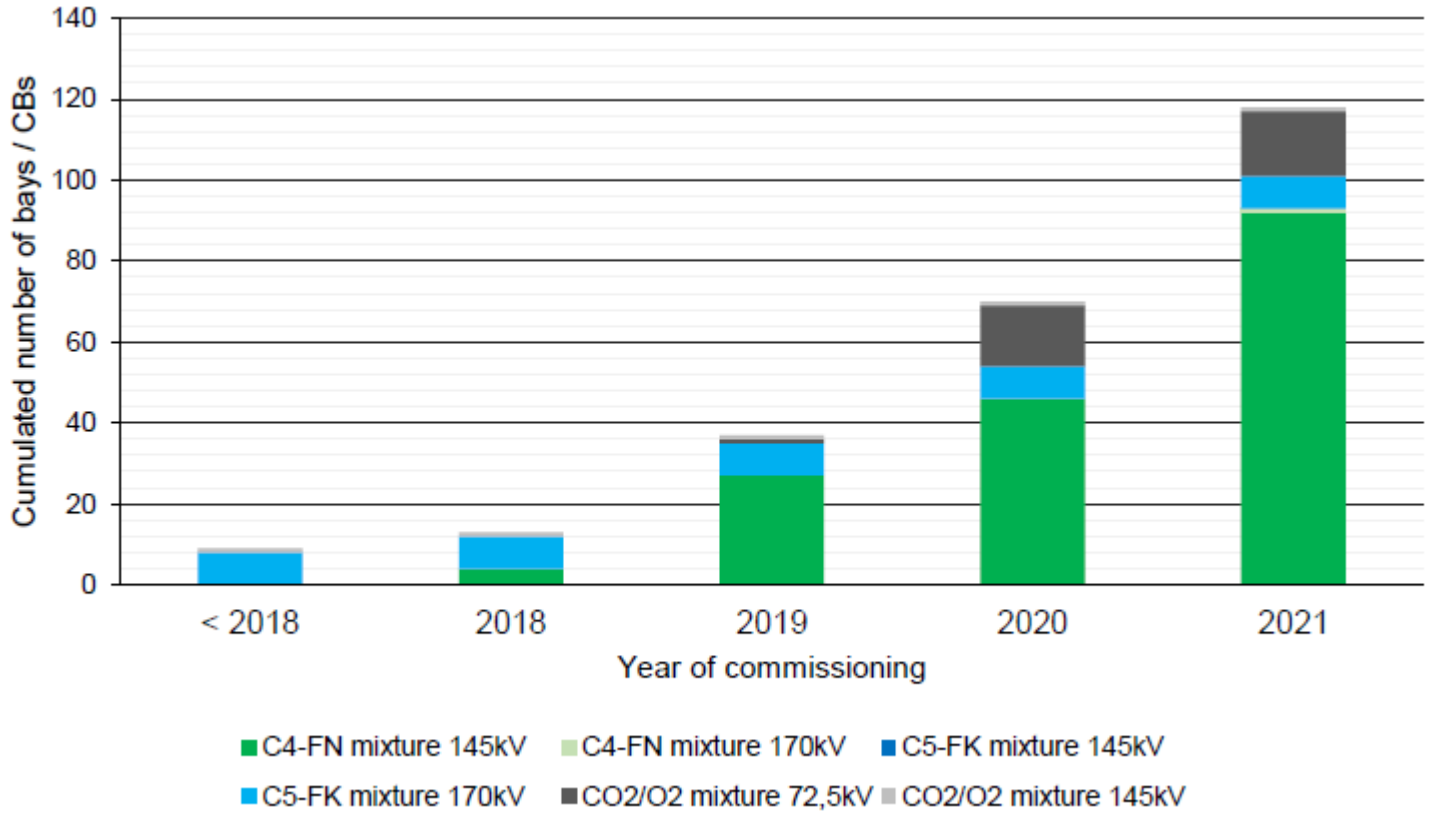
GE, Hitachi, and Siemens development plans





Commissioned Projects

- There are ~79000 substations in US
- Cases of NON-SF_6 commissioning's are counted in the hundreds
  - 30% of reviewed cases are in the US, 60% in Europe
- New procurement SF_6 vs non-SF_6 : Any where between 10:1 & 3:1



Data Chart from: CIGRE WG A3.41, TB 871 - Current Interruption in SF_6-free Switchgear, Paris: CIGRE, 2022

Government Efforts

California imposes an annual maximum rate of SF_6 emissions that was reduced by 1 percent over a ten-year period from 2011 to 2020. From 2020 onwards, the maximum emission rate is not to exceed 1 percent. CARB is also proposing regulatory amendments to phase out use of SF_6 in gas-insulated equipment (GIE) starting in 2025. The phaseout schedule limits the GIE owners' ability to acquire new SF_6 GIE without an approved SF_6 phaseout exemption.

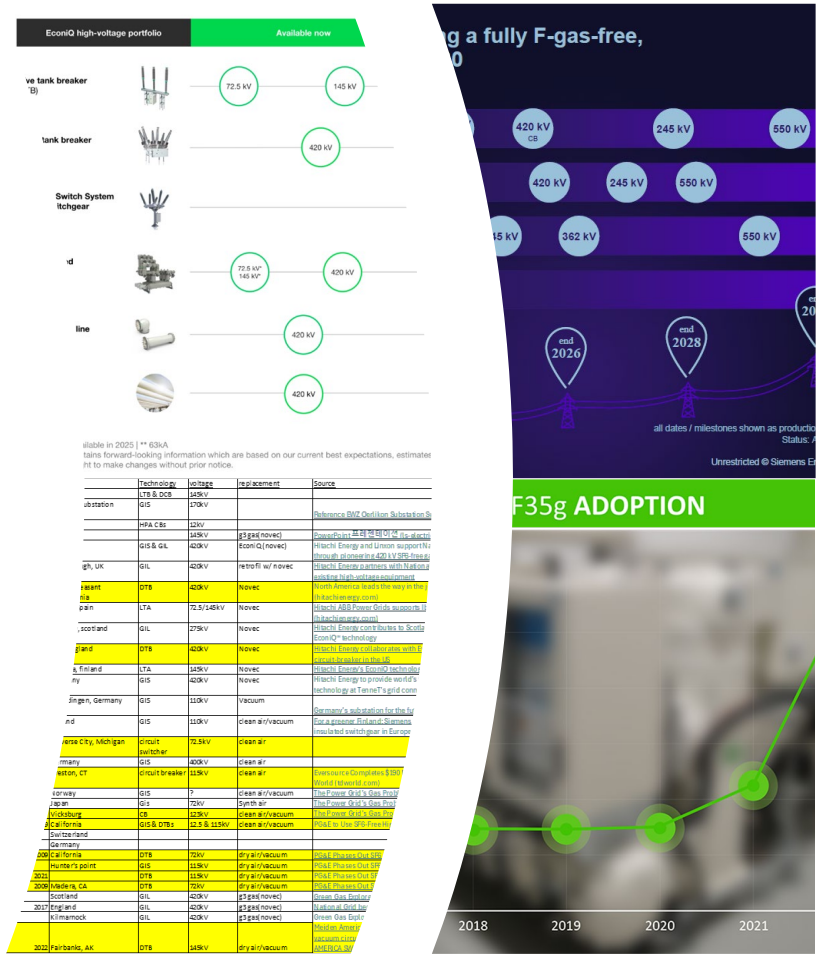
The state of Massachusetts also operates its own SF_6 regulation. Emissions are both reported annually and limited from 3.5%/yr. (2015) to 1.0%/yr. (2020 and beyond).

The SF_6 & Alternatives Coalition compromised of , Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont aim to cap and reduce CO_2 emissions but are also aiming to retire SF_6 equipment.

National Electrical Manufacturers Association (NEMA), maintains a website with current information on regulatory activity and other topics related to SF_6 and alternatives. Other states considering broad regulatory action on greenhouse gasses which may include SF_6 are, Colorado, Montana, New Mexico, Oregon, Texas, and Washington.

Findings

- Utilities
  - Wide acceptance
  - Superior maintenance costs
  - Renewable growth demand, Data centers, developing nations
  - Demand being filled with SF_6 and non- SF_6
  - Some sharing 10+ yr plans with suppliers
  - There are ~79,000 substations in US
- Manufacturing
  - Lots of demand, wait times a result of rising demand
  - Matching production to demand – very conservative
  - China and Africa drive global demand
  - 3 major technology players: Hitachi, GE, Siemens
- Supply Chain
  - No new limitations identified
  - Novec, synair and vacuum domestically available
  - Domestic vs foreign Steel



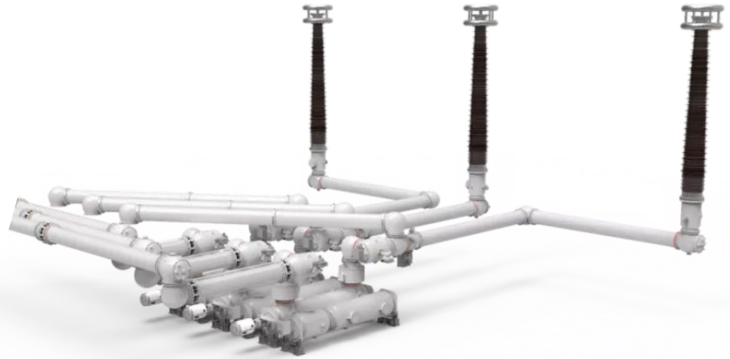
Successes – Global Impact

- Briefed Assistant Secretary Light
  - Current state of SF_6 market
  - US manufacturing base for NON-SF_6 alternatives

- Informing DOE-International Affairs' global negotiations with G7 and G20 countries

Path Forward-Technology

- Develop 765kV and up non-SF_6 breaker technology
- R&D fit form and function gas replacement in existing SF_6 infrastructure
- Industry research partnerships to improve production capacity



Path Forward-Policy

- Best practices and procedures
  - 10-year plan sharing
- SF_6 Monitoring Programs and leak requirements
  - California imposes maximum emission rate is not to exceed 1 percent.
  - CARB is also proposing regulatory amendments to phase out use of SF_6 in gas-insulated equipment (GIE) starting in 2025.
  - The SF_6 & Alternatives Coalition aims to cap and reduce CO_2 emissions and to retire SF_6 equipment.
  - National Electrical Manufacturers Association (NEMA) maintains a website with current information on regulatory activity and other topics related to SF_6 and alternatives.
- Phase out regulations

Path Forward-Partnerships

- Develop SF_6 phaseout roadmap by collaborating with key manufacturers, utilities, and other stakeholders.
  - The roadmap will act as a baseline set of recommendations for reasonable regulations to eliminate or reduce SF_6
- Key Considerations:
  - Regulations needed and timelines
  - Utility requirements
  - Manufacturing capabilities, current and future
  - Supply Chain resilience

Western Area Power Administration

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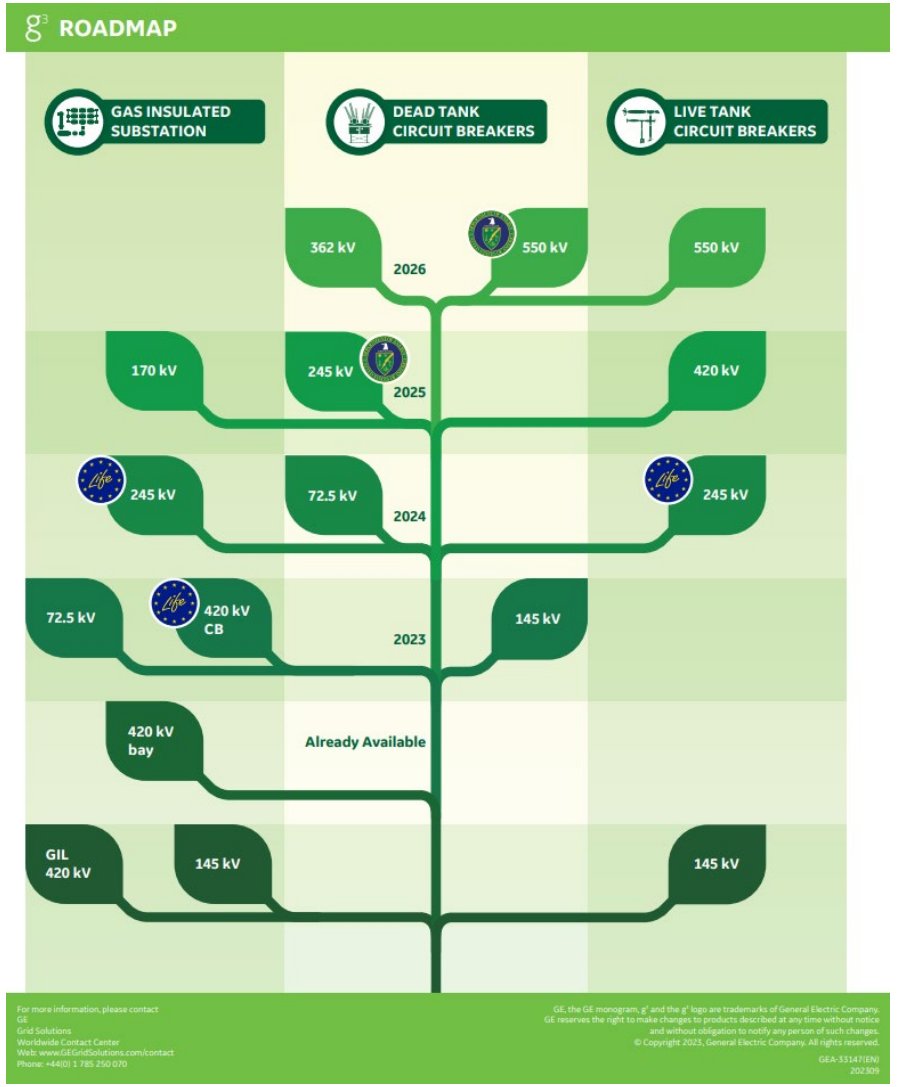
Accounting for SF_6

- When do we count SF_6 loading into the environment
  - At the time of SF_6 manufacturing?
    - Counts all SF_6 contained in switch gear
    - Projects SF_6 parity with CO_2 as a global warming contributor within the next decade
      - Assuming top projected growth rates with no SF_6 mitigations.
  - When SF_6 is emitted into the atmosphere?
    - Controlled with maintenance
    - SF_6 parity with CO_2 many decades away
      - Assumes top SF_6 projected growth rates and no additional mitigations.

- 9,040 tons of SF_6 was released in 2018 which accounted for ~0.5% of the Global Warming Value (GWV) emitted in the form of CO_2 in the same year. (The increasing atmospheric burden of the greenhouse gas, sulfur hexafluoride (SF_6) Atmos. Chem. Phys., 20, 7271–7290, 2020https://doi.org/10.5194/acp-20-7271-2020 © Author(s) 2020. Peter G. Simmonds1, et. al.)
  - Assuming 0.25% leak rate there was 3.62 Megatons of SF_6 in global use in 2018.
  - The potential global output of SF_6 can be estimated between 50-100k tons annually. This is based on a dividing the global market value of the SF_6 gas by current prices. It is crude but gives an initial order of magnitude estimate.

General Electric g³ Development Plan

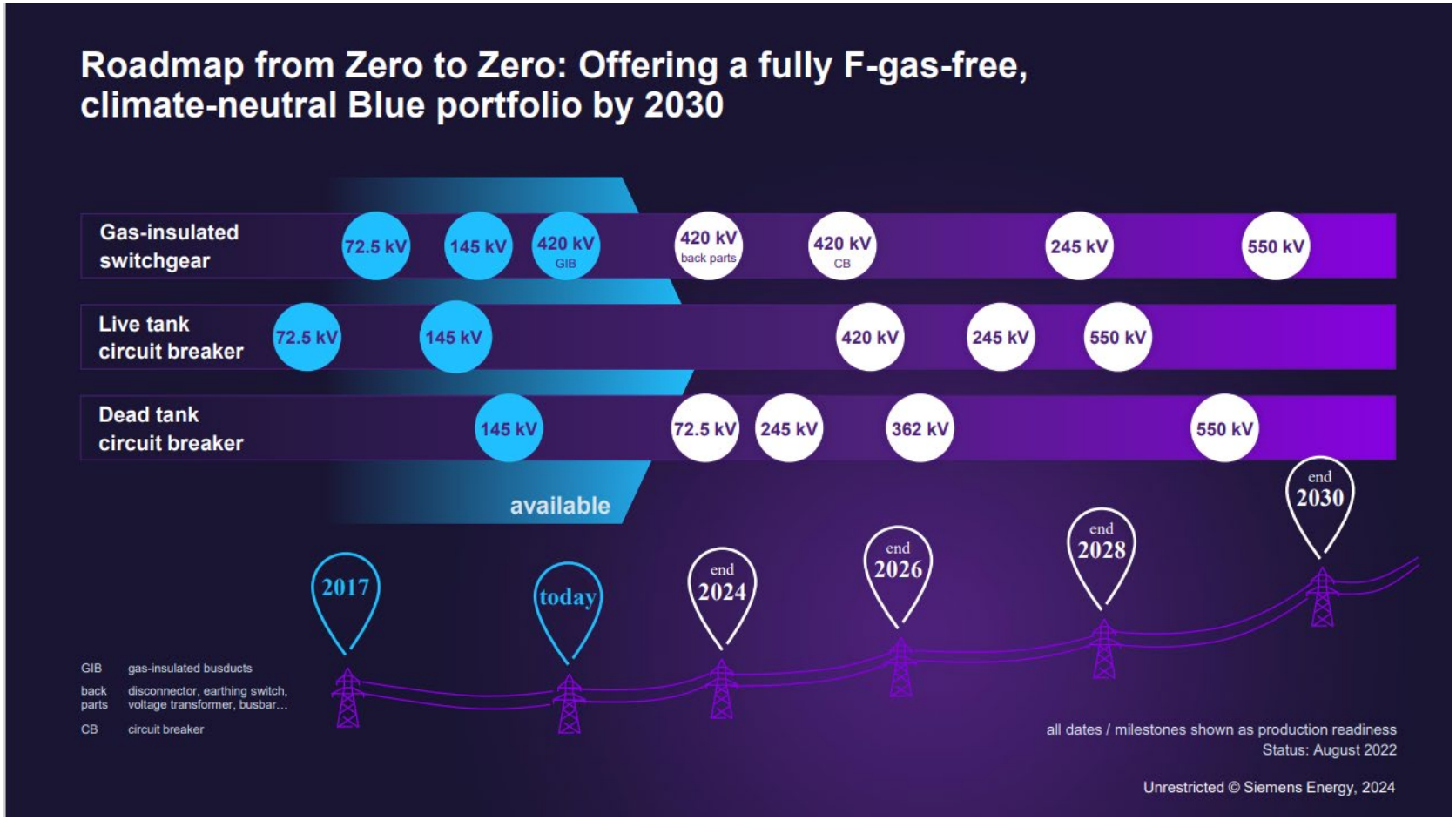


Hitachi Development Plan

EconiQ™ - Eco-efficient high-voltage portfolio | Hitachi Energy

* 60 Hz will be available in 2025 | ** 63kA
This roadmap contains forward-looking information which are based on our current best expectations, estimates and projections.
We reserve the right to make changes without prior notice.

Siemens Development Plan



Scope

- There are ~79000 substations in US
- Cases of NON-SF_6 commissioning's are counted in the hundreds
  - 30% of reviewed cases are in the US, 60% in Europe
- New procurement SF_6 vs non-SF_6 : Any where between 10:1 & 3:1

manufacturer	utility	year	location	Technology	voltage	replacement	Source
ABB		2010		LTB & DCB	145kV		
Hitachi	ewz, switzerland	2015	Oerlikon substation	GIS	170kV		Reference EWZ Oerlikon Substation Switzerland | Hitachi Energy
ABB	Kemijoki Oy	2023	Finland	HPA CBs	12kV		
LS electric	KEPCO?	2016	Korea		145kV	g3 gas(novec)	PowerPoint 프레젠테이션 (ls-electric.com)
Hitachi	NG	2023	London	GIS & GIL	420kV	EconiQ (novec)	Hitachi Energy and Linxon support National Grid in achieving sustainability targets through pioneering 420 kV SF6-free gas-insulated switchgear technology
Hitachi	NG	2021	Richborough, UK	GIL	420kV	retrofil w/ novec	Hitachi Energy partners with National Grid on world's first replacement of SF_6 in existing high-voltage equipment
Hitachi		2023	Mount Pleasant Pensylvania	DTB	420kV	Novec	North America leads the way in the journey toward an SF_6-free world (hitachienergy.com)
Hitachi	Iberdrola	2021	Murcia, Spain	LTA	72.5/145kV	Novec	Hitachi ABB Power Grids supports Iberdrola's efforts towards carbon-neutrality (hitachienergy.com)
Hitachi	SP energy	2025	Glasgow, scotland	GIL	275kV	Novec	Hitachi Energy contributes to Scotland's sustainability targets with game-changing EconiQ™ technology
Hitachi	Eversource	2023	New England	DTB	420kV	Novec	Hitachi Energy collaborates with Eversource to install the first EconiQ™ 420-kilovolt circuit-breaker in the US
Hitachi	Fingrid	2022	Heinola, finland	LTA	145kV	Novec	Hitachi Energy's EconiQ technology contributes to Fingrid's environmental goals
Hitachi	TenneT	2026	Germany	GIS	420kV	Novec	Hitachi Energy to provide world's first SF_6-free 420 kV gas-insulated switchgear technology at TenneT's grid connection in Germany
Siemens	netze BW GmbH	2022	Burladingen, Germany	GIS	110kV	Vacuum	Germany's substation for the future (siemens-energy.com)
Siemens	Fingrid	2022	Finland	GIS	110kV	clean air/vacuum	For a greener Finland: Siemens Energy seals largest order for SF 6-free gas-insulated switchgear in Europe (siemens-energy.com)
Siemens	TCL&P	2020	Traverse City, Michigan	circuit switcher	72.5kV	clean air	
Siemens	TransnetBW	2029	Germany	GIS	400kV	clean air	
?	Eversource	2024	Preston, CT	circuit breaker	115kV	clean air	Eversource Completes $190 Million Eastern Connecticut Reliability Program | T&D World (tdworld.com)
Siemens	Fagne	?	Norway	GIS	?	clean air/vacuum	The Power Grid's Gas Problem | T&D World (tdworld.com)
Toshiba	TEPCO	2023	Japan	Gis	72kV	Synth air	The Power Grid's Gas Problem | T&D World (tdworld.com)
Siemens	Entergy	2023?	Vicksburg	CB	123kV	clean air/vacuum	The Power Grid's Gas Problem | T&D World (tdworld.com)
Siemens	PG&E	2019	California	GIS & DTBs	12.5 & 115kV	clean air/vacuum	PG&E to Use SF6-Free High-Voltage Products From Siemens | T&D World
GE	Axpo		Switzerland				
GE	TenneT		Germany				
	PG&E	2009	California	DTB	72kV	dry air/vacuum	PG&E Phases Out SF6 in HV Substation GIS | T&D World (tdworld.com)
	PG&E		Hunter's point	GIS	115kV	dry air/vacuum	PG&E Phases Out SF6 in HV Substation GIS | T&D World (tdworld.com)
	PG&E	2021		DTB	115kV	dry air/vacuum	PG&E Phases Out SF6 in HV Substation GIS | T&D World (tdworld.com)
Hitachi	PG&E	2009	Madera, CA	DTB	72kV	dry air/vacuum	PG&E Phases Out SF6 Greenhouse Gas | T&D World (tdworld.com)
GE	SSEN		Scotland	GIL	420kV	g3 gas(novec)	Green Gas Explorer (gegridsolutions.com)
GE	NG-UK	2017	England	GIL	420kV	g3 gas(novec)	National Grid begins journey to SF6-free HV substations (gegridsolutions.com)
GE	SPEN		Kilmarnock	GIL	420kV	g3 gas(novec)	Green Gas Explorer (gegridsolutions.com)
Meiden	GVEA	2022	Fairbanks, AK	DTB	145kV	dry air/vacuum	Meiden America Switchgear, Inc. delivers world's first ecofriendly 145kV dead tank vacuum circuit breaker, free of harmful SF₆ gas | 2022 | MEIDEN AMERICA SWITCHGEAR (meidensha.com)