2026 International Conference of Doble Clients

From Specification to Installation: 345 kV Natural Ester GSU Transformers

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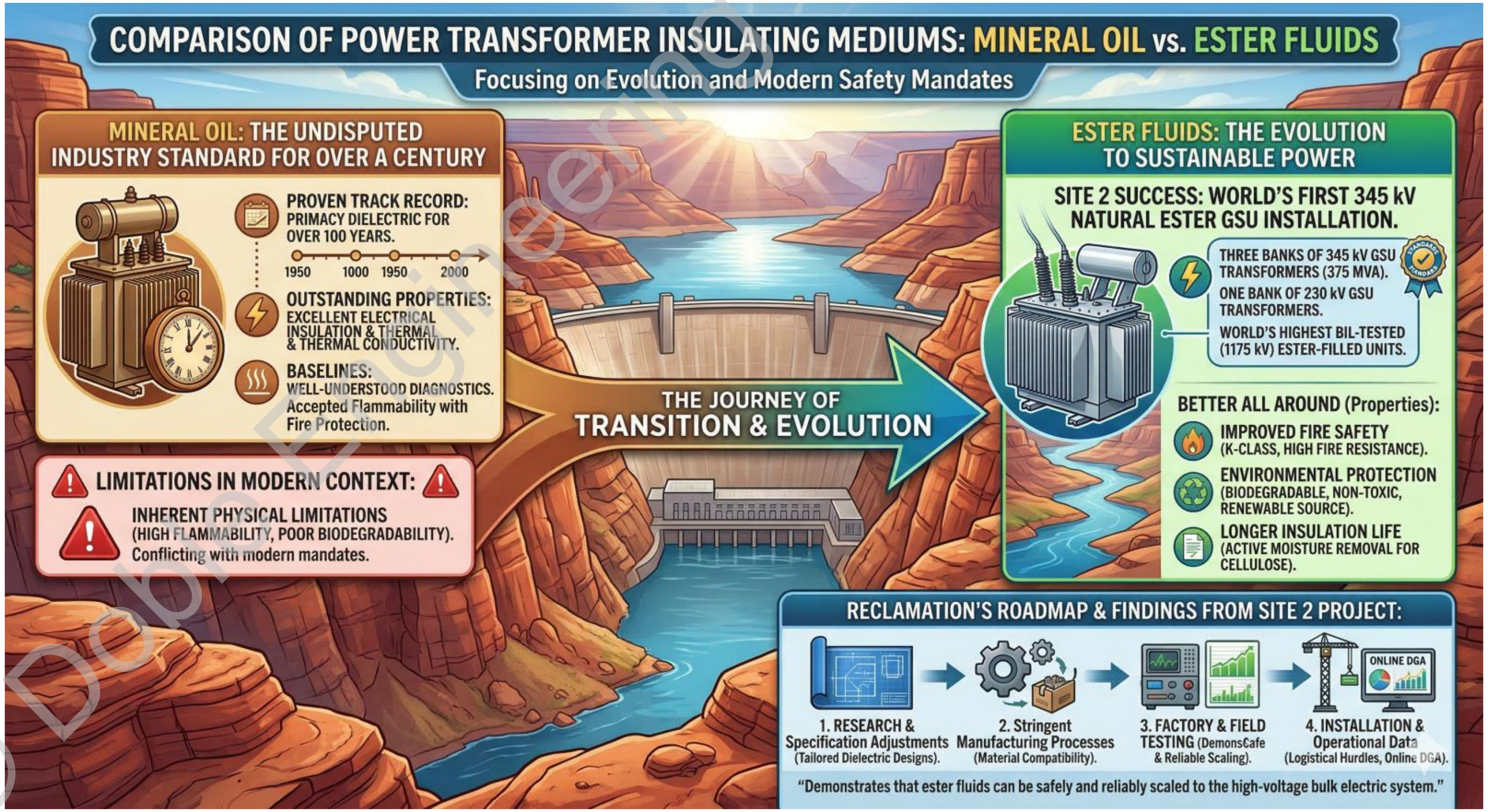
Introduction

- Research and Development
- Capabilities and Initial Steps
- Elevating the Specifications
- Design, Manufacturing, FAT
- Installation Challenges
- Early Operations
- Lessons Learned
- The Road Ahead



The Paradigm Shift:
A Research-Backed Foundation

RECLAMATION
Managing Water in the West

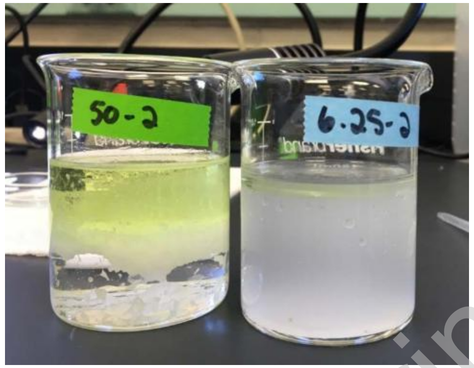
Alternate Insulating Fluids for Power Transformers

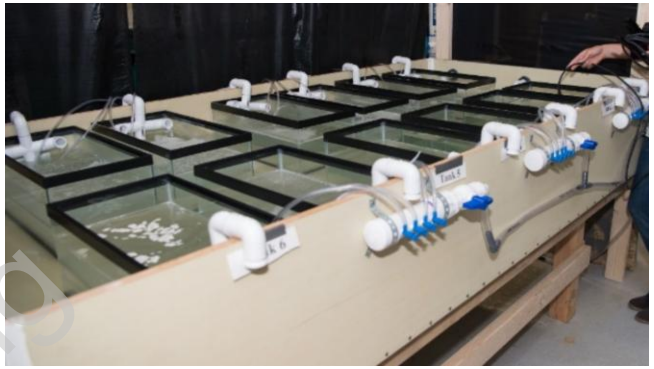
Research and Development Office
Science and Technology Program
(Final Report) ST-2019-100-01

Appendix A – Fire Testing

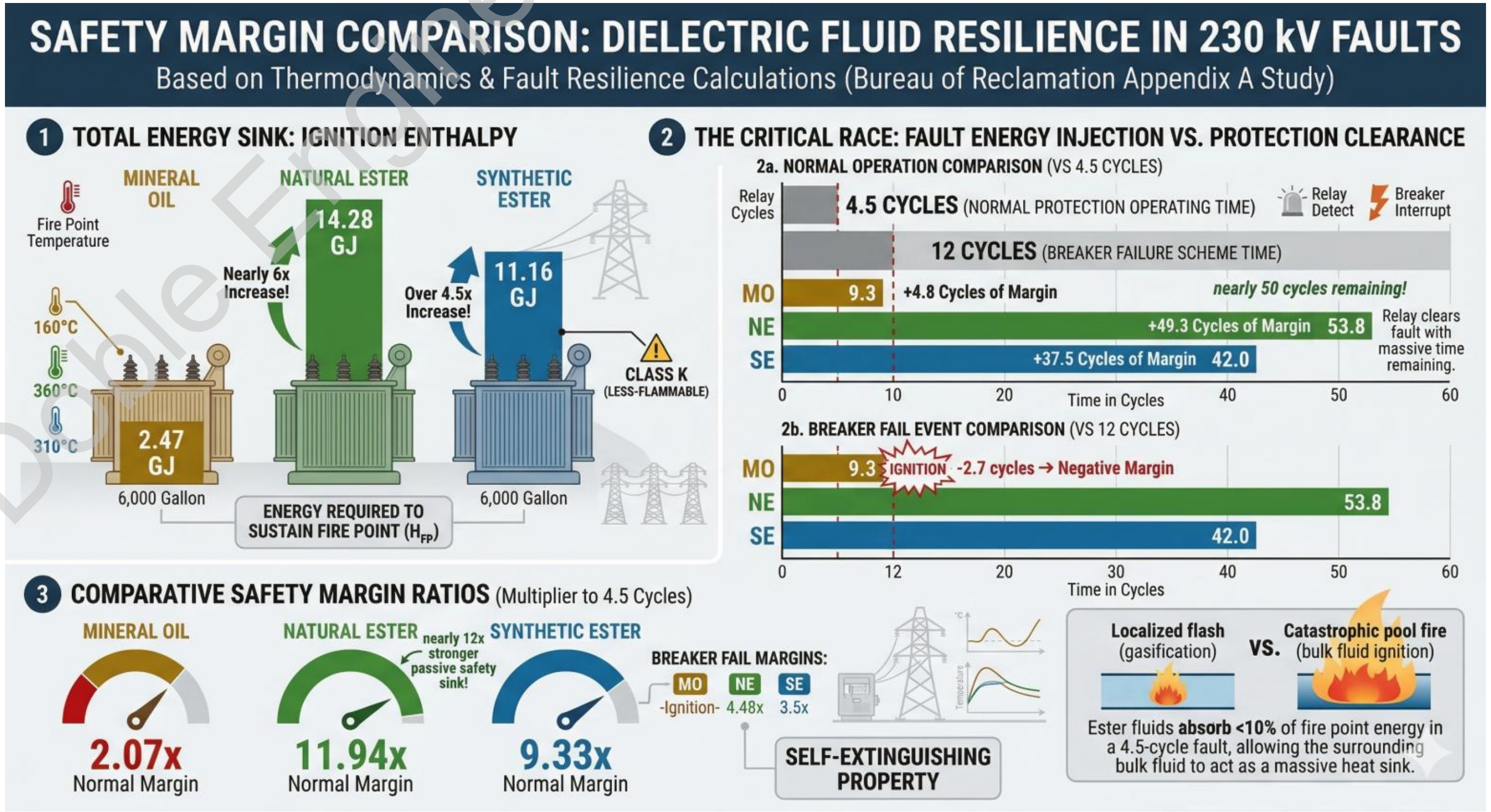
Appendix B – Toxicity Testing

Envirotemp® FR3™, MIDEL 7131, and MIDEL eN 1204 Toxicity Tests





Testing shows Envirotemp FR3, MIDEL 7131, and MIDEL eN 1204 do not exhibit toxic characteristics.



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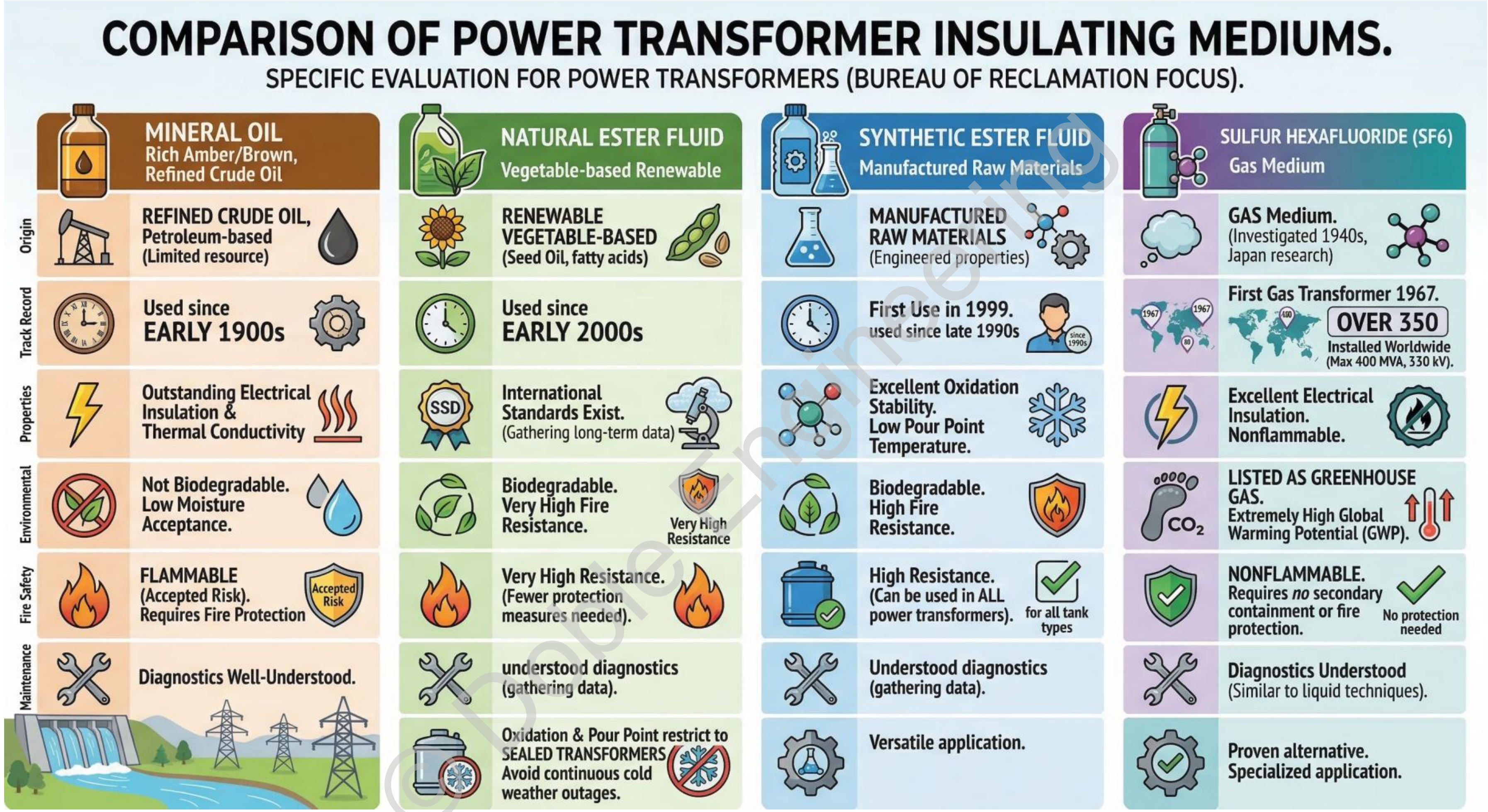
The Paradigm Shift: A Research-Backed Foundation



Topic	Mineral Oil	Natural Ester Fluid	Synthetic Ester Fluid	SF_6 Gas
Fire Safety	Disadvantage	Advantage	Advantage	Advantage
Environmental Impact to Waterways	Disadvantage	Advantage	Advantage	Advantage
Life Expectancy	Disadvantage	Advantage	Advantage	Neutral
Oxidation Stability	Advantage	Disadvantage	Advantage	Advantage
High Temperature Operation	Disadvantage	Advantage	Advantage	Neutral

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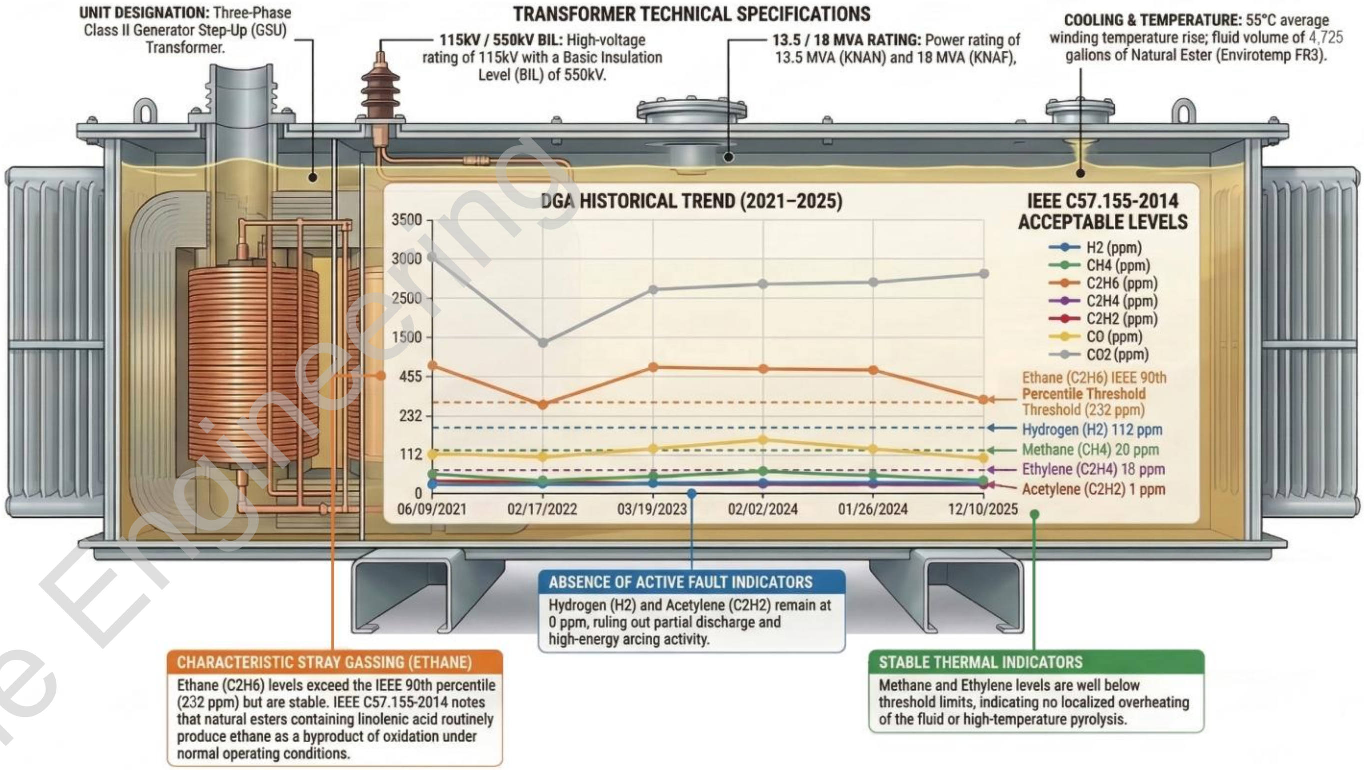
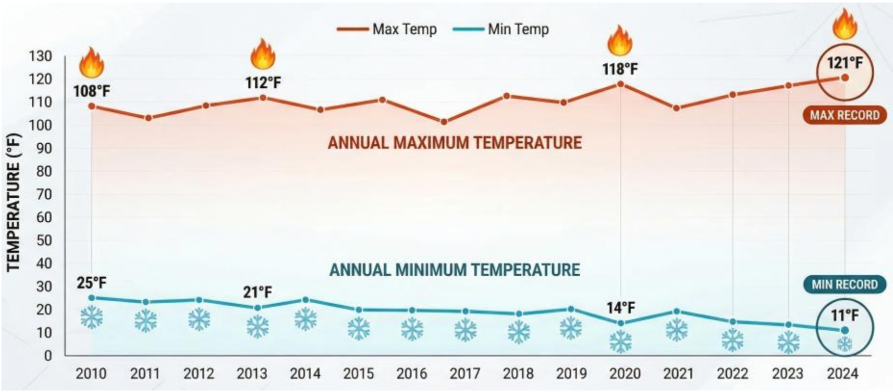
Initial Experience and Capabilities

2008 – The First Installation

- **Fleet Uniformity**: How many transformers are at the site? Will there be one consistent type of fluid on the transformer deck after the completion of the project?
- **Local Knowledge and Training**: Does the local maintenance team thoroughly understand the differences in fluid types? Are they trained on the different gassing rates, handling procedures, and electrical testing baselines required for esters?
- **Environmental and Spatial Constraints**: Does the location have higher environmental implications? Does it have restricted footprint space that makes massive secondary containment or traditional fire protection measures difficult to implement?
- **Operational Demands**: Would the location benefit from a higher operating temperature limit without sacrificing paper life?
- **Climate Extremes**: Does the location experience extreme cold temperatures during outage windows that might approach pour point values, requiring special cold-start protocols?





Initial Experience and Capabilities

- **Possibility**: Retrofilling older transformers with ester fluids can improve fire safety, reduce environmental risk, and extend asset life.
- **Caution**: Reclamation treats retrofilling **<u>cautiously</u>** because it significantly alters dielectric and thermal performance.
- **Full Analysis**: Detailed pre-analysis is required, including:
  - Verification of dielectric clearances and cooling capability
  - Assessment of insulation (paper) condition and asset health
  - Material-compatibility checks for legacy gaskets and seals
  - Evaluation or upgrade of the fluid-preservation system to prevent oxidation
- **Application**: This framework was applied to aging transformers at Site 3.
  - After engineering reviews and targeted upgrades, the units were confirmed as viable candidates for synthetic-ester retrofilling.

2025 – The First Retrofill

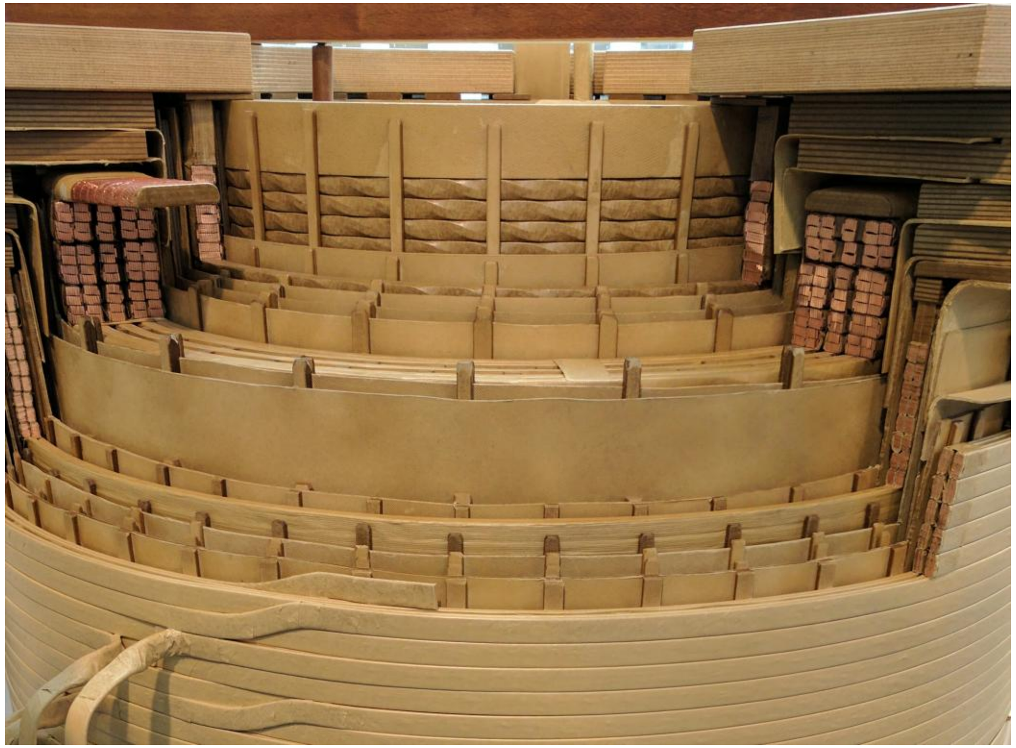
The Site 2 Catalyst

- **Fluid Choice is Key**: The facility is critical to Western power reliability and environmentally sensitive.
- **Decision**: identified a K-class, fully biodegradable natural ester as the best fit due to high environmental concerns and spatial constraints.
- **Major Infrastructure Upgrades**, including:
  - Three banks of 345 kV, 125 MVA single-phase transformers + one spare
  - One bank of 230 kV, 125 MVA single-phase transformers + one spare
  - Isolated-phase bus circuits for each bank
  - Seismic anchorage, fire protection, and secondary containment
- **Implementation**: natural ester in 345 kV GSUs at 1175 kV BIL was an industry first and exceeded previous proven levels.
- **New Territory**: Natural esters met environmental and fire-safety goals but required new engineering approaches.
- **Impacts**: The scale and voltage class of Site 2 led to a full redesign of GSU specifications, design processes, manufacturing, and testing.

Elevating the Specifications: Designing for Ester

Procuring a 345 kV natural-ester GSU required specifications far beyond standard IEEE guidance due to lack of ester information. (2010-2012 timeframe)

- Ester fluids interact differently with core, windings, tank, and accessories, requiring purpose-built engineering.
    - ASTM D877 vs D1816
- Dielectric Design & Fluid Impregnation
    - High-voltage (1175 kV BIL) design demanded redesigned dielectric clearances and insulation structures.
    - Natural esters behave differently under fast impulse transients, requiring increased fluid gaps and modified barriers.
    - Reclamation required full factory impregnation with natural ester to ensure representative dielectric testing.
        - Testing with mineral oil followed by ester filling was prohibited due to dielectric mismatch risk.
- Thermal & Mechanical Testing
    - Ester's higher viscosity required redesigned cooling ducts and unique thermal profiles.
    - Every transformer had to undergo a full temperature-rise test; design testing was not allowed.
    - A full short-circuit test was required to validate the redesigned mechanical structure.



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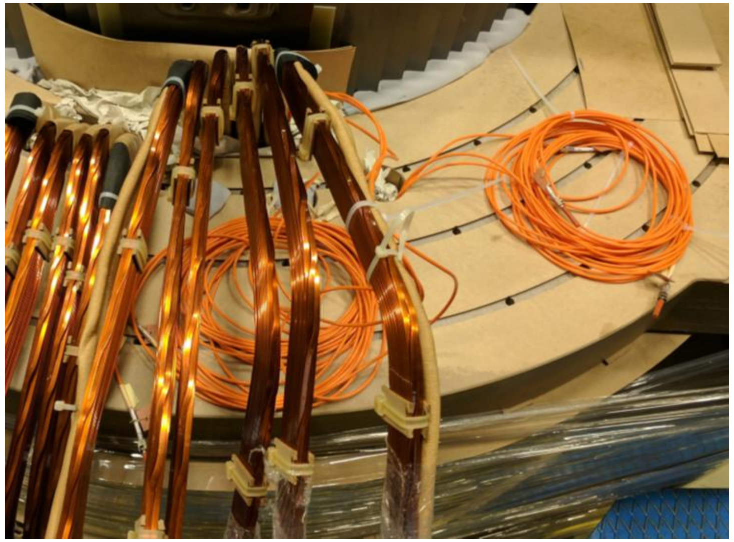
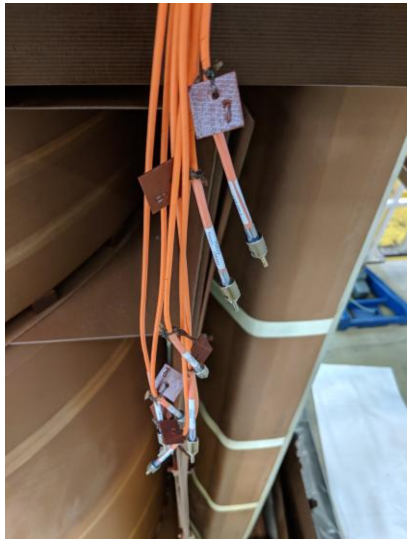
Elevating the Specifications: Designing for Ester

- General Protection
  - Conservative even though we understand the theories of ester fluids.
  - Reducing the possibility of a fire (flexible tank, pressure relief devices, fast depressurization device)
- Fire Protection and Containment
  - Activation: Remove differential protection as an input, Add Linear heat detectors on tank for confirmed fire detection.
  - Protection and Suppression: Dedicated fire suppression release panels with 10-minutes of water (cycling deluge valve)
  - Containment wall calcs including fire suppression water
- Real-Time Monitoring (fiber optics and DGM)
  - Using CT on winding and fiber optic probes
  - Online dissolved gas monitors
- Material Compatibility
  - Non-oil, non-porcelain type bushings
  - Gaskets to prevent swelling

Fire Suppression				
565	GPM	10	minutes	5650 Gallons
			Transformer Oil	9906 Gallons
Each Containment Individually Calculated			Total	15556 Gallons
				2079.679 cubic feet

Total Containment		
528.94 area	5.744792 height	3038.65 cubic feet
Transformer Area plus Curb to be Removed		
166.7831 area	4.744792 height	800.5779 cubic feet
Rapid Pressure Release Canister Area to be Removed		
9.621128 area	4.77 height	45.89278 cubic feet
Remaining Area after Containing Fluids		
		112.5002 cubic feet





Design, Manufacturing, and FAT: Proving the Build

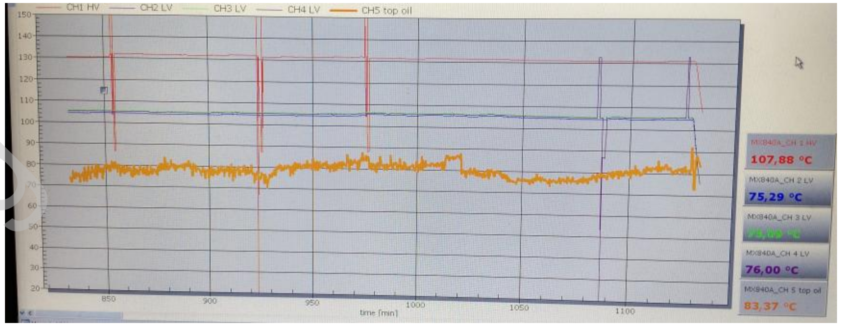
- **Iterative Design Reviews (over-the-wall vs partnering)**
  - 345 kV / 1175 kV BIL design required revised cooling channels and larger dielectric clearances for ester fluid.
  - Each change triggered detailed checks to keep thermal and electrical limits within tank constraints.
- **Manufacturing**
  - Impregnation Process (x3 to x4 times longer)
  - Ester fluids result in hotter temps, different capacitance/DFR/SFRA/IR limits, slower gas dissolution, and longer impulse wait times.
  - Accurate testing requires using the same ester fluid the transformer will operate with; mineral-oil testing produces invalid baselines.
- **Prototype Testing (345kV)**
  - Initial FAT established baseline dielectric and thermal performance.
  - Full short-circuit test verified mechanical strength.
  - Active part was removed and inspected for any damage.
  - Final FAT confirmed no issues after the short-circuit test.
- **Manufacture and Test**
  - Once Prototype passed full test sequence, authorizing production of remaining 13 units.





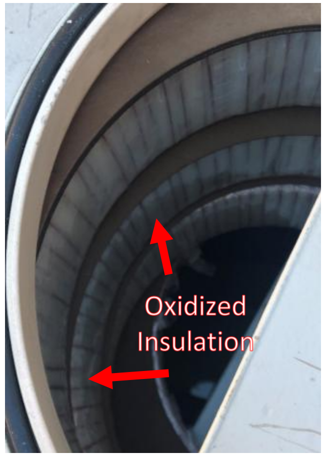
Design, Manufacturing, and FAT: Proving the Build

- Necessity of On-Site Witness of FAT
  - Technical Experts
  - Checking the build process, fluid impregnation, testing setup and calibration, test results and interpretation.
  - Clears transformer for shipping (must be done onsite if you're not paying for storage fees at the factory)
- Transportation:
  - Weight limits required shipping transformers without fluid.
  - Natural ester insulation made oxidation protection critical.
  - Units were fully drained, sealed, and pressurized with dry nitrogen.
  - Monitoring devices tracked shock and handling throughout transit.
  - Measures ensured transformers arrived with insulation integrity preserved.



Installation Challenges: Rubber Meets the Road

- Gas Storage Limits
  - COVID-19 delays forced long-term nitrogen storage, creating significant preservation risks.
  - Extended gas-only storage and ester chemistry made insulation and oxidation vulnerability critical.
  - Early oxidation on separately shipped HV turrets showed how quickly ester degrades without protection.



- Vacuum Filling
  - Emergency fluid-fill and extended vacuum processing were required to safely restore insulation after storage exceeded limits (12-months).
  - Deep vacuum: 0.125–0.150 Torr (held 96 hrs).
  - Heated ester at ~65°C.
  - 3–4 days total processing per unit.
  - Stand time >60 hrs.

Transformer Designation	Voltage Class	Nitrogen Fill Date	Ship from Factory Date	Site Arrival Date	Ester Field Fill Date	Approx. Time Under Gas
2101	345 kV	Aug 1, 2018	Oct 16, 2018	Dec 14, 2018	Mar 15, 2019	~7.5 months
2102	345 kV	Oct 15, 2018	Oct 16, 2018	Dec 14, 2018	May 17, 2019	~7.0 months
2103	345 kV	Sept 14, 2018	Oct 16, 2018	Dec 14, 2018	Apr 9, 2019	~7.0 months
2104	345 kV	Aug 17, 2018	Oct 16, 2018	Dec 14, 2018	May 20, 2019	~9.0 months
3101	345 kV	Jun 26, 2019	Sept 19, 2019	Jan 08, 2020	Jan 14, 2021	~18.5 months
3102	345 kV	Jul 1, 2019	Sept 19, 2019	Jan 08, 2020	Jan 14, 2021	~18.5 months
3103	345 kV	Sept 18, 2019	Sept 19, 2019	Jan 08, 2020	Jan 14, 2021	~16.0 months
4101	345 kV	Sept 18, 2019	Nov 13, 2019	Feb 07, 2020	Jan 19, 2021	~16.0 months
4102	345 kV	Oct 28, 2019	Nov 13, 2019	Feb 07, 2020	Jan 19, 2021	~14.5 months
4103	345 kV	Oct 28, 2019	Nov 13, 2019	Feb 07, 2020	Jan 19, 2021	~14.5 months
5101	230 kV	Feb 4, 2019	Not Recorded	Apr 15, 2020	Dec 11, 2020	~22.0 months
5102	230 kV	Dec 7, 2018	~Dec 8, 2018	Feb 18, 2019	Dec 11, 2020	~24.0 months
5103	230 kV	Nov 30, 2018	~Dec 8, 2018	Feb 18, 2019	Dec 11, 2020	~24.5 months
5104	230 kV	Nov 30, 2018	~Dec 8, 2018	Feb 18, 2019	Dec 11, 2020	~24.5 months

Installation Challenges: Rubber Meets the Road

- Field Tests and Baseline Values
  - Power factor naturally higher in esters but still tested exceptionally low on these units.
  - Esters absorb far more moisture than mineral oil; moisture levels must be judged within ester saturation limits.
  - AC breakdown voltages consistently exceeded IEEE minimums, confirming strong dielectric performance.

	Dielectric Breakdown Voltage ASTM D1816 1mm		Moisture Parameters			Dissipation Factor – Fluid ASTM D924	
Transformer Designation	Measured Values (kV)	Acceptable Values (kV)*	Moisture (ppm)	Relative Saturation (%)	Acceptable Values (ppm)*	Measured Values (%)	Acceptable Values (%)*
2101	35[+]	> 35	16	2.0	< 100	0.09	< 0.5
2102	36	> 35	11	1.0	< 100	0.139	< 0.5
2103	35	> 35	17	2.0	< 100	0.133	< 0.5
2104	36	> 35	14	1.0	< 100	0.125	< 0.5
3101	42	> 35	17	1.2	< 100	0.17	< 0.5
3102	36	> 35	24	1.9	< 100	0.153	< 0.5
3103	42	> 35	31	2.6	< 100	0.188	< 0.5
4101	38	> 35	11	1.0	< 100	0.177	< 0.5
4102	43	> 35	18	1.5	< 100	0.156	< 0.5
4103	41	> 35	13	1.1	< 100	0.150	< 0.5
5101	38	> 35	24	2.0	< 100	0.301	< 0.5
5102	36	> 35	9	1.3	< 100	0.120	< 0.5
5103	38	> 35	10	1.0	< 100	0.192	< 0.5
5104	37	> 35	38	2.8	< 100	0.255	< 0.5

*Values listed are per IEEE C57.147-2018.
[+]Initial test results were low and required reprocessing. Resampling provided acceptable results.

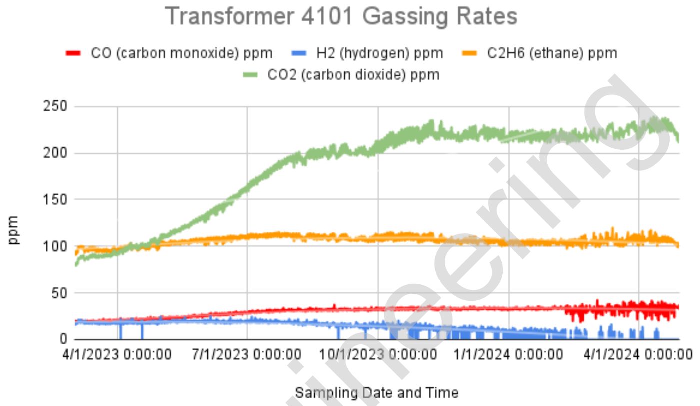
Transformer Designation	Dissipation Factor Test Results (%)			Acceptable Values (%)*
	CH	CHL	CL	
2101	0.229	0.219	0.462	< 0.5
2102	0.285	0.295	0.581	< 0.5
2103	0.259	0.261	0.462	< 0.5
2104	0.250	0.277	0.503	< 0.5
3101	0.284	0.311	0.502	< 0.5
3102	0.255	0.282	0.466	< 0.5
3103	0.303	0.317	0.511	< 0.5
4101	0.296	0.311	0.453	< 0.5
4102	0.272	0.296	0.422	< 0.5
4103	0.274	0.305	0.423	< 0.5
5101	0.254	0.241	0.462	< 0.5
5102	0.261	0.228	0.494	< 0.5
5103	0.263	0.251	0.519	< 0.5
5104	0.263	0.251	0.520	< 0.5

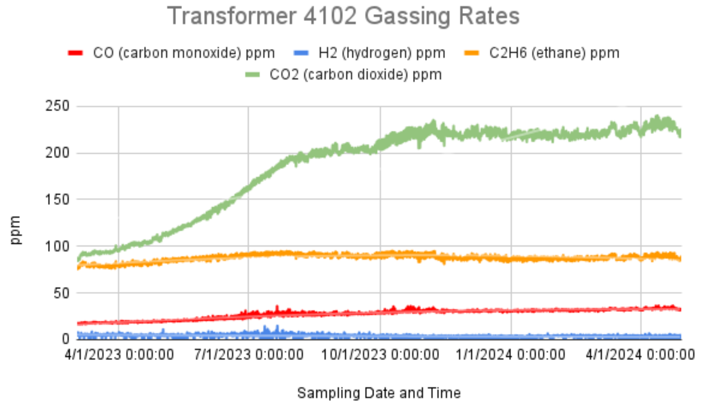
*Acceptable test values are from IEEE C57.152 (2013 edition). The new edition (2026) will include acceptable values of < 1.0% for ester fluid transformers.

- Plant Wiring
  - Control panels were fully rebuilt with new wiring to cleanly integrate modern monitoring systems.

Commissioning and Early Operations

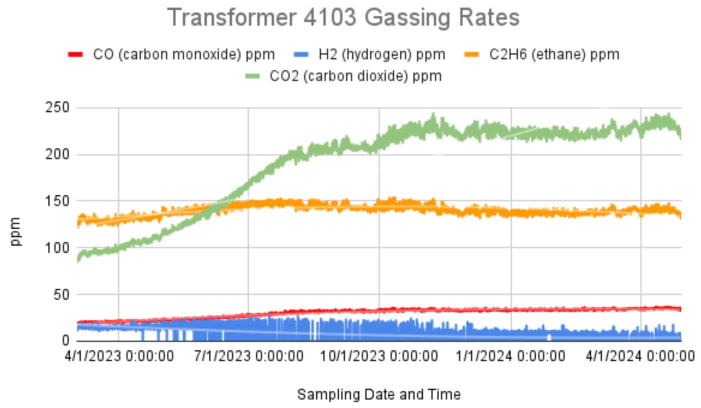
- The Baseline Rate of Change
  - Banks energized after resolving legacy controls; DGA shifted to IEEE C57.155.
  - Online DGMs established ester-specific baseline rates using high-frequency sampling (35,000 data point).
  - Manual lab samples validated DGM accuracy during the first-year baseline phase.
  - Initial gas surge stabilized over time, confirming healthy equilibrium conditions.





Planned Sample	Days from Energization
Beginning of Energization (voltage soak 24-hours)	0
End of Energization (voltage soak)	1
End of Initial Loading	3
24-Hours After Normal Loading	4
72-hours After Normal Loading	6
First Week of First Month	19
Second Week of First Month	33
Third Week of First Month	40
Fourth Week of First Month	47
4-Months After 1st Month	152
8-Months After 1st Month	271
12-Months After 1st Month	397

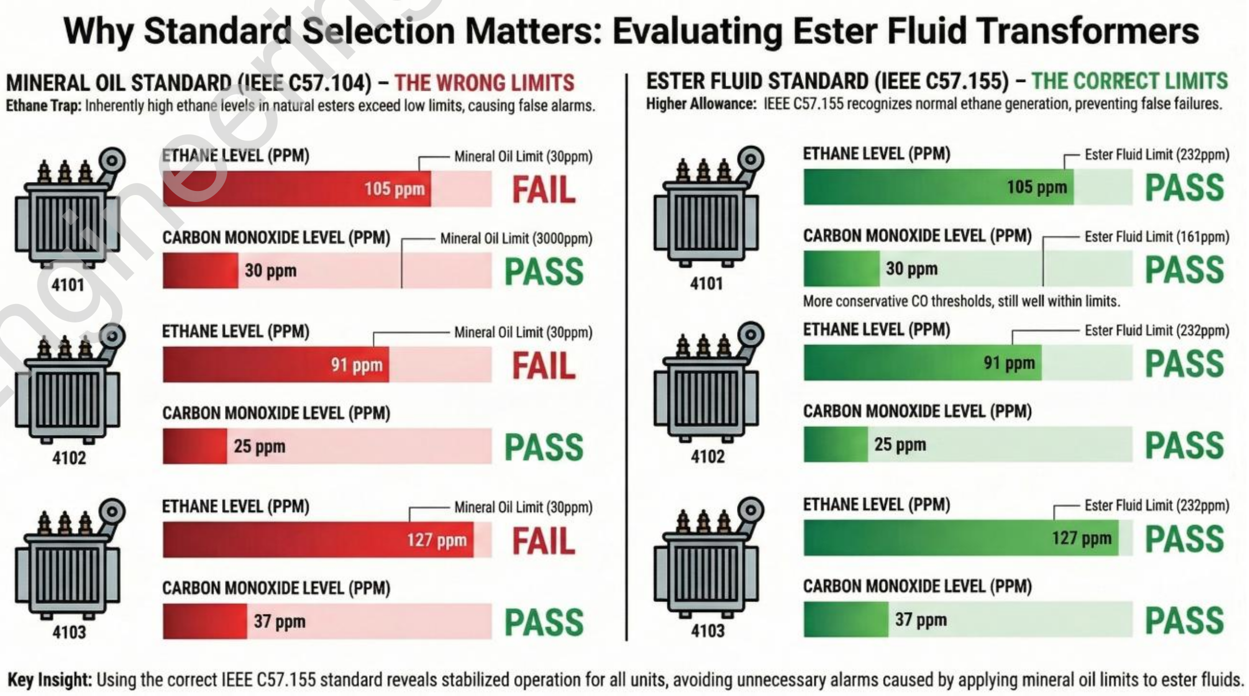
Advanced monitoring only works when trained, on-site personnel actively manage the system. Without ownership, fluid-specific expertise, and expert interpretation, data becomes unreliable, alarms occur unnecessarily, and early-life ester gas generation can be misread as faults rather than normal commissioning behavior.



Transformer	Energization Date	Stabilization Time Frame	Hydrogen (H_2)	Methane (CH_4)	Ethane (C_2H_6)	Ethylene (C_2H_4)	Carbon Monoxide (CO)	Carbon Dioxide (CO_2)
4101	Mar 2, 2023	Nov 15, 2023	10.7	1.0	105	1.0	36	220
4102	Mar 2, 2023	Dec 01, 2023	3.7	0.8	87	0.5	30	218
4103	Mar 2, 2023	Dec 15, 2023	11.2	2.0	140	1.2	33	222
Note: Acetylene values were non-detectible throughout testing.								

Commissioning and Early Operations

- The Stray Gassing Phenomenon
  - Mineral-oil DGA limits mislabel ester ethane levels as severe faults.
  - Natural esters naturally produce ethane and hydrogen through benign stray gassing.
  - Rate-of-change, not absolute ppm, is the correct diagnostic metric for esters.
  - Correct fluid-specific analysis prevents costly false-positive fault responses.
- Application of Fault Detection
  - Mineral-oil diagnostics (Duval 1, IEEE C57.104) misdiagnose ester DGA; ester-specific models Duval 3/3b/6 and Pentagons 3/4/4b per IEEE C57.155 are required.
  - Correct C57.155-based diagnostics prevent false fault indications and ensure accurate classification.



Lessons Learned and The Road Ahead

Field performance of the 345 kV and 230 kV ester-filled GSUs now informs future Reclamation specifications and supports ongoing IEEE standard revisions.

- Key Project Lessons
  - Ester systems require purpose-built specifications, materials, and dielectric design.
  - On-site FAT expertise is essential for accurate testing and interpretation.
  - Strict nitrogen protection and disciplined field processing prevent oxidation failures.
  - Continuous monitoring must use ester-specific diagnostics and rate-of-change logic.

- Fire Protection and Secondary Containment
  - Ester's K-class fire behavior can enable a reduced reliance on deluge systems and smaller containment footprints where spatial constraints exist.

- The DGA Paradigm Shift and IEEE Contributions
  - Site 2's commissioning data is contributing to updates for IEEE PC57.155.
  - The new guide (IEEE C57.155-2028) introduces status-based evaluation, the Normalized Energy Index (NEI), revised rate-of-change criteria, and expanded ester-specific Duval Pentagons for accurate fault identification.

Key Documents to Watch For

- IEEE C57.93 — 2030
  Installation and maintenance of liquid-immersed transformers
- IEEE C57.140 — 2030
  Life-extension practices for liquid-filled transformers
- IEEE C57.155 — 2028
  DGA interpretation for natural and synthetic esters
- IEEE C57.166 — 2026
  Acceptance and maintenance of insulating liquids
- IEEE C57.637 — 2027
  Reclamation and reuse criteria for insulating liquids

Lessons Learned and The Road Ahead

Fleet Expansion and 500 kV Applications

- Site-specific evaluations continue, with ester adoption expanding across the fleet:
  - Ongoing: Rehabilitation/Retrofill of 69 kV units utilizing synthetic ester
  - Pending Award: Three power plants at 230 kV with synthetic ester
  - Design Phase: Three power plants at 115 kV specifying natural ester
  - Procurement Phase: One power plant at 230 kV and one power plant at 500kV specifying synthetic ester
- Recent (2022-2025) 750–765 kV transformer testing proves ester insulation coordination at extreme stresses, enabling reliable 500 kV deployment with superior fire safety and environmental benefits.

Operational Optimization and Footprint Reduction

- Ester fluids extend insulation life by pulling moisture from cellulose, enabling higher allowable operating temperatures.
- Higher thermal ratings allow smaller transformers with the same power output. This allows for reduced fluid volume, increased equipment spacing, and lower secondary-containment volumes.

Any Questions?