FROM SPECIFICATION TO INSTALLATION:
345 KV NATURAL ESTER GSU TRANSFORMERS

Jeremiah Bradshaw, P.E.
Bureau of Reclamation

ABSTRACT

The Bureau of Reclamation recently completed a major transformer replacement project at one of its facilities (Site 2), involving three banks of 345 kV, 375 MVA and one bank of 230 kV, 375 MVA transformers. The 345 kV units, filled with natural ester insulating fluid for improved fire safety, environmental protection, and longer insulation life, were the world's highest BIL-tested (1175 kV) ester-filled transformers at their time of manufacture. This paper presents the rationale for selecting ester fluid at this site and details the development and refinement of the technical specifications required to manage new transformer designs due to differing insulating fluid. It outlines lifecycle adjustments, including tailored dielectric designs, stringent manufacturing processes, and material compatibility. Furthermore, it details key insights gained during installation, overcoming logistical hurdles like long-term nitrogen preservation and impacts on ancillary systems. Finally, the paper compares factory and field test results and highlights online dissolved gas analysis (DGA) data collected during early operation. This paper demonstrates that ester fluids can be safely and reliably implemented into the high-voltage bulk electric system.

INTRODUCTION

For over a century, the global power sector has relied on petroleum-based mineral oil as the primary dielectric and heat transfer medium in liquid-filled transformers. Its low cost, widespread availability, and well-understood dielectric properties made it the undisputed industry standard. However, the inherent physical limitations of mineral oil, specifically its high flammability and poor biodegradability, have increasingly conflicted with modern safety and environmental mandates.

As custodians of public infrastructures and their proximity to waterways, Reclamation initiated a long, deliberate journey to transition our fleet to ester-based insulating fluids (both natural and synthetic) where appropriate. The culmination of this effort was the successful installation of the world's first 345 kV (1175 kV BIL), short-circuit tested, natural ester Generator Step-Up (GSU) transformers at Site 2.

The goal of this paper is to share the journey, research, and specification adjustments that drive necessary manufacturing procedures, as well as key testing parameters, and the installation lessons learned from Site 2, and to provide a roadmap for other organizations looking to make the shift to less-flammable, biodegradable insulating fluids.

THE PARADIGM SHIFT: A RESEARCH-BACKED FOUNDATION

The shift required extensive internal research, empirical testing, and pilot programs to validate the technology for high-stakes applications. When seeking an alternative to mineral oil, Reclamation evaluated the three primary high-voltage insulating mediums available to the industry: Sulfur Hexafluoride (SF_6), Natural Esters, and Synthetic Esters.

- Sulfur Hexafluoride (SF_6): SF_6 is a non-flammable gas with exceptional dielectric strength, and because it is not a liquid, it eliminates the risk of oil spills or pool-fire scenarios entirely. It remains a viable option in unique applications where traditional liquid-filled transformers pose untenable fire or spill risks, such as subterranean power plants carved into canyon walls or other locations with extremely limited spatial footprints. In these environments, the ability to avoid secondary containment systems and remove fire-protection infrastructure can be critical. However, SF_6 is also a potent greenhouse gas with stringent handling requirements, higher capital costs, and specialized maintenance needs. For these reasons, while SF_6 is acceptable in specific, high-risk or space-constrained installations, it is not considered a fleet-wide replacement for liquid-filled transformers.
- Natural ester (NE) fluids, produced from vegetable oils, provide strong dielectric performance, are fire-safe, fully biodegradable, and have high moisture absorption that benefits insulation systems. Their high fire point can reduce the need for traditional fire-protection systems, potentially lowering capital and long-term maintenance costs. Because NE fluids have lower oxidation stability, they require sealed or nitrogen-blanketed designs and warrant additional care during major maintenance activities such as bushing replacements. They also have higher viscosity and higher pour points, which can influence cold-weather startup and cooling performance, though these situations are uncommon in the

continental U.S. and manageable with proper procedures. Like all ester fluids, NE fluids have higher material cost than mineral oil but are generally less expensive than SE fluids. NE fluids offer strong environmental, moisture-saturation, and fire-protection characteristics, making them a preferred choice over mineral oil for sealed distribution and power transformers.

- Synthetic ester (SE) fluids, manufactured through controlled chemical processes, also provide strong dielectric performance, are fire-safe, biodegradable, and offer good moisture tolerance for transformer insulation systems. Their high fire point likewise reduces reliance on traditional fire-protection systems, helping minimize both initial capital cost and long-term maintenance. SE fluids have higher oxidation stability, making them suitable for both sealed and free-breathing transformers with reduced sensitivity to oxygen exposure. Their lower viscosity and lower pour points support dependable cold-weather startup and enhanced cooling performance in high-load or low-ambient conditions. Although SE fluids have a slower biodegradation rate and slightly reduced effectiveness in drying cellulose insulation when compared to NE, the differences are limited. SE fluids are the highest-cost ester option, but offer enhanced oxidation stability while maintaining environmental, moisture-tolerance, and fire-protection characteristics, making them a preferred choice over mineral oil for a broad application of distribution and power transformers.

The research, detailed extensively in Reclamation's *Alternate Insulating Fluids for Power Transformers* [1], focused on a rigorous comparison between conventional mineral oil and these fluids. By analyzing the attributes of these fluids side-by-side, Reclamation established the scientific foundation required to update our transformer specifications. While SF_6 gas-insulated transformers remain an essential tool for specific spatial constraints, ester fluids (both natural and synthetic) present the most viable, scalable alternative for most of Reclamation's transformers. Consequently, the remainder of this paper will focus exclusively on the transition to ester fluids.

Electrical Aspects: Stress Balancing, Moisture Limits, and Dielectric Concerns

Beyond basic dielectric breakdown strength, esters offer a distinct operational advantage in electrical stress distribution. The dielectric constant (permittivity) of ester fluids is much closer to that of cellulose paper than mineral oil is. This results in a highly balanced sharing of electrical stress between solid and liquid insulation. Furthermore, esters possess exceptionally high moisture saturation limits. Being highly hygroscopic, they actively draw moisture out of the cellulose paper. This continuous drying effect significantly extends the thermal life of the solid insulation, allowing the transformer to safely operate at higher continuous temperatures and result with duration of acceptable tensile strength (paper life).

Esters are not perfect, drop-in replacements. Due to their higher kinematic viscosity, their cooling dynamics are altered, requiring larger cooling ducts to prevent localized hot spots. More critically, their impulse behavior is distinct from mineral oil. Esters exhibit a tendency to produce early streamers during breakdown under highly non-uniform electrical fields; fortunately, transformers are designed to reduce or eliminate non-uniform electrical fields. This fundamentally requires design engineers to rethink the internal dielectric clearances and insulation structures for high-voltage and high-BIL units.

Fire Protection: Thermal Margin and the Enthalpy of Ignition

One of the primary reasons for the adoption of ester fluids is their classification as K-class, less-flammable, liquids. To empirically demonstrate that ester-based dielectric fluids provide a significantly higher safety margin than mineral oil, rendering them "self-extinguishing" under standard transformer conditions, Appendix A: *Thermodynamic Enthalpy and Fault Resilience Calculations* analyzes the specific enthalpy of ignition. Additionally, Reclamation performed tests to authenticate the situation on a small scale as explained in *Alternate Insulating Fluids for Power Transformers* [1]. Although these processes give excellent empirical evidence for a significant reduction in a potential transformer fire, each project within Reclamation is analyzed individually for the appropriate fire protection scheme.

By evaluating a standard 6,000-gallon system experiencing a 230 kV, 40 kA symmetric 3-phase fault, the analysis quantified the massive disparity in thermal security between the three insulating mediums.

The calculations focused on ignition enthalpy, the total amount of energy required to raise the bulk fluid from its operating temperature to its sustained combustion threshold (Fire Point). Under the modeled fault conditions, mineral oil requires only 2.47 GJ of energy to reach a state of sustained combustion. In stark contrast, natural esters require 14.28 GJ, and synthetic esters require 11.16 GJ.

When an internal arc occurs, the extreme heat will instantaneously gasify fluid in the immediate vicinity of the plasma channel, potentially causing a localized flash if the transformer tank is ruptured and oxygen enters the system. However, sustained combustion requires a larger volume of fluid to reach its fire point. Modern microprocessor relays typically clear a high-energy fault in roughly 4.5 cycles. At this clearing mark, the mineral oil is already approaching half of its required ignition energy (a low 2x safety factor).

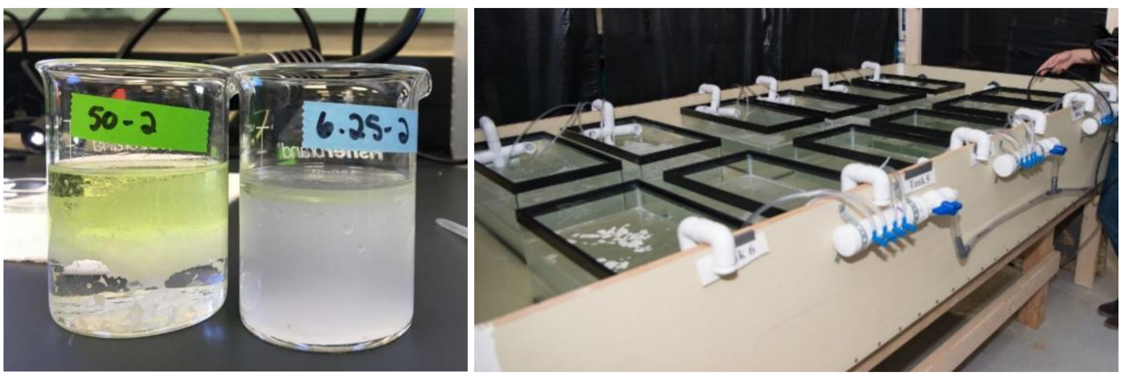
Conversely, at the 4.5-cycle clearing mark, the natural ester has absorbed less than 9% of the energy required to sustain a fire (a 12x safety factor), and the synthetic ester has absorbed less than 11% of its required energy (a nearly 9x safety factor). Once the protection system removes the energy source of an internal fault, the massive thermal inertia of the surrounding 20,000 kg of ester fluid acts as an immense heat sink. Because the bulk of ester fluid remains hundreds of degrees below its flash point, it rapidly dissipates the heat from the arc zone, immediately quenching the localized ignition and starving it of combustible vapors.

Validating this self-extinguishing property for both natural and synthetic esters fundamentally changes how organizations can approach substation and power plant design. Historically, fire protection schemes for mineral oil transformers rely heavily on external active and passive systems: surrounding water deluge networks, thick concrete firewalls, and massive rock-filled catchment basins designed to contain pool fires.

With ester fluids, the dielectric medium itself becomes the primary, passive layer of fire protection. Because both synthetic and natural esters ensure that an internal fault remains a localized electrical event rather than escalating into a catastrophic pool fire, organizations can adopt a new defense-in-depth strategy. For many installations, utilizing K-class fluids allows engineers to comply with industry guidelines while safely reducing or eliminating the need for expensive, maintenance-heavy active deluge systems, and significantly reducing the spatial footprint of required fire barriers [2] [3].

Biodegradability and Environmental Impact

Protecting the waterways downstream of the dams is mandated by 40 CFR Part 112 [4]. Reclamation conducted extensive aquatic toxicity studies comparing ester fluids against standard metrics. Utilizing protocols comparable to the Cal/EPA DTSC testing, static toxicity tests on species such as *D. pulex* and *fathead minnow* demonstrated that the LC_{50} values for ester fluids were well above regulatory standard limits. The results proved that fluids like Envirotemp FR3® (a natural ester), MIDEL eN 1204 (a natural ester), and MIDEL 7131 (a synthetic ester) did not exhibit toxic characteristics for aquatic organisms.



Comparison of Mixtures (left) and Fathead Minnow Toxicity Testing Tanks (right)
Figure 1

Furthermore, Reclamation recognized that static laboratory tests are extremely conservative compared to an actual environmental release downstream of a hydroelectric facility. Due to the high-water flow rates and turbulence typically below dams, any large-scale spill would be rapidly diluted. While there is a minor risk that insulating fluid could pool in slower-moving eddies further downstream leading to a more concentrated exposure to an organism with the eddies, the inherently non-toxic nature of the esters drastically mitigates ecological damage.

The actual breakdown of the fluid in the environment is a critical metric. Insulating fluids are designed to have strong chemical bonds to resist breakdown while in operation, yet when released into the environment, these strong bonds can be harmful if they persist. Biodegradability is typically assessed using standardized tests that measure how much of a substance is converted by microorganisms into carbon dioxide, water, and biomass. A fluid is considered readily biodegradable if it achieves at least 60% biodegradation within 28 days and meets the required test criteria, such as the 10-day window for single organic substances. Materials that biodegrade more slowly, showing more than 20% biodegradation in 28 days but not meeting the criteria for ready biodegradability, are classified as inherently biodegradable [5]. While traditional petroleum-based mineral oil is not biodegradable, both vegetable-based natural esters and acid/alcohol-based synthetic esters achieve the highest "readily biodegradable" classification.

When comparing the two ester families directly, it is important to note that the manufactured chemical bonds of acid/alcohol-based synthetic esters make them break down slightly less rapidly than agricultural-based natural esters. Most synthetic esters show a

60-90% biodegradation in 28 days depending on the molecular structure; however natural esters commonly achieve >90% biodegradation in 28 days. This trade-off in biodegradation rate is directly tied to their operational stability. The inherently organic composition of natural esters facilitates their environmental degradation, yet this same characteristic poses a primary operational challenge: limited oxidation stability. Because they are designed by nature to decompose easily, natural esters will readily oxidize and polymerize if exposed to ambient air during operation or major maintenance. To fully realize the environmental advantages of natural esters, utilities need to manage operational challenges such as using sealed tanks or closely regulated positive-pressure nitrogen blanket systems, as well as being mindful of limited exposure times during maintenance. In contrast, synthetic esters provide greater flexibility in these areas.

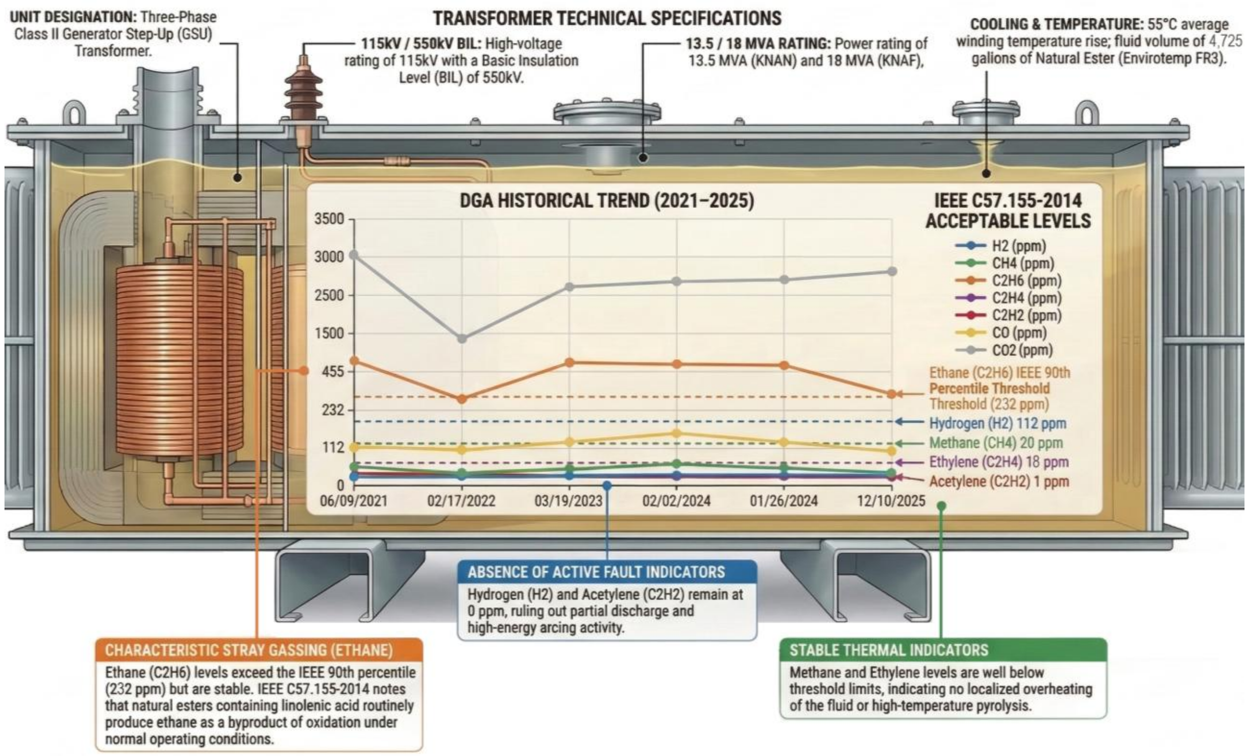
The First Installation and The Decision Tree

Reclamation's experience with ester fluid filled transformers began in 2008 with the successful commissioning of a natural ester transformer at Site 1. The operation of this unit demonstrates the successful application of natural ester fluid in a 115 kV environment, maintaining high dielectric integrity and operational stability.

Table 1
Site 1 Transformer Data

Type and Class	Three-phase, outdoor, Class II generator step-up		
Capacity	13.5 / 18 MVA (KNAN/KNAF)		
Temperature Rise and Loading Conditions	**Average Winding (°C)**	**Winding Hottest-Spot (°C)**	**Insulating Liquid (°C)**
	55	70	55
	High Side (kV)	**Low Side (kV)**	**High Side Neutral (kV)**
Voltage / Connection	115	4	66.4
Winding BIL	550	110	250
Bushing BIL	550	150	250
Tap Changer	±2.5, ±5% on High Side		
Impedance (Z, Z_0)	7.6% on 13.5 MVA base		
Extreme Site Ambient Temperatures 2008-2026	**24-hr Ave Minimum (°C)**	**24-hr Ave Maximum (°C)**	
	1.7 (2013)	32.2 (2022)	
Manufacturer	Delta Star, Inc. San Carlos Operation		

From a fluid maintenance perspective, the transformer has operated reliably with a dielectric breakdown voltage of 47 kV, remaining consistently higher than acceptable values. However, the pilot provided a learning curve regarding fluid diagnostics. The Dissolved Gas Analysis (DGA) revealed elevated levels of Ethane (C_2H_6), which would be of concern in a mineral oil unit. However, this behavior is consistent with the stray gassing phenomenon inherent to natural esters containing linolenic acid. The stability of these gas levels, coupled with a negative Total Dissolved Combustible Gas (TDCG) rate of change (-0.2 ppm/day), indicates that the transformer is not experiencing an active thermal or electrical fault, but rather a benign chemical interaction between the fluid and its environment.



Transformer Health Assessment for Site 1
Figure 2

The success of the Site 1 transformer proved the viability of the fluid in a Reclamation facility, but it also reinforced that adopting esters requires a strategic, site-specific evaluation rather than a blanket specification change.

Recognizing this, Reclamation follows a decision matrix. It was determined that each project must be independently assessed for the application of the proper insulating fluid based on several topics. An excerpt of key parameters is shown below:

- **Fleet Uniformity**: How many transformers are at the site? Is the facility replacing all of them, or will this create a mixed-fluid deck? 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?

By systematically applying this matrix to every prospective site, Reclamation is ensuring that the transition to ester fluids is executed logically, safely, and effectively across our generation fleet.

Existing Asset Applications: Retrofilling

While procuring new equipment explicitly designed for ester fluids is a long-term strategy, Reclamation manages a large fleet of power transformers with a portion greater than 40 years old. For these older assets, "retrofilling," the process of draining the mineral oil and replacing it with a K-class ester fluid, presents an appealing opportunity to capture the benefits of enhanced fire safety, environmental risk reduction, and life extension through moisture mitigation.

However, Reclamation’s stance on retrofilling is highly cautionary. Retrofilling is fundamentally not an "oil change"; it is a complex intervention that alters the transformer's entire dielectric and thermal operating system. Prior to considering a transformer as a candidate for retrofilling, an exhaustive pre-analysis must be performed.

- **Dielectric and Thermal Verification**: Because less-flammable ester liquids have a higher kinematic viscosity than mineral oil, the pressure drop through the winding cooling ducts will increase. Engineers must evaluate the existing pumps, radiator capacities, and potential increases in top-liquid and hottest-spot temperatures to determine if the unit will require load de-rating. Furthermore, because esters exhibit different early streamers and impulse breakdown characteristics in non-uniform fields, the internal clearances that were adequate for mineral oil must be verified to ensure they can withstand system overvoltages when submerged in ester. These details are typically not available to the end user, and the original manufacturer must be consulted.
- **Asset Health and Solid Insulation Condition**: Retrofilling cannot heal an existing mechanical or electrical fault; it is an investment in a healthy asset. The ultimate limiting factor for candidacy is the mechanical condition of the cellulose insulation (paper). If the paper is already severely degraded (e.g., a Degree of Polymerization (DP) <500) [6], the aggressive mechanical stresses involved in the deep-vacuum draining, flushing, and filling process required could physically destroy the brittle paper, leading to immediate dielectric failure upon energization. Many times, accurate DP values cannot be obtained, and furan analysis is the only realistic method. A historical understanding of the transformer must be obtained to confirm if the fluid has been reprocessed in the past; effectively removing any furan elements that would provide a proper evaluation.
- **Material Compatibility**: The chemical polarity of ester fluids interacts differently with legacy sealing materials. Older nitrile rubber (NBR), neoprene, or cork-based gaskets will often exhibit severe contraction, excessive swelling, or loss of tensile strength when exposed to esters. A thorough audit is required, and all accessible liquid-immersed gaskets must typically be replaced with highly compatible elastomers, such as fluorocarbon (Viton).
- **Fluid Preservation System Assessment**: Particularly when utilizing natural esters, which are highly susceptible to oxidation, the existing transformer's fluid preservation system must be evaluated. Free-breathing conservator systems without a protective bladder cannot be safely retrofilled with a natural ester unless the preservation system is fundamentally upgraded. The assessment must confirm the presence and functionality of a tightly sealed tank, a positive-pressure nitrogen blanket system, or a high-quality bladder-style conservator to prevent ambient air ingress and subsequent fluid polymerization.

To bridge this evaluation framework with real-world application, Reclamation is actively applying this assessment matrix as part of a rehabilitation project currently underway at a location referred to as Site 3.

Due to funding constraints, replacement of 60+-year old transformers was not an option. Therefore, the engineering teams utilized the feasibility framework to thoroughly analyze the existing transformers at Site 3 for synthetic ester retrofilling. By systematically verifying the dielectric clearances with the original manufacturer, assessing the thermal cooling capacities against the plant's operational demands, planning the material compatibility upgrades, and incorporating a modification to the fluid preservation systems, the assets at Site 3 were verified as viable retrofill candidates.

Existing 1960s Transformer (left) and Retrofilled/Rehabilitated Transformer (right)
Figure 3

The Site 3 project highlights one of the most critical operational hurdles of retrofilling: managing Residual Mineral Oil (RMO). The primary fire safety benefit of a retrofill relies entirely on achieving a final fluid mixture with a fire point exceeding 300°C. Because removing all residual mineral oil is very difficult and the oil impregnated into the cellulose paper will eventually leach out into the new ester fluid over time, a cautionary process must be followed. To maintain the K-class safety rating, Reclamation's execution plan at Site 3 is engineered to ensure the final RMO concentration does not exceed 3.5%. This execution phase requires highly controlled field procedures:

- **Extended Drip Times**: After the initial drain, a minimum drip time is achieved during the replacement of bushings, gaskets, and a thorough internal inspection. This allows trapped oil to migrate from the core and windings.
- **Active Flushing**: The transformer (with opened radiator valves) is filled with synthetic ester fluid and circulated for a minimum of 3 hours to physically wash away trapped mineral oil. This flush fluid will be used for each transformer and then discarded. This complexity compounds the RMO concentration after each transformer is flushed.
- **Vacuum Filling**: Hot fluid circulation and vacuum dry out is performed prior to filling. Target values for new installations are applied to the retrofill.

Table 2
Site 3 Fluid Contamination Calculations

	Starting Fluid		Flush Fluid		Final Fill		Flush Mix		
5-5-4	Mineral Oil Fluid	2300	Ester Flush Fluid (gallons)	2123.13	Ester Fluid	2286.399	Start	After	
Transformer	Mineral Oil Left in Tank	176.87	Mineral oil (gallons)	176.87	Mineral oil (gallons)	13.6013	2300	2136.731	Ester
Designation							0	163.2687	Mineral oil
			Fluid Remaining after draining (gallons)	176.87			0.00%	7.10%	Mix
			Approx Ester Fluid Remaining (gallons)	163.2687					
			Approx Mineral Oil Remaining (gallons)	13.601303					
			Percent Mineral Oil Remaining	7.69%	Percent Mineral Oil in Fluid	0.59%			
	Starting Fluid		Flush Fluid		Final Fill		Flush Mix		
5-5-1	Mineral Oil Fluid	2300	Ester Flush Fluid (gallons)	1972.4167	Ester Fluid	2274.809	Start	After	
Transformer	Mineral Oil Left in Tank	176.87	Mineral oil (gallons)	327.58333	Mineral oil (gallons)	25.19116	2136.731	1985.052	Ester
Designation							163.2687	314.9475	Mineral oil
			Fluid Remaining after draining (gallons)	176.87			7.10%	13.69%	Mix
			Approx Ester Fluid Remaining (gallons)	151.67884					
			Approx Mineral Oil Remaining (gallons)	25.191158					
			Percent Mineral Oil Remaining	14.24%	Percent Mineral Oil in Fluid	1.10%			
	Starting Fluid		Flush Fluid		Final Fill		Flush Mix		
5-5-2	Mineral Oil Fluid	2300	Ester Flush Fluid (gallons)	1832.4019	Ester Fluid	2264.042	Start	After	
Transformer	Mineral Oil Left in Tank	176.87	Mineral oil (gallons)	467.59807	Mineral oil (gallons)	35.95829	1985.052	1844.141	Ester
Designation							314.9475	455.8592	Mineral oil
			Fluid Remaining after draining (gallons)	176.87			13.69%	19.82%	Mix
			Approx Ester Fluid Remaining (gallons)	140.91171					
			Approx Mineral Oil Remaining (gallons)	35.958292					
			Percent Mineral Oil Remaining	20.33%	Percent Mineral Oil in Fluid	1.56%			
	Starting Fluid		Flush Fluid		Final Fill		Flush Mix		
5-5-3	Mineral Oil Fluid	2300	Ester Flush Fluid (gallons)	1702.3263	Ester Fluid	2254.039	Start	After	
Transformer	Mineral Oil Left in Tank	176.87	Mineral oil (gallons)	597.67367	Mineral oil (gallons)	45.96111	1844.141	1713.232	Ester
Designation							455.8592	586.7681	Mineral oil
			Fluid Remaining after draining (gallons)	176.87			19.82%	25.51%	Mix
			Approx Ester Fluid Remaining (gallons)	130.90889					
			Approx Mineral Oil Remaining (gallons)	45.961105					
			Percent Mineral Oil Remaining	25.99%	Percent Mineral Oil in Fluid	2.00%			

THE SITE 2 CATALYST

While retrofilling presents a viable life-extension strategy for existing assets, the procurement of new, large-scale generation equipment presents an entirely different set of challenges and opportunities. This was precisely the scenario Reclamation faced at Site 2.

The Stakes: Powering the West and Protecting the Environment

Site 2 is an important facility for Reclamation and the electrical power system in the west. Maintaining a reliable power system and taking advantage of environmentally conscience solutions was paramount for this project. Utilizing the decision matrix outlined in the previous sections, the choice was clear: the environmental sensitivity and the spatial constraints of the site called for the use of a K-class, fully biodegradable fluid. Natural ester was selected as the insulating medium. Reclamation started a research project in parallel with the purchase of these transformers to prepare our organization for the differences in manufacturing, installation, operations, and maintenance with respect to ester fluids. The research report was finalized during factory acceptance testing and released in 2019 [1].

Transformer Deck at Site 2 (2016)
Figure 4

The Scope of the Project
This was not a small-scale pilot program using lower-voltage distribution transformers; it was a massive infrastructure overhaul. Site 2 has a capacity of 1320 MW and produces approximately 5 billion kilowatt-hours annually. The procurement scope included:

- Three (3) banks of 345 kV, 125 MVA single-phase transformers and one (1) spare.
- One (1) bank of 230 kV, 125 MVA single-phase transformers and one (1) spare.
- Isolated phase bus circuits for each transformer bank, including taps to station service transformers (not in scope)
- Transformer ancillary systems: seismic anchorage, fire protection, and secondary fluid containment.

At the time of specification, deploying natural ester fluid in 345 kV GSUs with a 1175 kV Basic Impulse Level (BIL) was a first-of-its-kind endeavor and pushed the boundaries of what had been widely proven in the industry (230 kV was the high mark). The decision matrix clearly pointed to natural esters as the solution to environmental and fire risks, but the fundamental physics of the fluid, specifically its impulse behavior and kinematic viscosity, meant that Reclamation could not treat the change as a simple drop-in replacement within the standard mineral oil specification.

The sheer scale and voltage class of Site 2 required a complete engineering overhaul of how high-voltage GSUs are specified, designed, manufactured, and tested.

ELEVATING THE SPECIFICATIONS: DESIGNING FOR ESTER

To successfully procure a 345 kV natural ester GSU, Reclamation had to elevate its technical specifications beyond standard IEEE minimums. The initial design phase (2010–2012), industry standards barely recognized ester fluids for high-voltage applications. Because many established IEEE standards/guides and baseline values were implicitly written for mineral oil, their application required understanding and analysis to determine if a modification was needed or if entirely new requirements needed to be written into the specifications to account for the unique properties of natural ester. Because ester fluids physically and electrically interact with the transformer's active parts differently than mineral oil, the design of the core, windings, tank, and protective accessories had to be purposefully engineered around the fluid.

Dielectric Design and Fluid Impregnation

The most critical engineering adjustment involved internal dielectric clearances. Operating with 1175 kV BIL, the transformers had to be designed to handle massive impulse voltages. While natural esters excel at balancing electrical stress between the fluid and the cellulose paper (due to their closely matched permittivity), their behavior under fast-rising impulse transients in highly non-uniform fields differs from mineral oil. To prevent early streamer generation, the manufacturer had to completely redesign the winding insulation structures, increasing specific fluid gaps and modifying barrier boarding.

To ensure the integrity of this balanced dielectric system, the specification mandated that the transformers be impregnated at the factory using the operational fluid: natural ester. While factories often prefer mineral oil for its lower viscosity, reduced processing time, and ease of usage, such a practice renders the Factory Acceptance Tests (FAT) unrepresentative.

Testing a transformer impregnated with mineral oil, only to later fill it with ester, creates a dielectric 'mismatch' where the electrical stress distribution during testing does not mirror the 'as-built' reality of the field. By requiring dedicated ester impregnation, Reclamation ensures that the insulation system is fully validated under its true operational parameters, confirming that the higher dielectric constant of the ester is properly accounted for within the solid insulation from the first energization and test. Although current international standards do not require that the transformer is impregnated or tested with the same operational fluid, working groups within IEEE are addressing the impacts of this issue.

Thermal and Mechanical Testing

Because the shift to natural ester required a different internal mechanical structure and larger cooling ducts to accommodate the fluid's higher kinematic viscosity, Reclamation could not rely on historical mineral oil design tests. It was recognized that the thermal and mechanical operating profile of these units would be entirely unique.

To mitigate this risk, Reclamation's specification went beyond standard industry practices in two major areas:

- **100% Temperature Rise Testing**: IEEE standards generally allow for temperature rise (heat run) tests to be performed on only one unit of a specific design family. Given the cooling uncertainties associated with high-viscosity ester in a novel 345 kV design and the fact that transformers are produced heavily by manual processes, Reclamation mandated that *every single transformer* undergo a full temperature rise test at the factory. This policy is a standard requirement in Reclamation specifications regardless of the insulating fluid, and its importance was reinforced during the Site 2 project.
- **Short-Circuit Testing**: Because the winding geometries and internal blocking were redesigned to accommodate the ester's dielectric clearances and cooling flow, the mechanical strength of the active part was fundamentally altered. To prove the integrity of this new physical arrangement, a short-circuit test was required; a relatively rare and highly aggressive requirement for transformers of this size.

Defense-in-Depth Fire Protection and Containment

Natural ester fluid reduces the risk with respect to fire hazards and environmental contamination. However, due to the lack of firsthand experience at this voltage level, Reclamation decided to take a conservative approach to the ancillary protection systems for this project.

Reclamation adopted a "defense-in-depth" fire protection strategy. The project scope included the installation of physical fire walls between the transformers and a comprehensive upgrade of the plant's active fire protection system to include linear heat detectors and full deluge suppression. Fluid containment systems received the same approach with capacity to accommodate the transformer fluid and a discharge of deluge for 10 minutes.

To reduce the possibility of a catastrophic tank explosion that could breach the containment, Reclamation specified a flexible tank design equipped with standard pressure relief devices paired with an active fast-depressurization system.

Transformer Fire Protection and Secondary Fluid Containment Systems
Figure 5

To reduce the probability of fire suppression and possible containment breach, the fire detection system used two method linear heat detectors applied to the top of the transformer tank and removed the differential protection signal as an initiating input for fire suppression. Due to the size of the differential zone at this site, eliminating this as a trigger for suppression, removed non-fire event signals from initiating nuisance deluge releases.

Modernizing Components and Real-Time Monitoring
The goal was to drastically reduce any fire risk on the transformer deck, and that included identifying other sources of mineral oil. While the main tanks were filled with natural ester, traditional high-voltage bushings are often filled with mineral oil. To stay consistent with the "less-flammable" convention, the specification strictly mandated non-oil, non-porcelain bushings. By utilizing dry-type, resin-impregnated paper (RIP) bushings with polymer housings, Reclamation eliminated the last remaining flammable liquid from the asset and removed the risk of porcelain shrapnel during a failure.

Finally, because these units acted as the first large-scale implementation of natural esters at this voltage class, Reclamation required granular operational data. The specification mandated the installation of fiber optic temperature sensors directly embedded throughout the transformer windings to provide absolute, real-time hottest-spot monitoring. Reclamation also specified the integration of online Dissolved Gas Monitors (DGMs) to continuously record dissolved gases during operations, allowing a baseline to actively be built for the understanding of ester gassing behavior under load.

The Evolution of Material Compatibility
Site 2 served as a massive learning opportunity for Reclamation. Today, specifications for ester-filled transformers look distinctly different than they did five years ago, largely due to lessons learned regarding material compatibility.

Early in the transition to alternate fluids, it was assumed that most standard transformer materials were broadly compatible with esters. However, the chemical polarity of natural and synthetic esters interacts aggressively with certain legacy sealing materials.

Through experience, Reclamation learned that standard nitrile rubber (NBR) and standalone neoprene gaskets can exhibit unpredictable swelling, loss of tensile strength, and eventual leaking when exposed to high-temperature esters over time.

Today, specification explicitly restricts these materials for ester applications. All accessible liquid-immersed gaskets and sealing rings must be specified as high-grade fluorocarbon elastomers (e.g., Viton), ensuring long-term mechanical integrity and leak-free operation.

DESIGN, MANUFACTURING, AND FAT: PROVING THE BUILD

Transforming these specifications into a physical, functioning 345 kV transformer required a deeply integrated approach. For Site 2, Reclamation partnered with Yellowstone Electric as the prime contractor and Siemens Energy, utilizing their specialized manufacturing facility in Linz, Austria.

Because Reclamation was pushing the boundaries of natural ester applications at this voltage class, the traditional "over-the-wall" engineering model, where a customer hands off a specification and waits for a finished product, was fundamentally inadequate. The design phase required constant, iterative collaboration directly between the contractor, the manufacturer's dielectric experts, and Reclamation's engineering team to ensure the nuances of the natural ester were accounted for in every aspect of the build.

Iterative Design Reviews

The clarity of the design review process was paramount. The mechanical and electrical characteristics of the 345 kV / 1175 kV BIL design had to be meticulously scrutinized.

To address the thermal realities of the ester's higher kinematic viscosity, the Siemens engineering team had to modify the internal cooling channels within the windings to prevent localized hot spots, which subsequently altered the mechanical footprint of the active part. Concurrently, to address the fluid's impulse behavior in non-uniform fields, internal dielectric distances and barrier boarding were extended. Every structural change triggered a cascading series of engineering checks, requiring exceptional attention to detail from all parties to ensure the final design met both thermal and dielectric constraints without compromising the physical limits of the transformer tank.

Prototype Testing

Because the internal geometry of the active part had been modified to accommodate the ester fluid, the project team could not assume the mechanical blocking would perform identically to a legacy mineral oil unit under fault conditions. Therefore, Reclamation mandated a strict "prototype" approach to manufacturing.

Before the remaining units in the fleet could be fully manufactured, the first transformer was required to pass a multi-stage proving process:

- **Initial FAT:** The fully assembled, ester-impregnated unit underwent a comprehensive suite of baseline dielectric and thermal tests.
- **Short-Circuit Testing:** The unit was then subjected to a full short-circuit test, a violent and rare procedure that actively attempts to tear the internal windings apart using massive fault currents. This verified that the widened cooling channels and altered geometry could withstand grid-level mechanical stress.
- **Tear-Down and Inspection:** Following the short-circuit test, the active part was pulled from the tank and inspected for any signs of mechanical deformation, paper tearing, or blocking displacement.
- **Final FAT:** After reassembly, the unit underwent a final, complete FAT to ensure no hidden dielectric damage had occurred during the short-circuit event.

Only after the successful, unbroken completion of this sequence was the Siemens facility authorized to proceed with the manufacturing of the remaining units. The prototype transformer was planned for use as the spare 345kV transformer at the facility.

Prototype Transformer in Short-Circuit Test Configuration
Figure 6

The Necessity of On-Site FAT Witnessing

A central tenet of Reclamation's quality assurance program, one reinforced during the Site 2 project, is the necessity of having a dedicated technical specialist physically present at the factory for every FAT. Since the 2020 pandemic, the industry has seen an accelerating trend in which end users sacrifice this physical oversight in favor of 'virtual witnessing' via webcams and shared data streams. While this pivot toward convenience may be acceptable for standardized, highly repeatable distribution equipment, it represents a dangerous sacrifice for custom-engineered power transformers.

The Site 2 FAT execution with Siemens Energy was highly collaborative and transparent, underscoring their strength as a premier manufacturer. However, engineering a first-of-its-kind 345 kV natural ester transformer inherently pushes the boundaries of standard manufacturing and testing. During the testing phases, the project team naturally encountered nuanced electrical anomalies and edge cases specific to the novel interaction between the high-voltage design and the ester fluid. The physical presence of Reclamation's technical expert allowed for immediate, real-time problem-solving alongside Yellowstone and Siemens' engineering teams. When test results differed from expectations, test setups required adjustments, or results fell into the "gray areas" of standard test codes, having an expert on the factory floor proved imperative. It allowed the combined team to mutually evaluate the data and validate the asset's integrity without settling for a mere "check-box" pass.

This experience solidified the philosophy: an on-site expert is the only defense against the inherent ambiguity of standard test codes. The IEEE C57.12.90 standard test code provides a flexible framework that allows for significant variance in how a test is executed. Without a technical expert on-site, clauses allowing for "mutual determination" often default to whatever the factory's existing setup allows.

Furthermore, the unique physical properties of ester fluids demand strict adherence to extended testing rhythms, which can clash with standard factory pacing. In standard industry practices, factories may attempt to begin dielectric tests just hours after the final fluid fill to save time. An on-site expert actively intervenes to enforce the mandatory resting period required for the highly viscous ester fluid to fully impregnate the cellulose and for micro-bubbles to dissipate, thereby preventing "false fails" or "false passes" that mask latent discharge events.

During highly sensitive evaluations, such as Induced Potential Test (partial discharge measurement), an off-site engineer viewing a compressed screen-share lacks vital situational awareness. If PD levels hover near the acceptable limit, it can easily be dismissed by factory personnel as ambient noise from an overhead crane. An on-site expert has the authority to demand equipment shutdowns for background noise checks, request changes in test bushing grounding, or utilize acoustic sensors to prove whether the noise is actually due to an incipient fault or outside. Similarly, during lightning impulse testing, an expert ensures the test circuit is not over-filtered simply to produce a visually clean waveform on a monitor, but is sharp enough to stress the transformer's turn-to-turn insulation as designed.

Ultimately, the physical presence of an expert ensures that the test setup is robust, variances are justified, and the manufactured asset perfectly matches the high-voltage design required for the field.

Transportation: Preventing Oxidation

Once the FAT was successfully completed, coordinating the logistics of transporting the units from Linz, Austria, to Site 2 was the final manufacturing hurdle.

Because of highway and maritime weight restrictions, the transformers could not be shipped filled with fluid. While mineral oil units are often shipped partially filled or under dry air, the severe oxidation risk associated with natural esters dictated a different approach. The ester fluid was drained at the factory, leaving the highly hygroscopic, ester-impregnated cellulose paper exposed within the tank.

To protect both the paper and the residual ester from ambient moisture and oxygen during the months-long transit, the tanks were sealed and pressurized with a dry nitrogen gas system. This active preservation system, coupled with impact recorders to monitor mechanical shocks during the oceanic and overland journey, ensured the internal integrity of the transformers remained uncompromised upon arrival at the staging yard above the dam.

INSTALLATION CHALLENGES: RUBBER MEETS THE ROAD

The physical installation of the units on the Site 2 transformer deck presented a unique crucible of logistical, environmental, and technical challenges. Transforming a successfully factory-tested asset into a fully commissioned, field-ready unit is often where the most critical errors occur, particularly when introducing a high-viscosity ester fluid into a legacy hydro facility.

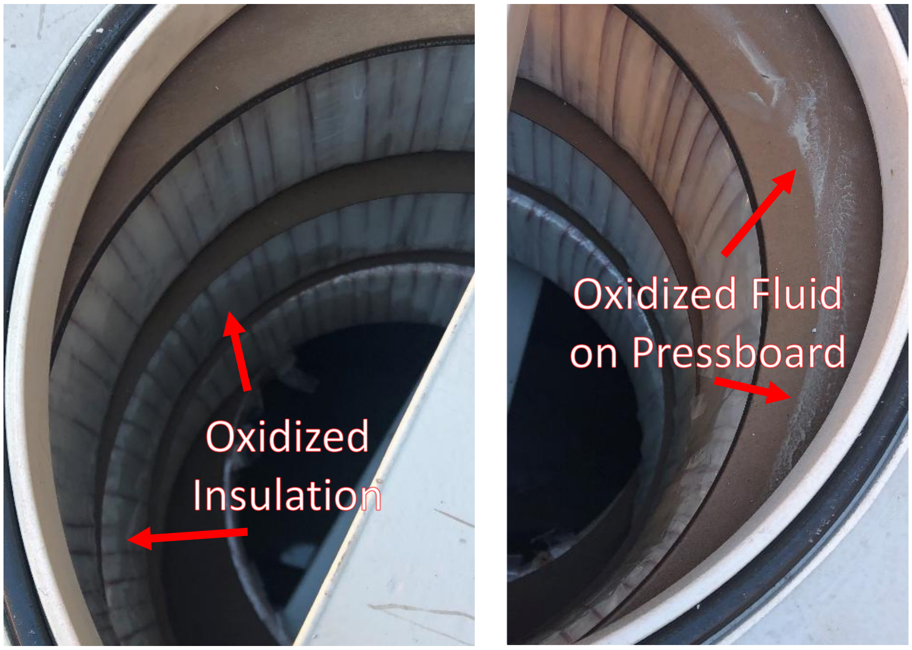
The Limits of Gas Storage

The transformers successfully completed their transit from Austria and arrived at the Site 2 staging yard sealed and pressurized under dry nitrogen. The first bank of transformers was moved to the transformer deck, assembled, filled, and tested in preparation for their installation (March 2020). However, the project schedule was immediately derailed by the onset of the global COVID-19 pandemic. Site access was strictly curtailed, and installation activities were suspended, leaving the remaining units sitting idle in the staging yard for an extended duration.

This delay transformed a standard logistical step into a high-stakes preservation mission. Power transformers are not designed to be stored under gas indefinitely. Over extended periods, the cellulose insulation will eventually lose its factory fluid impregnation, a physical reality that applies whether the unit was impregnated with traditional mineral oil or an ester fluid. As the liquid slowly drains from the paper capillaries, the dielectric integrity of the active part is compromised. According to the manufacturer's operation and maintenance manual, the transformers should not be safely stored under gas for more than 12 months.

Complicating this engineering deadline was the site specifics and chemistry of the natural ester. Because natural esters are highly susceptible to oxidation, any ambient air ingress into the tank during this standby period would cause the residual ester fluid to rapidly polymerize. This polymerization would ruin the cellulose insulation and effectively destroy the asset before it was ever energized. Due to site access constraints, the transformer could only be transported to the deck when in the shipping configuration (no bushings). Therefore the transformers remained in the staging area, under gas, at the top of the canyon until an outage was scheduled for installation. With hydroelectric facilities, operations and outages are typically restricted to water flow seasons. For Site 2, the outage window allowed only one bank of transformers to be installed per year; each bank of transformers required successful operation prior to the next outage.

The sheer vulnerability of the natural ester to ambient air was demonstrated early in the project during the arrival of the first set of transformers. Due to physical shipping constraints, the high-voltage turrets were removed after the factory acceptance tests and shipped to the site separately. Unlike the main tanks, these separate turret enclosures were not shipped or stored under a positive nitrogen purge. The ambient air ingress reacted with the residual natural ester fluid left on the internal bushing current transformers. The ester polymerized, creating a thick, oxidized layer over the coils as shown in Figure 7.



Current Transformer at Different Angles with Oxidized Insulating Fluid
Figure 7

This localized polymerization could not be safely cleaned or flushed away, the oxidized CTs had to be completely removed and replaced in the field prior to the final assembly. Fortunately, because this issue was encountered on the first delivery, the lesson learned was immediately applied to the remaining units. Shipping and storage procedures for the turrets were amended to prevent any further ambient air exposure, ensuring the issue was not repeated on subsequent deliveries.

This incident served as a potent, real-world validation of exactly why the nitrogen preservation mandates for the main active parts were critical. While the earliest units delivered to the site were filled within the manufacturer's allowable window, the onset of the pandemic pushed the later phases of the project drastically past the 12-month expiration threshold for sitting under gas. Table 3 illustrates the varying durations the fleet spent under a nitrogen blanket, highlighting the extreme delays experienced by the later units.

Table 3
Transformer Nitrogen Storage Durations

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

Because these later units were pushed far past the 12-month limit, immediate, out-of-sequence corrective action was taken during the pandemic to save them. Emergency field operations were executed to fill the main tanks with fluid at the staging yard prior to their final installation on the deck, simply to ensure the active parts were resubmerged. Furthermore, because the insulation had been exposed to dry gas for such an extended period, the manufacturer mandated that the standard vacuum processing time prior to filling be doubled to a 96-hour minimum. This process ensured that the heavily drained paper could be safely re-impregnated with ester fluid without trapping micro-bubbles. Once fluid processing was complete, field testing of the transformers was performed to validate the integrity of the insulation system with no issues discovered.

Field Filling: Vacuum and Hot Fluid Dryout

The extended duration the transformers spent under the dry nitrogen blanket required a significant dry-out process prior to fluid filling. Most of the transformers went through two fluid filling processes: one at the staging area and one at the final location on the transformer deck. Natural ester fluid possesses a higher moisture saturation limit than mineral oil, which provides a wider margin for residual moisture. Despite this margin, the transformers were dried out as much as possible before fluid filling. The field team executed a hot-fluid vacuum filling process following IEEE guidelines. The following represents an average of results:

- **Deep Tank Vacuum:** The processing target was to pull the vacuum below 0.750 Torr before initiating holding stages. Across all units, the deepest vacuum levels achieved averaged between 0.125 and 0.150 Torr, with some units reaching as low as 0.038 Torr. These deep vacuums were typically held for extended durations (48 to 96 hours) to evacuate moisture accumulated during transit and staging.
- **Heated Fluid Injection:** The rig's outlet oil temperature was consistent across the fleet, maintained between 60°C and 70°C, yielding an average heating fluid temperature of roughly 65.5°C.
- **Vacuum Filling:** The hot ester was slowly introduced into the tank under full vacuum. The combination of heat and negative pressure forced the ester into the microscopic capillaries of the cellulose. The total average processing time, from starting the vacuum rig to concluding hot oil circulation, lasted approximately 3 to 4 days per transformer.
- **Extended Stand Time:** An extended stand time (above 60 hours) was held prior to any electrical testing. This critical waiting period allows any remaining micro-bubbles, which rise much slower in ester than in mineral oil, to fully absorb into the fluid or escape to the surface.

Field Testing and Baseline Values

When performing standard field testing on ester-filled power transformers to establish a baseline, expect several key differences compared to mineral oil. While standard IEEE C57 tests follow identical procedures for transformers with any fluid type, the unique chemical properties of natural esters require adjusted baselines and acceptance limits.

- **Dielectric Dissipation Factor (Power Factor)** The dielectric dissipation factor, or power factor, is significantly higher in transformers using natural ester fluids due to their polar molecular structure. At 25°C, dissipation factors range from

0.2% to 0.5%, rising to 3%–8% at 100°C. In contrast, mineral oil typically exhibits values near 0.05% at 25°C and 0.3%–0.5% at 100°C. After temperature correction to 20°C, ester units generally show a baseline power factor approximately 0.1% to 0.3% above equivalent mineral oil counterparts. Although this distinction should be known, the project team was able to achieve exceptionally low dissipation factor results when testing the transformers.

Table 4
Dissipation Factor Results - Transformer

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.

- **Moisture Absorption** Natural esters are hydrophilic and can hold approximately 1,100 ppm of water at 20°C, compared to about 55 ppm in mineral oil. This property means ester-filled transformers naturally contain higher absolute moisture levels without experiencing dielectric degradation. Moisture and dissipation results must be interpreted within this specific saturation context rather than evaluated against legacy mineral oil limits.
- **Breakdown Voltage** Natural ester fluids exhibit AC breakdown voltages that are equivalent to or higher than mineral oil in uniform fields. However, their impulse breakdown behavior in highly non-uniform fields is distinct, which drove the initial design adjustments for the 1175 kV BIL rating. During field testing, a key metric for fluid acceptance is the AC dielectric breakdown voltage. Field samples processed at the Site 2 staging area consistently tested well above the 60 kV minimum threshold required by IEEE C57.147 for new natural ester fluid in equipment class 345 kV, confirming the dielectric integrity of the field-processed fluid.

Table 5
Fluid Measurement Results Post Fill

	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.

In summary, when establishing field-test baselines on ester-filled transformers, engineers must be acceptant of elevated dissipation factor values and higher absolute moisture levels while comparing these to acceptable dielectric breakdown results. Adjusting diagnostic thresholds to accommodate this ester behavior is necessary to avoid interpreting normal operating characteristics as faults.

Modernizing 1960s Plant Wiring

Over a 60-year operational life, a hydroelectric facility undergoes countless incremental electrical circuit modifications. During the transformer replacement project, Reclamation took the opportunity to fully update existing drawings and correct any inaccuracies found. Integrating new transformer technology, such as fiber optic hottest-spot monitors, online Dissolved Gas Monitors (DGMs), and active fast-depressurization systems, demanded wiring accuracy.

During the installation and commissioning of these transformers, the project team executed a complete overhaul of the interface control cabinets. Rather than patching compromised circuits or working around undocumented modifications, the existing panels were completely gutted. All legacy wiring, terminal blocks, and relays were removed. The panels were subsequently rebuilt utilizing new wiring, modern terminal interfaces, and updated control components based entirely on verified point-to-point field data. This comprehensive replacement eliminated any unforeseen issues with integrating a new system into a legacy system, ensuring the natural ester GSUs and their advanced monitoring systems were integrated into a clean, fully documented control interface.

COMMISSIONING AND EARLY OPERATIONS

Energization of the 345 kV and 230 kV banks proceeded sequentially following the resolution of legacy control circuits and baseline electrical testing. Upon energization, diagnostic monitoring transitioned to continuous Dissolved Gas Analysis (DGA). Evaluating ester fluid DGA requires distinct standards, replacing the IEEE C57.104 mineral oil guidelines with IEEE C57.155.

Establishing The Baseline Rate-of-Change

To monitor the operational health of the new natural ester fleet, Reclamation integrated continuous online Dissolved Gas Monitors (DGMs). Because concentrations in some gases in ester fluids naturally differ from mineral oil norms, diagnostic evaluation relies on rate-of-change monitoring rather than absolute concentration thresholds. Initial DGA samples pulled from the Site 2 units established the fluid-specific operational baselines, which then allowed alarm points to be set. Online DGM sampling was performed on a 4-hour basis for the first year of operation with manual samples taken as shown in Table 6. During the initial operational period, these monitors generated massive datasets, logging over 35,000 data points for each specific gas. Despite this wealth of automated data, physical laboratory samples were required to validate the online DGM readings. Executing the manual samples ensured accuracy during the critical baseline establishment phase and provided a full-spectrum fluid analysis that field sensors cannot independently replicate. After the baseline phase, 1-year, the transformer manual sampling returned to a once per year per Reclamation's Facility Instructions Standards and Techniques (FIST) 3-30 [7].

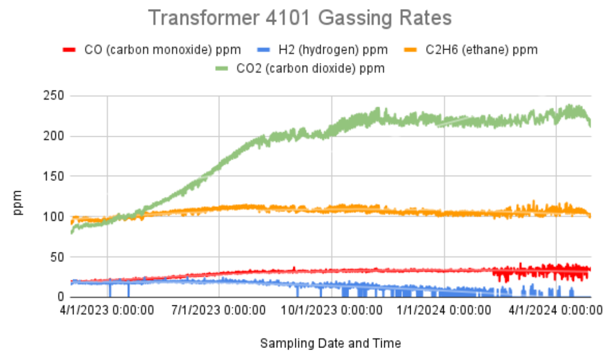
Table 6
Schedule of Manual Sampling During 1st Year Operations

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

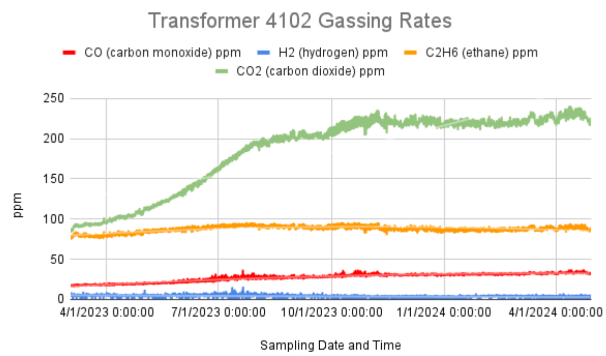
While high-frequency data collection provides granular visibility into the transformer's operational health, it introduces a significant operational challenge. Deploying advanced monitoring infrastructure is only effective if the organization possesses the dedicated resources and fluid-specific knowledge required to interpret the results. Without onsite personnel taking true ownership of the monitoring assets, data can become unreliable or lost to exhausted consumables. Furthermore, the organization must possess the proper chemical context of the insulating fluid; without it, massive data volumes can quickly lead to alarm fatigue and the misdiagnosis of benign chemical reactions as active faults.

Although networking data points to receive autonomous triggers is the 'operational dream,' the reality is that facilities often operate on minimal resources and hurdle through restrictive policies that hinder operational necessities. Even with these hurdles, online monitoring is modeled as the solution to transformers seen as 'black boxes' to most. However, while organizations may model the dream, it is the crews that deliver reality. The true 'online monitor' isn't just a sensor; it is the dedicated professionals who refuse to let the mission get lost in the noise.

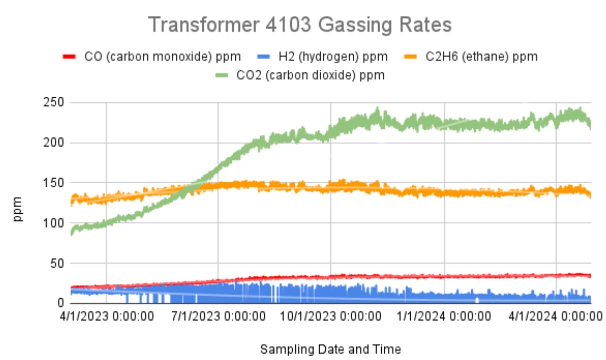
Upon energization and the introduction of initial operational load, the natural ester fluid within the Site 2 GSUs predictably began generating combustible gases. Continuous monitoring through the DGMs revealed a clear progression: an early period of rapid gas accumulation during the first weeks of thermal stress, followed by a gradual slowing in generation. These trends are illustrated in the figures below.



Gassing Rates for Transformer 4101
Figure 8



Gassing Rates for Transformer 4102
Figure 9



Gassing Rates for Transformer 4103
Figure 10

As operating conditions stabilized, the gas production rates eventually leveled off, indicating that the fluid had reached chemical equilibrium and establishing a steady, safe operational baseline. One of the transformer bank's stabilized gas concentrations, which now serve as the diagnostic reference values for ongoing monitoring, are summarized in the table that follows. For clarity, only the first year of data is shown.

Table 7
Stabilization Values for Dissolved Gasses

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.

The Stray Gassing Phenomenon

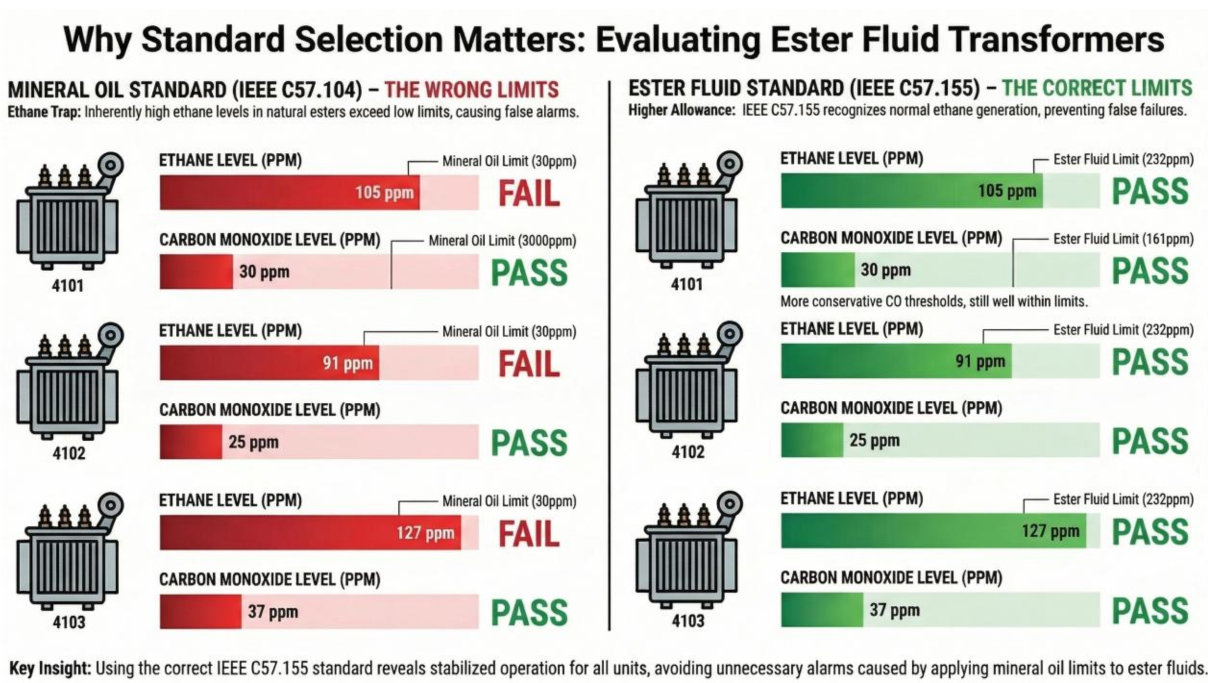
Comparing these stabilized values against industry standards demonstrates the stark difference in gassing tendencies between mineral oil and natural ester fluids.

If these units were filled with mineral oil, applying IEEE C57.104 would flag an ethane concentration exceeding 30 ppm as a Condition 3 state. A mineral oil transformer exhibiting these values would immediately trigger critical operational alarms, indicating a severe low-temperature thermal fault (T1/T2) or partial discharge, mandating immediate offline testing, load reduction, or complete removal from service.

However, natural esters require distinct evaluation standards, replacing IEEE C57.104 guidelines with IEEE C57.155. The chemical composition of natural ester fluid includes linolenic and linoleic fatty acids. Under normal operating temperatures (70°C to 90°C) and standard electrical stress, the fluid undergoes mild oxidation and thermal decomposition. This process naturally generates volumes of ethane (C_2H_6) and hydrogen (H_2) as benign byproducts, a characteristic defined as "stray gassing."

When analyzed under the correct IEEE C57.155 guide for natural ester fluids, these exact values represent normal, benign operation. Because gas concentrations in ester fluids naturally differ from mineral oil norms, diagnostic evaluation must rely on rate-of-change monitoring rather than absolute concentration thresholds. Because the 35,000+ data points pulled from the DGMs confirmed that the rate of gas generation had plateaued and stabilized, the transformer bank was verified as healthy.

This comparison underscores a critical mandate for modern utilities: online monitoring data must be paired with accurate, fluid-specific analytical parameters to prevent costly, false-positive fault investigations.



Evaluation Comparison Gas Evaluations Using IEEE Guides
Figure 11

Application of Fault Detection Techniques

The thermodynamic decomposition properties of natural esters require analytical adjustments for fault identification. Standard diagnostic frameworks, such as Duval Triangle 1, are calibrated exclusively for mineral oil. Plotting ester DGA results on Triangle 1 yields false fault interpretations due to differing gas generation proportions under identical fault temperatures.

Diagnostic monitoring for the Site 2 fleet utilizes Duval Triangles 3, 3b, and 6, alongside Duval Pentagons 3, 4, and 4b, as specified in IEEE C57.155. These adapted models incorporate modified relative percentage boundaries for key hydrocarbon gases. This ensures normal ester stray gassing is correctly filtered and actual thermal or electrical faults are accurately categorized. Diagnostic software must be explicitly configured for ester fluids to apply these correct geometrical boundaries.

LESSONS LEARNED AND THE ROAD AHEAD

The successful design, installation, and commissioning of the 345 kV and 230 kV natural ester GSUs at Site 2 provided critical operational data that is actively shaping Reclamation's future power transformer specifications and contributing to industry-wide standard revisions. This field-proven success has effectively bridged the gap between theoretical research and practical, grid-scale implementation.

Key Project Lessons

The Site 2 project served as a comprehensive testing ground for scaling natural ester technology to the 345 kV class. The most critical lessons learned span the entire asset lifecycle:

- **Specification and Material Compatibility:** Ester fluids are not drop-in replacements for mineral oil. Specifications must mandate ester-compatible elastomers (e.g., Viton), adjusted cooling ducts to accommodate higher kinematic viscosity, and specific dielectric clearances designed for non-uniform impulse fields.
- **FAT Execution and Oversight:** Standard IEEE test codes are highly flexible, which presents a liability for novel ester applications. Having a technical expert on-site during Factory Acceptance Testing is mandatory to enforce extended fluid impregnation times and to accurately interpret edge cases in temperature rise tests, partial discharge measurements, and lightning impulse testing.
- **Environmental Vulnerability and Field Processing:** Natural ester's vulnerability to oxidation mandates strict adherence to positive-pressure nitrogen blanketing during transit and storage.

Fire Protection and Secondary Containment

The transition to a K-class fluid necessitated a new fire protection analysis to determine the appropriate facility support systems. While the Site 2 project utilized a conservative defense-in-depth strategy integrating the less-flammable ester fluid with fire walls and deluge systems, independent validation in the fluid's self-extinguishing properties through large scale testing could alter future infrastructure requirements. Future specifications can leverage this thermal resilience to safely reduce the reliance on active fire suppression systems when spatial separation cannot be met. Moreover, minimizing deluge system requirements directly decreases the requisite capacity and footprint of secondary containment systems, providing substantial capital and spatial efficiencies at existing facilities.

The DGA Paradigm Shift and IEEE Contributions

The operational deployment highlighted the strict necessity of applying ester-specific design parameters and fluid diagnostics. The continuous online monitoring data collected during commissioning, specifically the precise tracking of the 8-to-9-month stabilization phase, generated a robust, real-world dataset. These data points have been shared directly with the working groups developing the upcoming IEEE PC57.155 revision.

The transition from IEEE C57.155-2014 marks a pivotal advancement in the technical oversight of ester-immersed transformers, harmonizing ester interpretative logic with the statistical rigor introduced in the mineral oil gassing guide (IEEE C57.104-2019). Key structural changes to the guide include:

- **Status-Based Evaluation**: The guide adopts the "DGA Status 1-3" system introduced in IEEE C57.104-2019, evaluating normalcy based on fluid-specific 90th and 95th percentile statistical thresholds rather than arbitrary fixed limits, categorizing units from acceptable (Status 1) to significant gas production (Status 3).
- **Introduction of the Normalized Energy Index (NEI)**: To accurately manage ester breakdown complexities, the draft implements the NEI metric. Rather than using the legacy Total Dissolved Combustible Gas (TDCG) sum, NEI serves as a weighted average based on the thermodynamic bond energy of generated hydrocarbon gases (Methane, Ethane, Ethylene, Acetylene). NEI rate-of-change provides a superior indicator of true abnormal behavior.

- **Targeted Rate-of-Change Analysis**: In a major departure from mineral oil standards, the draft restricts rate-of-increase evaluations strictly to Hydrogen (H_2) and the Normalized Energy Index (NEI). Applying generation rate thresholds to individual gases like ethane or carbon monoxide produced unacceptable false-positive rates, erroneously classifying roughly 54% of normal ester transformers as failing. The draft now emphasizes multi-point dynamic gas growth to average out analytical variance.
- **Expanded Duval Pentagons**: Fault identification now explicitly utilizes advanced geometric analysis. The draft heavily integrates the Duval Pentagon method, including customized versions (Pentagons 3, 4, and 4b) calibrated specifically for the distinct breakdown profiles of soybean, rapeseed, sunflower, and synthetic ester fluids, ensuring normal stray gassing is not miscategorized.

International guidelines and standards are in an evolutionary phase where implementation of new insulating fluids is growing. Key documents to watch are:

- IEEE C57.93 Guide for Installation and Maintenance of Liquid-Immersed Power Transformers (2030 release target)
- IEEE C57.140 Guide for Life Extension of Liquid Type Power Transformers and Reactors (2030 release target)
- IEEE C57.155 Guide for Interpretation of Gases Generated in Natural Ester and Synthetic Ester-Immersed Transformers (2028 release target)
- IEEE C57.166 Guide for Acceptance and Maintenance of Insulating Liquids in Transformers and Related Equipment (2026 release target)
- IEEE C57.637 Guide for Reclamation of Insulating Liquids and Criteria for Its Use (2027 release target)

Fleet Expansion and 500 kV Applications

Reclamation continues to evaluate each location independently to determine the most appropriate insulating fluid, ensuring selection is based on site-specific environmental, spatial, and operational constraints. Success at Site 2 has catalyzed further adoption of ester fluids across the generation fleet. Current and future deployments include:

- Ongoing rehabilitation project utilizing synthetic ester fluid in 1960s vintage 69kV class transformers.
- Three power plants pending contract awards for 230kV transformer replacements utilizing synthetic ester fluid.
- Three separate projects (115kV) currently in the design phase specifying natural ester fluid.
- Two projects nearing procurement with synthetic ester fluid at the 230kV and 500kV levels.

Specifying ester-filled 500 kV transformers for upcoming projects is a strategic move that aligns with recent breakthroughs in ultra-high voltage (UHV) testing and Reclamation's mission to manage and protect water and related resources in an environmentally and economically sound manner. While mineral oil was traditionally the only option at this voltage, the successful type-testing of 750 kV and 765 kV prototypes between 2022 and 2025 has effectively opened possibilities at the 500 kV level. These tests prove that specialized insulation coordination and the management of non-uniform electrical fields, the primary hurdles for esters at high voltages, have been solved by modern engineering. By moving to 500 kV, Reclamation leverages a technology that has already been proven at even higher stress levels, ensuring that the grid remains resilient while benefiting from the superior fire safety and environmental biodegradability that ester fluids provide.

Operational Optimization and Footprint Reduction

Because ester fluids actively draw moisture out of solid cellulose insulation, they significantly protect and extend the thermal life of the paper. This characteristic presents significant opportunities for future operational optimization. Future transformer procurements could specify higher continuous operating temperatures, allowing facilities to maintain power output while also decreasing the physical size of the transformer. Maximizing the MVA output within a smaller physical footprint inherently increases the spatial distances between assets and reduces the overall volume of insulating fluid, effectively reducing secondary containment capacity, optimizing both facility design and environmental safety.

CONCLUSIONS

The successful design, installation, and energization of the 345 kV and 230 kV natural ester GSU transformers at Site 2 represents a landmark achievement in the hydroelectric and bulk power sectors. The project validates that K-class, fully biodegradable fluids can be safely scaled to high-voltage, high-capacity generation assets. By making this transition, Reclamation has drastically reduced the catastrophic fire and environmental liabilities inherent to legacy mineral oil, proving increased security at one of the nation's most critical waterways.

However, the primary takeaway from this project is that ester fluids are not direct "drop-in" replacements. Transitioning a utility fleet requires a fundamental rewrite of standard engineering expectations. To successfully navigate this shift, utilities must adapt their specifications across the entire asset lifecycle. Based on the empirical research and operational realities of Site 2, the following critical checklist items could be used by organizations issuing a new ester-filled transformer specification:

- **Tailored Dielectric and Thermal Design:** Specifications must mandate internal clearance adjustments to account for ester's distinct early-streamer behavior in non-uniform impulse fields. Furthermore, internal cooling ducts must be adjusted to accommodate the fluid's higher kinematic viscosity and maintain required thermal performance.
- **Ester-Specific Material Compatibility:** Legacy materials cannot be trusted by default. Specifications must explicitly restrict incompatible elastomers (such as standard NBR or neoprene) and require high-grade fluorocarbon seals (e.g., Viton) for all liquid-immersed gaskets to prevent long-term degradation and leakage.
- **Dedicated FAT Oversight:** Standard IEEE test codes offer flexibility that presents a liability for novel ester applications. Utilities should require a physical, on-site engineering presence during factory acceptance testing to enforce fluid-specific impregnation stand times and to accurately evaluate edge cases in testing such as partial discharge, lightning impulse, and temperature rise testing.
- **Field Preservation and Processing:** Natural ester's vulnerability to oxidation requires adherence to positive-pressure nitrogen blanketing during transit and storage. During installation, field crews should execute hot-fluid filling (60°C–80°C) under deep vacuum, followed by extended stand times (48–72 hours) to overcome viscosity and ensure void-free cellulose impregnation.
- **Calibrated Diagnostic Baselines:** Applying legacy IEEE C57.104 mineral oil thresholds to ester fluids will trigger false-positive failure alerts. Organizations must establish new baselines that accept naturally higher Power Factor values and moisture limits. Furthermore, DGA monitoring must transition strictly to rate-of-change analysis utilizing IEEE PC57.155 (NEI tracking and ester-specific Duval Pentagons) to properly contextualize normal stray gassing.

By adopting these engineering parameters, utilities can begin developing their own directives for implementation of natural and synthetic ester transformers. By doing this the industry can move towards achieving a highly resilient, fire-safe, and environmentally friendly power grid.

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BIOGRAPHY

Jeremiah Bradshaw, P.E. is a licensed professional engineer in the state of Colorado with over 21 years of experience in electrical engineering. He serves as a subject matter expert in power transformers at the Bureau of Reclamation, where he leads a team of engineers specializing in high-voltage systems and transformer technologies. Jeremiah holds a Master of Science in Electrical Engineering and a dual undergraduate degree in mathematics and physics. He is an active member of the IEEE Transformer Committee, where he contributes to multiple subcommittees and working groups focused on advancing transformer standards and practices.

APPENDIX

APPENDIX A

Thermodynamic Enthalpy and Fault Resilience Calculations

A.1 Objective: To quantify the energy required to reach the sustained ignition point (Fire Point) for each insulating fluid and to evaluate the safety margin provided by these fluids during a 230 kV fault relative to modern microprocessor relay clearing times.

A.2 Methodology and Technical Assumptions: All calculations are based on the following engineering parameters and industry standards:

- Fluid Volume: 6,000 US Gallons (22.7125 m^3), defined as the reference volume at a 25°C fill temperature [8].
- Constant Mass Baseline: The system mass (m) is derived from the 25°C density and remains constant throughout the thermal event.
- Operating Temperature (T_{top}): 105°C top-liquid temperature at the onset of the fault.
- Fault Parameters: 230 kV system with a 40 kA symmetric 3-phase fault.
- Protection Speed: Modern microprocessor relay and breaker total clearing time assumed at 4.5 cycles.

It is important to note that this exercise is highly conservative in nature. In standard utility operations, power transformers are rarely operated at their maximum rated top-oil temperature. Typical loading profiles often result in operating temperatures significantly lower than this peak. By utilizing the maximum allowable operating temperature as our starting point, the "worst-case" scenario is being modeled. If the transformer was operating at a more typical 70°C or 80°C, the thermal margin to ignition would increase.

A.3 Determination of System Mass

The first step in quantifying thermal inertia is determining the physical mass of the "fuel" in the system. While volume changes with temperature, mass is constant. It is important to establish exactly how many kilograms of fluid were placed in the 6,000-gallon tank at the time of commissioning. Per IEEE C57.12.00, the standard reference temperature for filling is 25°C. Then adjust the standard 20°C density (ρ_{20}) to the 25°C fill state using the volumetric expansion coefficient (β).

Density Correction	$Fill\ Density\ (\rho_{25}) = \rho_{20}[1 - \beta \times (25 - 20)]$	(A1)

Table 8
Initial Density Parameters for Fluids

Fluid Type	$\rho_{20}\ (kg/m^3)$	β	$\rho_{25}\ (kg/m^3)$	System Mass (kg)
Mineral Oil	890	0.00070	886.89	20,143.5
Natural Ester	920	0.00074	916.59	20,818.1
Synthetic Ester	970	0.00073	966.46	21,950.7

The density of the fluid dictates the 'thermal weight' of the system. While mineral oil is the lightest, synthetic esters provide the highest mass for the same volume, followed by natural esters. This mass is the foundational variable for the system's ability to resist temperature spikes during an internal fault.

A.4 Derivation of Operational Specific Heat Capacity

Specific heat (c_p) is temperature dependent and requires the thermal coefficient of specific heat (α) to adjust for a temperature outside of the standard 20°C. To calculate the energy required to reach fire point, first determine the c_p at the operating temperature (T_{top}) and the Fire Point (T_{fire}), then use the Integral Average ($\bar{c}_p$).

Specific Heat Capacity	$c_p(T) = c_p(20) + \alpha(T - 20)$	(A2)

Table 9
Density Parameters During Fault

Fluid Type	c_p	α	$c_p(T_{top})$	$c_p(T_{fire})$	Avg ($\bar{c}_p$)
Mineral Oil	1.80 (20°C)	0.0038	2.12 (105°C)	2.33 (160°C)	2.23 (kJ/kg C)
Natural Ester	1.97 (20°C)	0.0034	2.26 (105°C)	3.13 (360°C)	2.69 (kJ/kg C)
Synthetic Ester	1.88 (20°C)	0.0032	2.15 (105°C)	2.81 (310°C)	2.48 (kJ/kg C)

Each fluid exhibits a distinct thermal response. Mineral oil's capacity rises modestly before reaching its 160°C threshold. In contrast, the high fire points of natural and synthetic esters allow them to continue absorbing energy across a much wider temperature range, significantly increasing their integral average specific heat ($\bar{c}_p$).

A.5 Calculation of Ignition Enthalpy

Ignition enthalpy (Q) is the total energy required to raise the mass (m) from T_{top} to T_{fire}. This value represents the total energy sink available to the transformer to prevent a sustained fire.

Energy to Reach Fire Point	$Q = m \times \bar{c}_p \times (T_{fire} - T_{top})$	(A3)

- Mineral Oil: 2.47 GJ
- Natural Ester: 14.28 GJ
- Synthetic Ester: 11.16 GJ

The results demonstrate a clear difference in energy absorption. Mineral oil provides a relatively low enthalpy of 2.47 GJ. Natural ester increases that energy sink by nearly 6x, while synthetic ester increases it by over 4.5x. This delta highlights the fundamental difference between standard (Class O) and less-flammable (Class K) fluids.

A.6 Fault Energy Injection and Protection Clearance

The "Self-Extinguishing" nature of a fluid is determined by comparing its ignition enthalpy to the energy delivered by a fault before protection systems isolate the transformer. Given the amount of energy needed to raise the bulk fluid to the fire point temperature, the fault energy occurring in a 230 kV system with 3-phase symmetric fault current of 40 kA can be factored into the equation.

Fault Power	$P = \sqrt{3} \times 230{,}000 volts \times 40000 amps = 15.93\ GW$	(A4)
Energy per Cycle	$E_{cy} = P \times {}^{1}/_{60} Hz = 0.2656\ {}^{GJ}/_{cycle}$	(A5)
Cycles to Ignition	$C_{ign} = Q/E_{cy}$	(A6)

Many modern microprocessor relays can detect and issue a trip signal within approximately 1-2 cycles (1.5 is typical). Associated medium-voltage breakers generally require roughly 50 milliseconds (3 cycles) to physically interrupt the fault [9]. Together, this results in a combined fault-to-energy-removal clearing time of roughly 4.5 cycles on a 60-Hz system, which will be used as the clearing time for this exercise. It is also key to note that if a breaker fails to trip, breaker failure schemes activate with clearing times occurring around 10 to 12 cycles.

Table 10
Safety Margins to Protection Clearance

Fluid Type	Q	C_{ign}	Safety Margin During Normal Protection Operations (vs 4.5 cycles)	Safety Margin During Breaker Fail Events (vs 12 cycles)
Mineral Oil	2.47 GJ	9.3 cycles	2.07x	-0.7x (ignition)
Natural Ester	14.28 GJ	53.8 cycles	11.94x	4.48x
Synthetic Ester	11.16 GJ	42.0 cycles	9.33x	3.5x

For mineral oil, this clearance (during normal protection operations) occurs only about 5 cycles before the fluid reaches its ignition threshold and during breaker fail events ignition could occur. For natural and synthetic esters, the protection removes the energy source while the fluids have nearly 38 to 49 cycles of safety margin remaining. Even during breaker fail operations, ester fluids provide significant time before enough energy could cause a sustained fire.

A.7 Analysis of Gasification and Self-Extinguishing Properties

A critical distinction in this analysis is the difference between instantaneous gasification at the fault site and the sustained combustion of the bulk fluid. When an internal arc occurs, the plasma temperature (reaching thousands of degrees Celsius) causes the immediate vaporization of the fluid in the immediate vicinity of the arc channel. This rapid gasification creates high internal pressure. If this pressure ruptures the transformer tank, these flammable gases may ignite upon contact with atmospheric oxygen, producing a visible flash or localized flame. However, the presence of a localized flash does not constitute a sustained transformer fire.

For a fire to be sustained, the bulk fluid must reach a temperature where it can provide its own fuel through continuous evaporation, the Fire Point. As shown in these calculations, even under a severe 40 kA fault, a microprocessor relay clears the energy source within 4.5 cycles. At this moment:

- Enthalpy Stability: Natural and synthetic esters have absorbed less than 10% of the energy required to reach their Fire Points.
- Vapor Starvation: Once the arc energy is removed by the breaker, the bulk fluid remains at or near its operating temperature, hundreds of degrees below the threshold required to generate flammable vapors.
- Quench Mechanism: The massive thermal inertia of the surrounding cooler fluid acts as a heat sink, rapidly dissipating the localized heat from the arc zone.

A.8 Final Conclusion

While any dielectric fluid will flash during a high-energy arc that ruptures a transformer tank, the "self-extinguishing" property of ester fluids results from the significant difference between protection clearing speed and ignition enthalpy. Since the fault is cleared well before the bulk fluid can sustain combustion, ester-filled transformers are effectively self-extinguishing. This provides a passive safety feature that ensures an internal fault remains a localized electrical incident, rather than escalating into a catastrophic pool fire.