Cooling Environments





Immersion Project

Fluid Oxidation and Electronic Reliability: A Multi-Fluid EID Measurement Study

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OCP BRONZE™ Member

Oxidation 101

A free-radical chain reaction influenced by fluid chemistry, operating conditions, and contamination

WHAT DRIVES IT

OPERATING CONDITIONS

- Heat
- Oxygen
- Time

CONTAMINATION

- Moisture
- Metals
- Particulates

FLUID CHEMISTRY

- Base chemistry

HOW IT PROCEEDS

● free radical ○ stable molecule



1 INITIATION

It starts

Heat, dissolved metals, or contamination breaks a carbon-hydrogen bond of the base fluid and a free radical forms

2 PROPAGATION

It feeds itself

That radical reacts with oxygen and surrounding molecules, producing additional radicals.

3 CHAIN BRANCHING

It accelerates

Peroxides and other intermediates break down into multiple free radicals, increasing the rate of degradation.

4 TERMINATION

It winds down

Free radicals combine to form stable products, slowing and eventually stopping the oxidation process.

THE TAKEAWAY

Inherent fluid stability drives long-term oxidation resistance.

Some fluids maintain oxidation resistance even after antioxidants are largely depleted.

Color alone is not a reliable indicator of oxidation.

The Gap

WHAT WE PERIODICALLY MEASURE TODAY

CHEMICAL

TAN Total acid number · ASTM D664	Acidic oxidation byproducts
FT-IR Fourier transform infrared spectroscopy	Oxidation byproducts and molecular changes
GC-MS Gas chromatography–mass spectrometry	Oxidation products and composition changes
PDSC Pressure differential scanning calorimetry	Induction time, onset temperature, and resistance to oxidative degradation

PHYSICAL

Kinematic viscosity	Molecular changes from oxidation and chain scission

ELECTRICAL

DDF Dielectric dissipation factor	Polar products, ionic species, and contaminants
Breakdown voltage	Ability to withstand electrical stress before failure

These all test the fluid.

?

WHAT WE NEED TO KNOW IN REAL TIME

- **Surface resistance at the board**
  Leakage current between conductors
- **Volume resistivity**
  Conductivity through the bulk fluid
- **Signal integrity**
  BER and eye diagram

These monitor hardware reliability.

No published thresholds link these measurements to board-level failure. That is the gap, and it is the reason this multi-phase study exists.

OCP Participants and Samples

Eight fluid manufacturers contributed fresh and in-service chemistry to an independent, blinded test.

STUDY SPONSORS

ExxonMobil

Shell

PARTICIPATING FLUID MANUFACTURERS

Castrol

oleon
a natural chemistry

Valvoline

EVONIK
Leading Beyond Chemistry

ENEOS Corporation

SOLTEX

Study Looked at Three Main Conditions

FRESH FLUID BASELINE

Unused fluid, straight from the manufacturer containers. Sets the electrical reference every later comparison is made against.

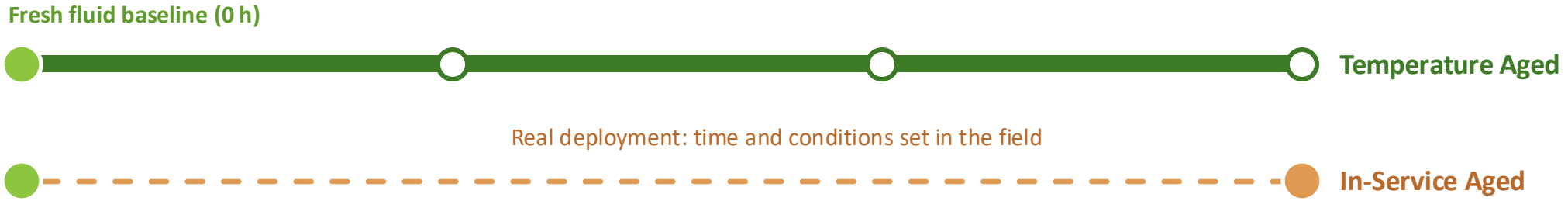
TEMPERATURE AGED (ACCELERATED)

Fresh fluids are aged under controlled laboratory conditions to evaluate how thermal exposure affects fluid chemistry and electrical performance.

IN-SERVICE AGED

Fluids returned from a real deployment, measured against their own fresh baseline.

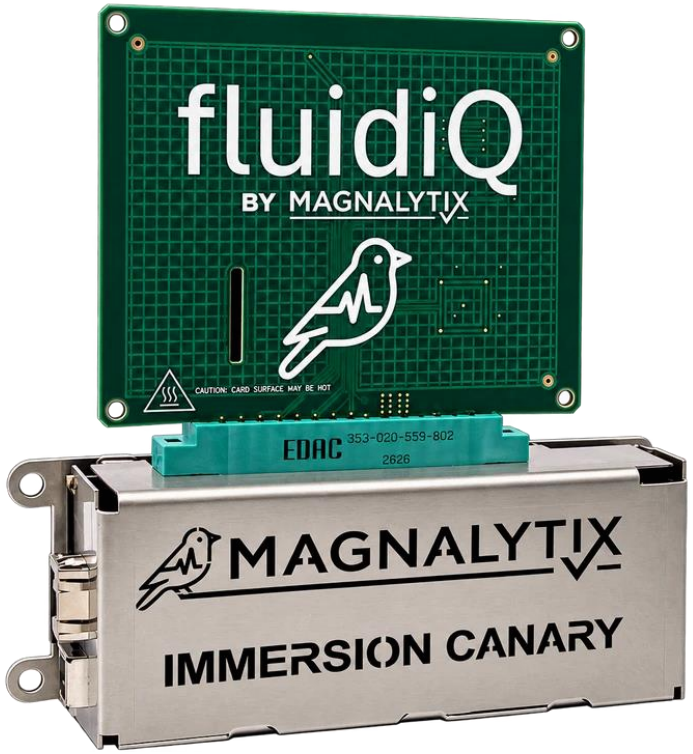
HOW THE THREE CONDITIONS CONNECT



IMPORTANT

- This test is intended to be a controlled comparison. Not a service-life prediction, or a pass or fail rating on any product.
- Measurement and lab testing all run at Magnalytix, and every fluid is reported by study code only.

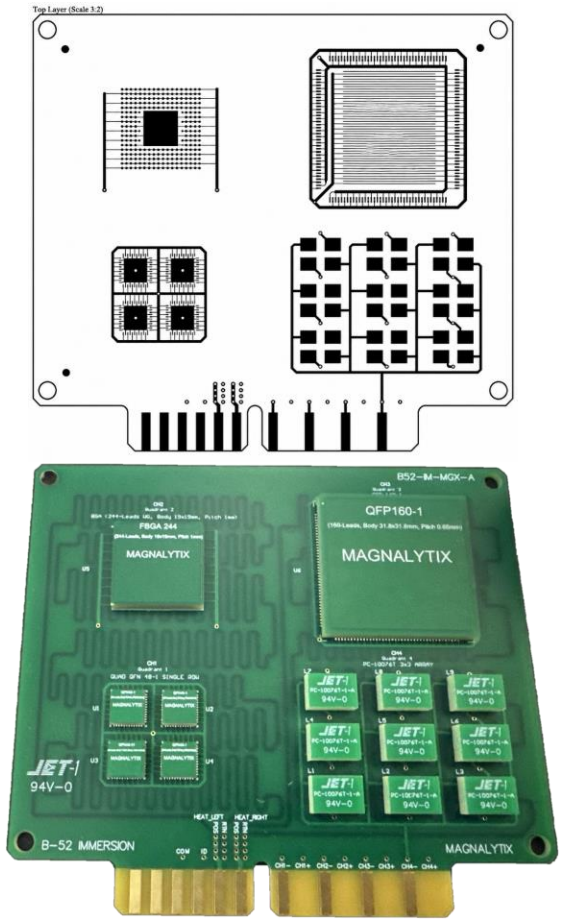
Measuring Electrical Effects Directly



TEST CARD PRODUCTION-LIKE SURFACES

CH1	Quad QFN 48-1 *0.5 mm pitch*
CH2	FBGA 244 *1.0 mm pitch*
CH3	QFP160-1 *0.65 mm pitch*
CH4	3 × 3 Power Choke array

Includes 2-channel embedded heaters for localized thermal control



INTENDED PRODUCTION USE

Continuous monitoring of fluid health in a tank

Intended to remain in the tank during normal operation, tracking real-time fluid-health trends to guide sampling, inspection, and further testing.

HOW THE MEASUREMENT WORKS

Each channel on the removable, immersed test card operates under continuous bias. Leakage current between conductors is converted to surface resistance and tracked against the fluid's fresh baseline.

The Test Protocol

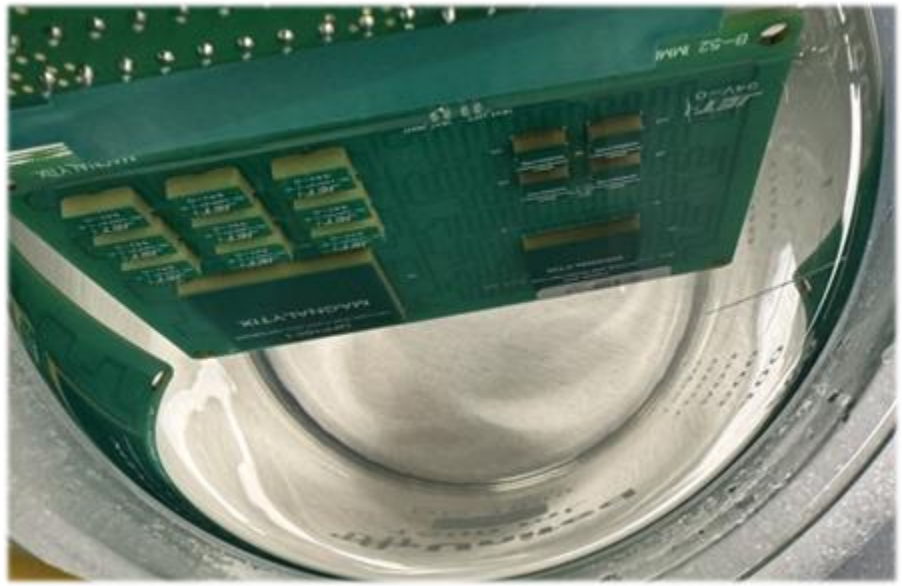
EXPOSURE TIMELINE

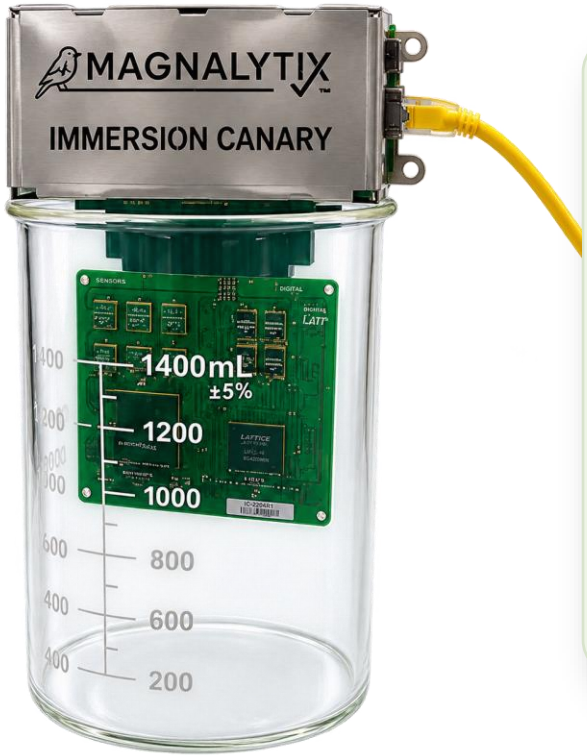
0 h
Cards in fluid
First Sample Taken

168 h
Sample Taken

336 h
Sample Taken

500 h
Test end
Sample Taken

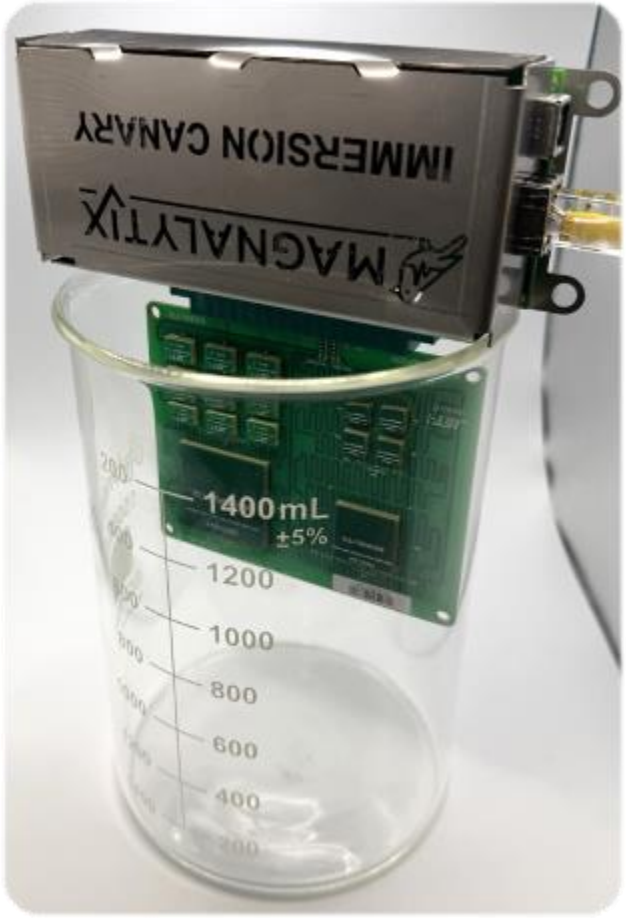


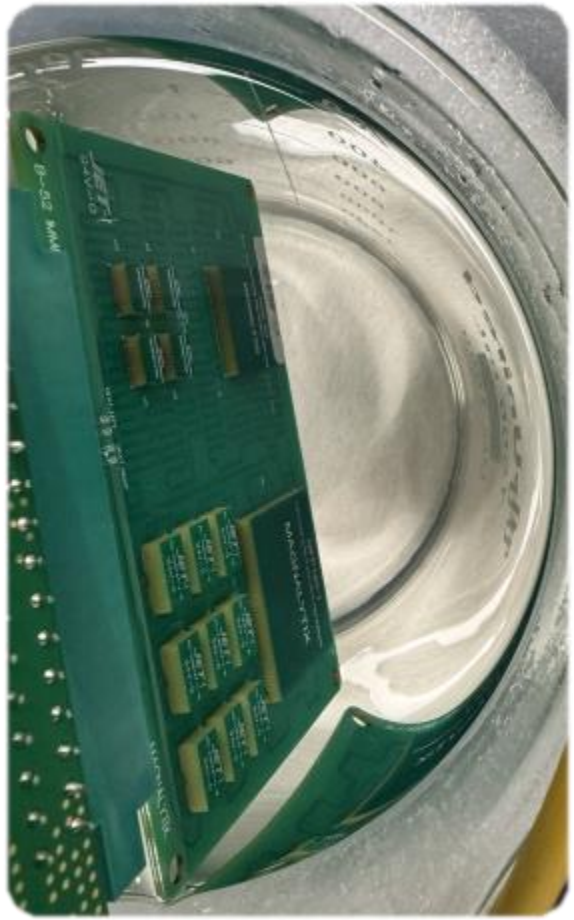


PARAMETERS

Bath Temperature	80 °C, accelerated aging
Duration	500 hours per condition
Test Card	four geometries, continuous 5V bias
Electrical Measurements	Surface resistance (logged continuously)
Fluid Measurements	TAN (total acid number) RI (refractive index °Brix) FTIR (Fourier transform infrared) Karl Fischer water test (end of study)

The Study in Practice









Photographs from the exposure in progress.

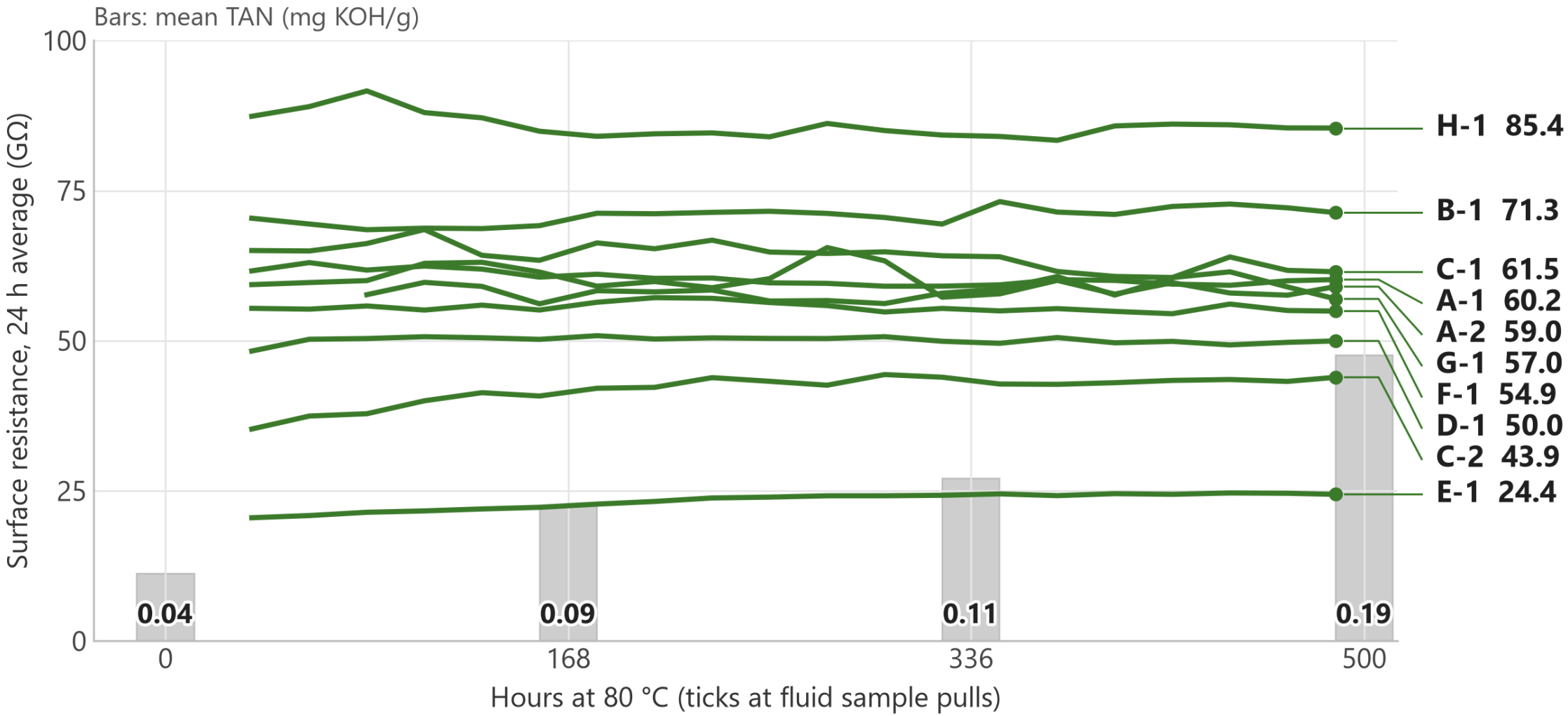
Experimental Controls

- **Covered Test Vessels** — minimized airborne contamination and foreign material ingress
- **Dedicated Thermometers** — individual monitoring for each test vessel to avoid cross contamination
- **Ambient Temperature & Humidity Monitoring** — laboratory room temperature continuously recorded
- **Controlled Fluid Volume** — consistent starting volume across test vessels
- **Consistent Test Geometry** — standardized beakers, card position, and immersion depth
- **Controlled Test Temperature** — common target temperature and exposure conditions
- **Dedicated Test Card & Instrument** — minimized cross-contamination between fluid samples
- **Standardized Sample Handling** — consistent handling, sampling, and measurement procedures
- **Continuous Data Logging** — electrical and environmental conditions recorded throughout exposure
- **Validated Test Equipment** — each test device was validated with known resistor values prior to test

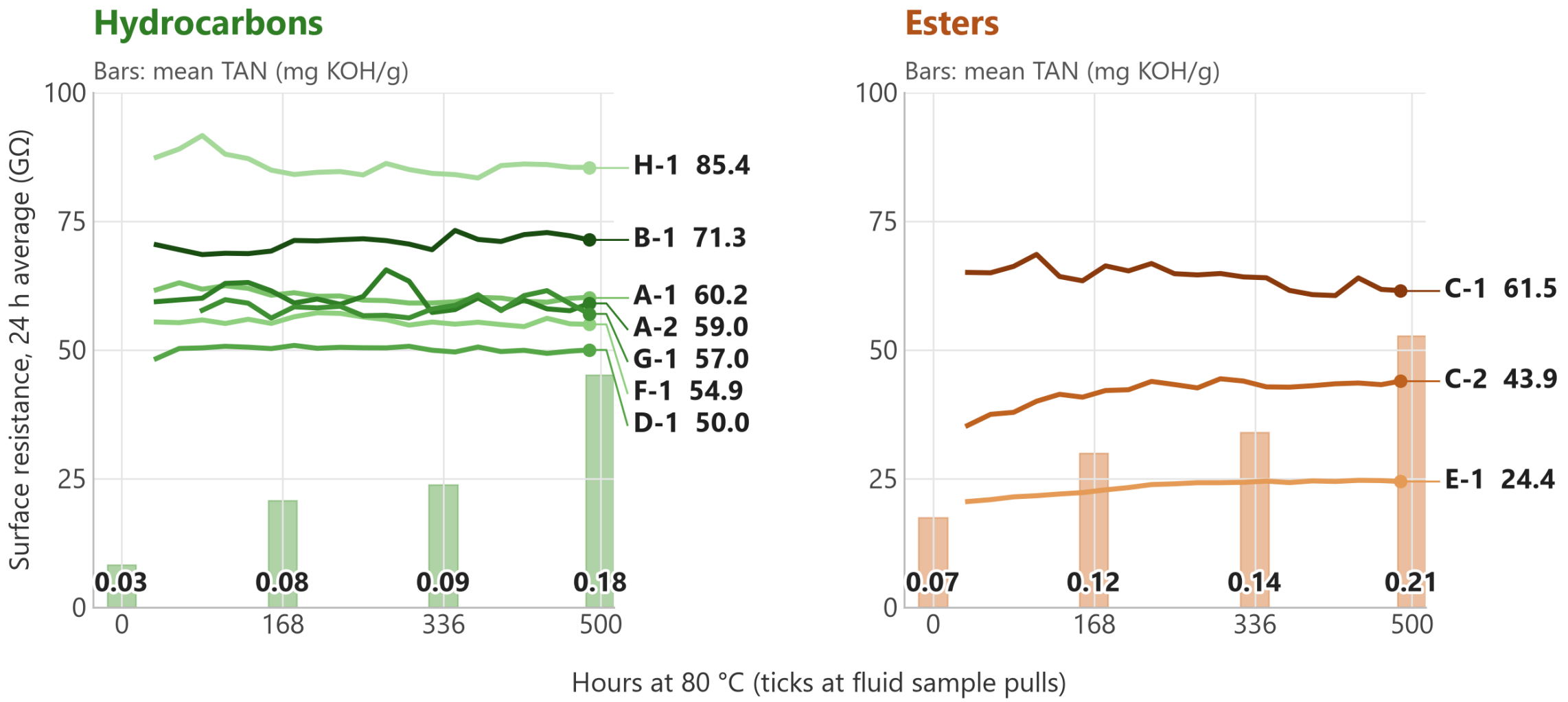
Results: Lab Data (All)

	TAN (mg KOH/g)			Refractometer (°Brix)			FTIR correlation	In-Service Aged	
Fluid	Fresh	Last pull (500 h)	Change	Fresh	Last pull (500 h)	Change	Temperature Aged vs fresh (168–500 h)	TAN	FTIR r
A-1	0.03	0.37	**+0.34**	61.0	60.9	−0.1	0.9997–0.9998	—	—
A-2	0.02	0.16	**+0.13**	65.3	65.2	−0.1	0.9997–0.9998	—	—
B-1	< 0.02	0.14	**+0.13**	63.3	63.3	0.0	0.9996–0.9997	0.17	0.9996
C-1	0.08	0.12	**+0.04**	57.9	57.8	−0.1	—	—	—
C-2	0.11	0.27	**+0.17**	65.1	65.2	+0.1	—	—	—
D-1	0.06	0.15	**+0.09**	63.3	63.3	0.0	0.9997	—	—
E-1	< 0.02	0.23	**+0.22**	61.3	61.2	−0.1	0.9998	0.25	0.9997
F-1	0.04	0.13	**+0.10**	63.4	63.4	0.0	—	—	—
G-1	—	—	—	—	—	—	—	—	—
H-1	0.03	0.13	**+0.10**	66.9	67.0	+0.1	—	—	—

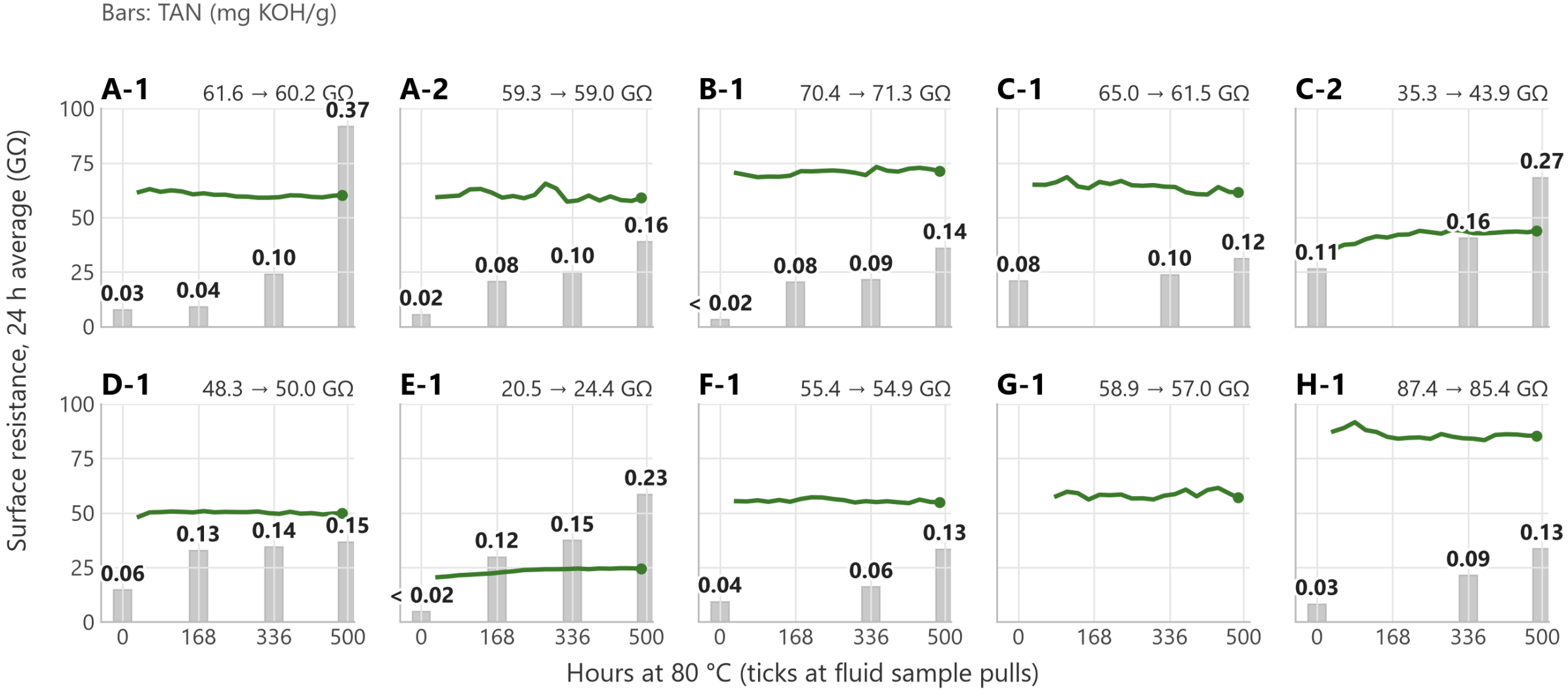
Surface Resistance Results: Lab Accelerated Aging



Surface Resistance Results: By Chemistry



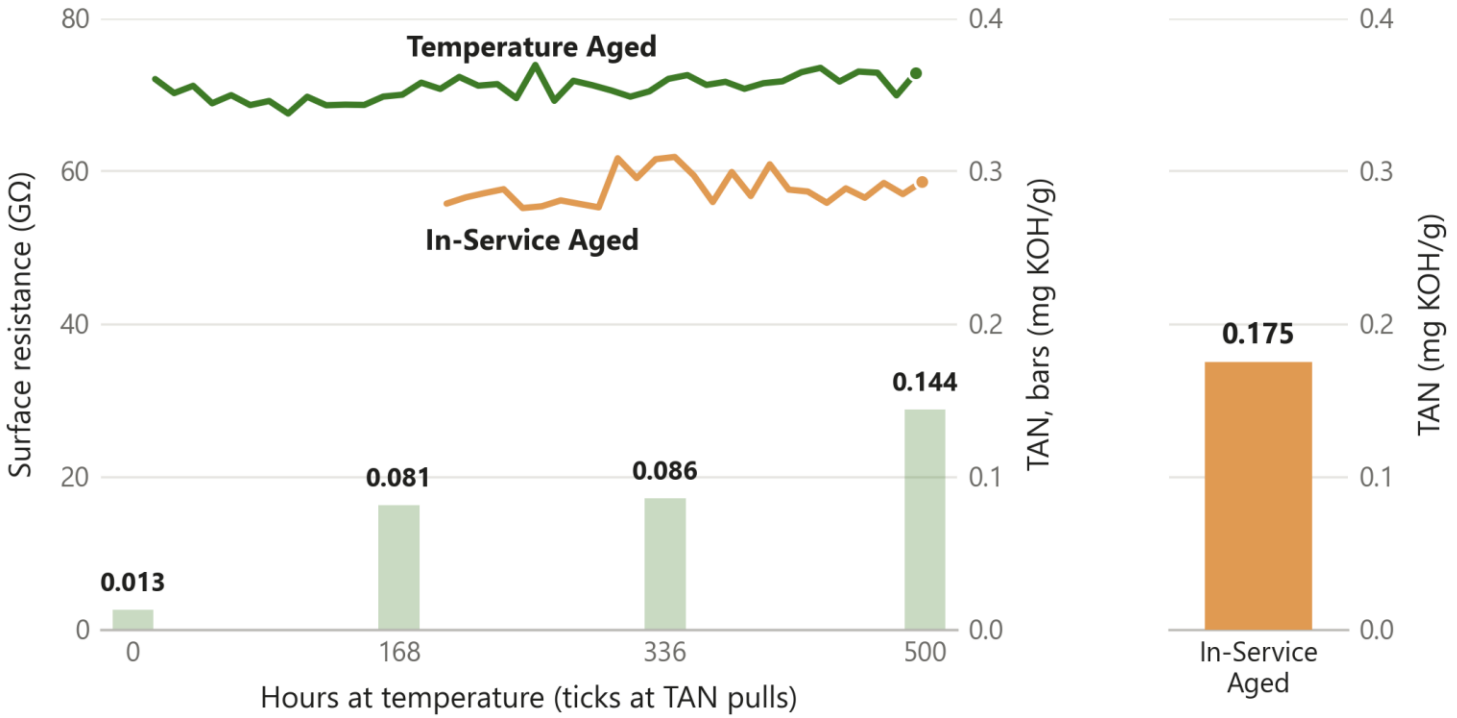
Surface Resistance Results: Individual

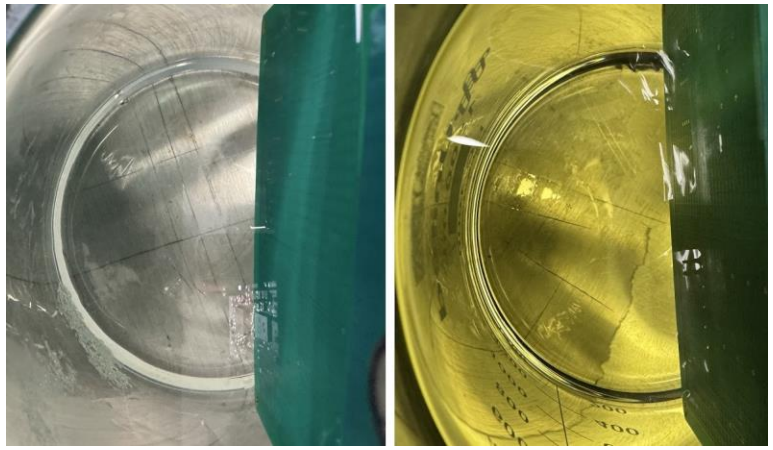


The Field-Aged Sample

Hydrocarbon B-1

In service, this fluid's TAN rose slightly past the 500-hour lab value.
Its board runs 13.8GΩ below the temperature-aged fluid.





Fresh Aged

SURFACE RESISTANCE SERVICE AGED

~2 years in service

19.3% lower than Temperature Aged

57.7 GΩ vs 71.5 GΩ (Fresh)

WHAT IT MEANS

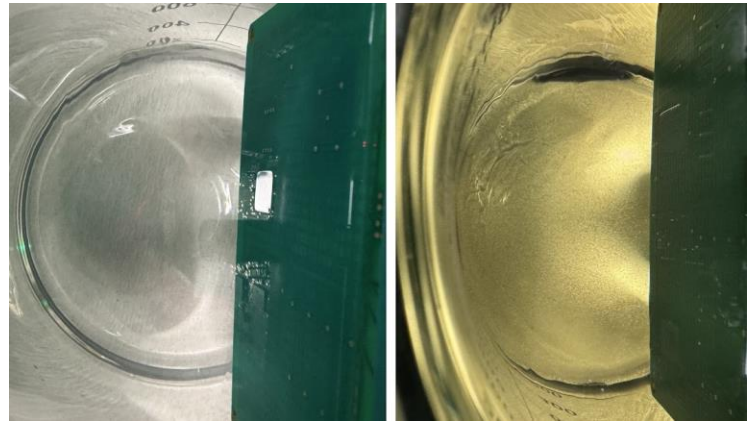
The fluid came back from service slightly more acidic than 500 hours at 80 °C made it, yet once settled its board ran lower than the temperature-aged fluid. Acidity alone did not predict an electrical result.

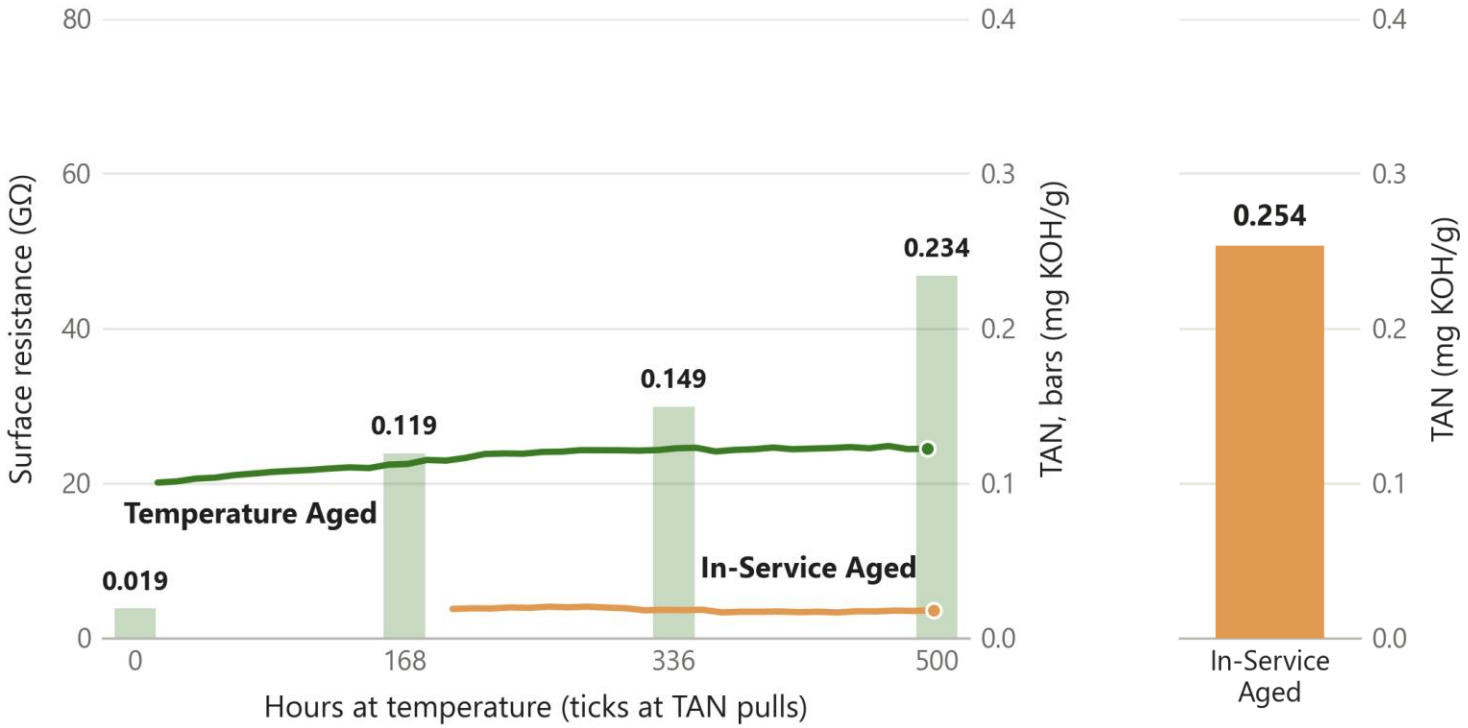
TAN flags this fluid as aged. The board says it is close to normal hydrocarbon data.

The Field-Aged Sample

Ester E-1

In service, this fluid's TAN is only slightly above the 500-hour lab value. Its board runs 20.6GΩ lower on nearly every channel.





A TAN story much like the hydrocarbon but dropped into a warning band in-service.

SURFACE RESISTANCE SERVICE AGED

~6 months in service

85.1% lower than Temperature Aged

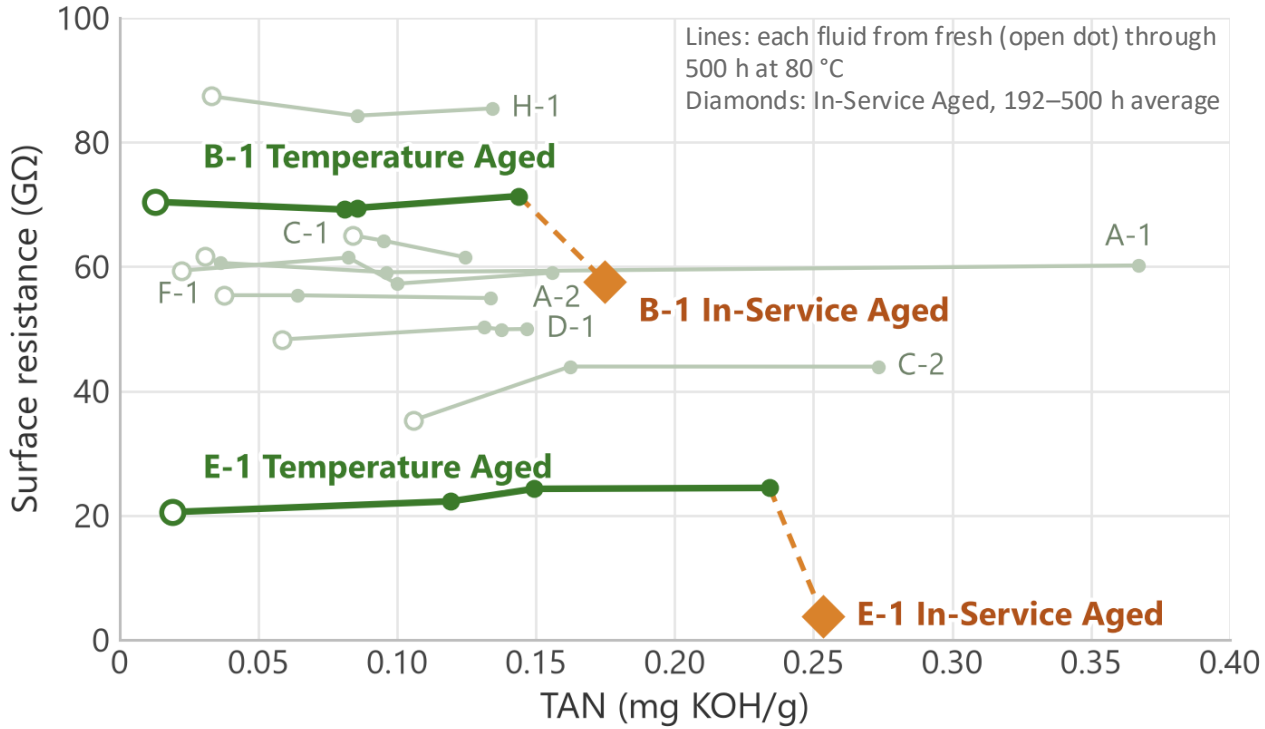
3.6 GΩ vs 24.2 GΩ (Fresh)

WHAT IT MEANS

The drop is persistent and shows on every package, so the cause travels with the bulk fluid. Though absolute isolation is still high, this is worth investigating. Not evidence of hardware failure.

Similar TAN, Lower Resistance in Service

Temperature Aged fluids rose in TAN without a drop in surface resistance.
At a similar TAN, the In-Service Aged fluids ran lower: E-1 20.6GΩ lower, B-1 13.8GΩ lower



What else can affect the electrical performance of a fluid?

- **Ionic contamination**
  Flux residues, organic acids and salts from the hardware
- **Water**
  Dissolved or free water; in esters, hydrolysis to acids
- **Metals and particles**
  Corrosion and wear products carried in the fluid
- **Leached material**
  From elastomers, cable jackets, plastics and coatings
- **Acid type, not amount**
  TAN counts all acid, not which acids or how ionic
- **Temperature and history**
  Service temperature, duty cycle, top-ups and handling

THE CHEMISTRY TAN, FTIR and refractometer readings of both In-Service Aged fluids sat close to their 500 h Temperature Aged values. Whatever lowered resistance, those tests did not see it.

OCP Test Methods: Is Clarification Needed?

	FTIR oxidation Base Spec §6.4	**Total acid number** Base Spec §5.10
OCP SPECIFIES	**FTIR analysis**, with ASTM D4310	**≤0.01 mg KOH/g** new hydrocarbon fluid **≤0.02 mg KOH/g** over its life
SUPPLIERS SENT	Results from different setups: ATR vs. Liquid Transmission Cell, varying cell types and optical path lengths	Results from **four methods**: IEC 62021-2, JIS K 2501 / ASTM D974, ASTM D664, AOCS Cd 3d-63
Study Method	ATR-FITR	Colorimetric TAN measurements
WHY IT MATTERS	Whole-spectrum ATR match **barely moved** (17 of 17 at 0.9996–0.9998); early oxidation needs a band-specific, longer-path setup	Most fluids we tested were **well above 0.02** mg KOH/g, yet showed no apparent operational issues
OPEN QUESTION	**Should we recommend a band-specific method (e.g. carbonyl area) and a defined cell path length?**	**Is 0.01/0.02 the right limit, and which method and protocol should verify it?**

OCP Base Specification for Immersion Fluids, Rev 1.0 (1 Dec 2022), §5.10 and §6.4 "Oxidation Potential". OCP Immersion Requirements Rev 2.10 SR 4.2-1. IEC 62021-2:2007 §10 · JIS K 2501:2003 §5.7 · ASTM D664-18e2, D664-24 · AOCS Cd 3d-63

Conclusions

- Fresh fluids retained broadly stable surface resistance through 500 hours of laboratory aging.
- Data collected confirms some of the original published work showing peak oxidation is typically beyond several years of operation.
- Longer-duration testing is needed to characterize later-stage oxidation and its relationship to electrical performance.
- The electrical test method distinguished in-service samples from their matched laboratory-aged counterparts, revealing lower surface resistance in the in-service fluids.
- TAN increased without a consistent decline in surface resistance. TAN, FT-IR, RI, and color alone did **not** establish electrical degradation under the conditions tested.
- TAN tracks bulk acidity. Understanding what fluid aging means for electronic reliability requires chemical characterization alongside direct electrical measurements.

Call to Action

CONTRIBUTE FIELD-AGED SAMPLES

- In-service fluids with their matched fresh fluid, acid number, and a real service history.
- We especially would like to test any fluids that have been in extreme conditions or perhaps were removed from service due to failing lab testing.

DOE PHASE 2: LONGER DURATIONS (RUN UNTIL FAILURE)

- Multiple participants have agreed to test their fluids until failure, which will help us classify the failure modes for various fluid chemistries.
- Testing is planned to begin in November 2026, with initial results targeted for OCP EMEA.

DOE PHASE 3: “BEYOND THE TAN” MATERIAL EFFECT ON ELECTRICAL DEGRADATION

- Controlled adding of bulk materials to test interactions with oxidized fluids.

DOE PHASE 4: FLUID AGING EFFECT ON SIGNAL INTEGRITY

- Record signal integrity metrics like BER, Df, Eye Diagram alongside volume resistivity and surface changes.

OPEN WHITEPAPER PUBLICATIONS

- All results will be published in a whitepaper (currently in draft) through the fluid oxidation workstream, blinded, with the method documented well enough to easily replicate it.

CONTACT US

fluidiQ BY MAGNALYTIX

FLUID OXIDATION WORKSTREAM

Thank You!



OCP GLOBAL SUMMIT

October 12-15, 2026
San Jose, California