TECHNICAL APPLICATION NOTE

Interfacial Tension of Insulating Oils

ASTM D971 ring-method measurement on the 3S tensiometer, condition limits by fluid type, and the data that make IFT an early-warning test

An insulating oil is judged by many numbers, but only one of them moves before the chemistry has visibly changed. Interfacial tension against water responds to dissolved polar species at parts-per-million levels, months before acidity rises and years before sludge precipitates. This note covers the physics, the ring method as written in ASTM D971, the practical chain around the 3S tensiometer, and the condition limits — which now differ by fluid type and are the most common source of false alarms in a mixed fleet.

DOCUMENT	REVISION	METHOD	READING TIME
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CONTENTS

1 Summary for decision-makers
2 Why IFT moves before the chemistry does
3 The Du Noüy ring: what the balance actually measures
4 ASTM D971, step by step
5 The 3S tensiometer in the measurement chain
6 Sampling: where IFT results are lost
7 Measurement data and condition limits
8 Three interpretation case studies
9 Pitfalls and troubleshooting
10 Specifications, validation and accreditation
11 Reporting checklist
12 References and appendices

Data provenance: condition limits, sludge statistics and decline rates are reproduced from the standards and technical literature cited in place, with the secondary source identified where the primary document was not consulted directly. Section 7.6 is a synthetic fleet dataset, built to demonstrate the decision logic, and is labelled as such.

1 Summary for decision-makers

Interfacial tension is measured between the oil and distilled water, and it falls when amphiphilic molecules — the acids, ketones and hydroperoxides of oxidation, or an external contaminant — accumulate at that interface. The useful consequence is diagnostic: IFT drops measurably while acidity is still low and long before any sludge becomes visible on the paper.

The measurement itself is one of the most demanding routine tests in an oil laboratory, because it depends on a clean platinum ring, pure water and controlled temperature. The interpretation is equally demanding, because the limits are no longer universal.

Six conclusions that shape a programme

- **IFT is the earliest of the routine chemical indicators.** In the fitted relationship between the two tests, acidity is still around 0.03 mg KOH/g when IFT has already fallen to 22 mN/m. A programme that waits for acidity has lost the early warning.
- **The limits depend on the fluid.** IEC 60422:2024 separates inhibited from uninhibited mineral oil (Poor below 22 and 20 mN/m respectively); esters have their own, lower bands — 16 mN/m for synthetic and 14 mN/m for natural esters. Applying mineral-oil limits to a new ester produces a false alarm (Section 7.1).
- **Sludge probability is not linear in IFT.** Above 24 mN/m, none of the transformers in the classic field dataset carried sludge; below 18 mN/m, 69 % did. The last few millinewtons before 18 are where the decision matters (Section 7.2).
- **The rate of change matters as much as the value.** A decline of 0.5–1.5 mN/m per year is typical in service; an acceleration at a still-acceptable absolute value is a signal about kinetics, not about condition (Section 7.4).
- **The method is unforgiving of contamination.** A fingerprint on the ring, a bottle of water left open, a 5 °C difference between the phases — each shifts the result by more than the annual ageing of a healthy oil. Roughly 5 % day-to-day agreement is what the ring method delivers when it is done properly (Section 5.3).
- **One number is not a diagnosis.** IFT locates neither an electrical fault nor a moisture problem; it reports the polar chemistry of the liquid. Its value comes from trend, from comparison with acidity, and from the fluid-specific band.

> **RULE OF THUMB FOR A FLEET PROGRAMME**
>
> Measure IFT at every routine oil sampling on inhibited mineral oil, and at least annually on uninhibited oil. Alarm on the band from the correct fluid standard, and open an investigation on any fall greater than about 5 mN/m between consecutive samples — that is roughly three years of normal ageing in a single interval, and it points to contamination or inhibitor depletion rather than to gradual oxidation.

2 Why IFT moves before the chemistry does

2.1 The oxidation arc

Mineral insulating oil oxidises through a sequence that is well described and slow at first: hydroperoxides form, then aldehydes, ketones and carboxylic acids, then higher-molecular-weight condensation products that remain dissolved as sludge precursors until they precipitate. IFT responds at the very beginning of that sequence and keeps responding through it, which is why a single number integrates the whole polar history of the fluid.

The practical consequence is a difference in timing. Acidity is a titration of what has already accumulated in the bulk; IFT is a measurement of what has concentrated at an interface. The second is sensitive to concentrations the first cannot yet resolve.

2.2 Gibbs adsorption: why the interface sees what the bulk hides

Dissolved polar species are amphiphilic: a non-polar hydrocarbon tail, a polar head. At an oil–water boundary the tail can stay in the oil while the head is solvated by water, so the molecule is thermodynamically driven to the interface. Each molecule that adsorbs displaces water–water interactions and lowers the measured tension. The Gibbs adsorption isotherm formalises this: a fall in interfacial tension with increasing solute concentration implies a positive surface excess — the interface is enriched relative to the bulk.

That enrichment is the reason a test with a detection limit in the millinewton range can respond to contamination in the parts-per-million range. It is also the reason the test is sensitive to the cleanliness of everything it touches.

2.3 Why oil–water and not oil–air

Surface tension — oil against air — changes only modestly as an oil degrades, because every oil molecule interacts with air through similar dispersion forces whether or not it has oxidised. The oil–water interface is different: it offers a polar phase that selectively attracts and concentrates exactly the molecules that oxidation produces. This is why the diagnostic test is the interfacial one, and why a result reported simply as “tension” is not interpretable until the interface is stated.

2.4 Where IFT sits in a maintenance programme

IEC 60422 has traditionally treated IFT as a complementary (Group 2) test. The 2024 edition adds a note that it can be a routine (Group 1) test for inhibited oil, and that it is most useful early in life, when it can indicate an early stage of oxidation or contamination. For a fleet, that translates into a simple rule: the test is cheap, the alternative is a sludge-related failure, and the early years are when the trend is still clean enough to be informative.

3 The Du Noüy ring: what the balance actually measures

3.1 Interfacial tension in one paragraph

Interfacial tension is the energy required to create unit area of a new interface between two immiscible liquids, expressed in mN/m (equivalent to mJ/m²). It is not a property of the oil alone: it belongs to the pair. Change the water — its purity, its temperature, its dissolved gas — and the number changes, which is why the method prescribes distilled or deionised water of verified surface tension.

3.2 The force balance

A platinum-iridium ring of known circumference is submerged in the water phase beneath the oil, then drawn upward through the interface. The liquid film that forms around the wire is stretched until it detaches, and the maximum force recorded just before detachment is proportional to the interfacial tension:

$$IFT = f \cdot F / (4\pi R)$$

where F is the measured force, R the mean radius of the ring and f a correction factor for the non-ideal geometry of the meniscus. The correction — the Harkins–Jordan factor — depends on the force itself, the ring dimensions and the density difference between the two phases. It is not a constant, and a value quoted without stating that the correction was applied is not a finished result.

3.3 What “interfacial tension” means in a non-equilibrium test

The ring method does not measure a true equilibrium value. It measures the tension at a defined time after the interface is created — nominally 60 s in ASTM D971, extended to 180 ± 30 s in IEC 62961. That difference is not cosmetic: longer equilibration allows more polar species to reach the interface, so an aged oil can read lower under the IEC protocol than under the ASTM one. For an ester fluid, where diffusion is slower and the interfacial film more structured, the difference is larger still.

Two consequences follow. Never compare results obtained under different equilibration times, and state the protocol in the report. If a laboratory changes from D971 to IEC 62961, the whole trend line acquires an offset that has nothing to do with the transformer.

3.4 Temperature and purity: the two sensitivities that dominate

Interfacial tension falls as temperature rises, and both phases must be at the same temperature — the method specifies a working window of 18–25 °C rather than a single set point. A cold oil and a warm water phase produce a measurement of the thermal gradient as much as of the chemistry.

Water purity is the second dominant term. The method requires water whose own surface tension is verified, conventionally in the 70–74 mN/m range. Water left standing in an open vessel adsorbs atmospheric organics and its surface tension falls within hours; using it silently lowers every result in the batch.

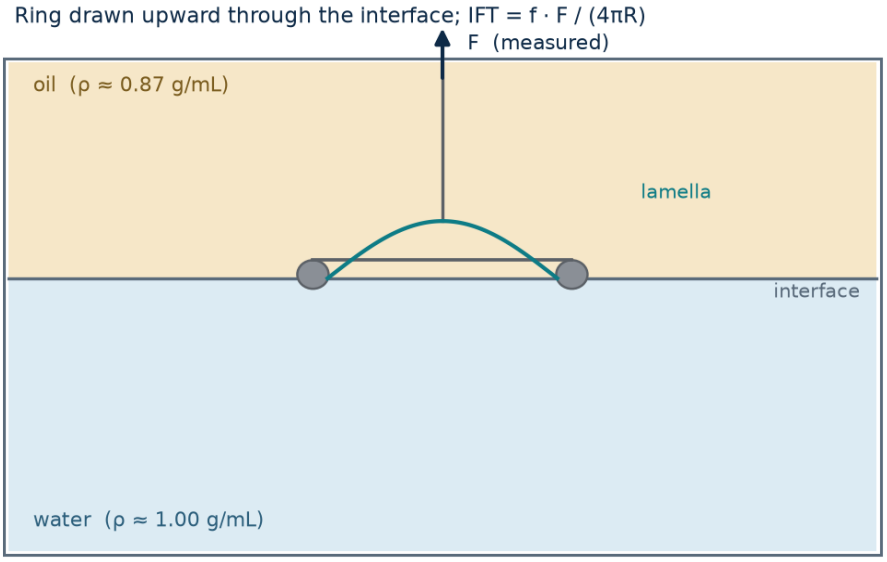


Figure 1 — The ring is submerged through the oil into the water and drawn back up; the maximum force before the lamella detaches is the measurement. The correction factor f accounts for meniscus geometry and is computed from the force, the ring dimensions and the density difference.

4 ASTM D971, step by step

The method is short, and almost all of its difficulty is in preparation rather than in measurement. The sequence below follows ASTM D971 as the reference method, with the IEC 62961 differences noted where they matter.

4.1 Apparatus

A ring tensiometer with a platinum-iridium ring, a thermostatted vessel, a means of raising the stage or lowering the ring at controlled speed, and a force sensor with sufficient resolution for the range of interest. For insulating oils the working range is roughly 5–50 mN/m, so a resolution of 0.1 mN/m is adequate; the limiting factor is never the sensor but the cleanliness of the ring.

4.2 Ring preparation

The ring is cleaned by rinsing in solvent, then held in a reducing flame until it glows. Flame annealing removes organic residues and restores the complete wetting that the calculation assumes. It is done before each measurement, not once per batch. A ring that has been sitting in a drawer is a ring with an unknown contact angle.

4.3 Water phase

Distilled or deionised water, freshly drawn, at the same temperature as the oil. Verify its surface tension before the series — a reading outside 70–74 mN/m means the water or the ring is contaminated, and neither the oil result nor the day's other results can be trusted.

4.4 Procedure

1. Pour the water into the thermostatted vessel, then carefully layer the oil on top. Avoid mixing: the interface must be quiescent and flat.
2. Lower the ring through the oil layer into the water, keeping it centred and fully submerged.
3. Allow the temperature to equilibrate and the interface to settle for the time the method specifies (60 s in ASTM D971; 180 ± 30 s in IEC 62961).
4. Raise the ring at the prescribed rate until the lamella detaches, recording the maximum force.
5. Apply the correction factor and report the result to 0.1 mN/m, with the temperature, the equilibration time and the water check.

Aspect	ASTM D971	IEC 62961:2018
Equilibration before measurement	60 s	180 ± 30 s
Temperature window	Controlled, phases at the same temperature	18–25 °C, phases equalised
Ring	Platinum-iridium, cleaned and flame-annealed	Same; annealing before each measurement
Water	Distilled, purity verified	Surface tension 70–74 mN/m verified
Scope	Insulating liquids lighter than water	Insulating liquids, including esters
Status	Long-standing reference in North America	Increasingly the international reference

Table 1 — The two ring-method standards side by side. The equilibration time is the difference most likely to shift a trend line when a laboratory changes method.

4.5 Calculation and reporting

Report the corrected interfacial tension in mN/m at the measured temperature, together with the method and its edition, the equilibration time, the water check value and the ring identification. Without the water check, a low result cannot be separated from a contaminated batch.

4.6 Ring, plate or pendant drop

The ring is the reference method in both standards. The Wilhelmy plate measures the wetting force without tearing the interface and needs no correction when the plate is completely wetted, which makes it attractive for continuous monitoring; it is not specified in the transformer-oil standards. The pendant drop is optical, needs no contact with the interface, and works with small samples, but heavily aged or opaque oils obstruct the optical path.

Method	Strength	Limitation	Status in oil testing
Du Noüy ring	Reference method; well characterised	Ring cleanliness dominates; tears the interface	Specified: ASTM D971, IEC 62961
Wilhelmy plate	Continuous, time-resolved; no correction	Plate wetting must be perfect; cleaning critical	Not specified in the standards
Pendant drop / spinning drop	Small sample; no contact; optical	Opaque or dark oils; equipment cost	Research and problem-solving

Table 2 — Method comparison for insulating liquids. For compliance and trending, the ring is the only defensible choice.

5 The 3S tensiometer in the measurement chain

The instrument is one link in a chain that runs from the sampling bottle to the reported number, and the ring method fails at whichever link is weakest — usually not the electronics. This section lists what the chain has to provide, so that each item can be checked against the instrument's specification and against the laboratory's own practice.

5.1 What the measurement chain must provide

- **A force sensor calibrated over the working range**, with the calibration traceable and the certificate held by the laboratory. For insulating oils the range of interest is 5–50 mN/m; a 0.1 mN/m resolution is sufficient, and a sensor that is accurate only at the top of its range is not.
- **A ring of certified dimensions** — mean radius and wire diameter — because both enter the correction factor. Record the ring identifier with every result: two rings do not give the same number unless both are clean and both dimensions are known.
- **A flame-annealing station** able to bring the ring to red heat without deforming it. This is the single most important accessory, and the one most often improvised.
- **A thermostatted vessel** holding both phases within the method window (18–25 °C) and, more importantly, at the same temperature. A jacket that controls only the water phase is not sufficient.
- **A controlled raising mechanism** with a documented speed, recording the maximum force rather than a smoothed average.
- **The correction applied in software or by hand**, with the density of both phases entered for each sample rather than taken from a default.

Presented this way, the list doubles as an audit checklist: each item either exists and is documented, or it is a gap that will show up as scatter between operators.

5.2 Daily verification

Two checks catch almost all failures. The first is the water blank: measure the surface tension of the water used for the day's work against air, and confirm 70–74 mN/m. A low blank means contaminated water or a contaminated ring — and if it is the ring, every oil result that day will be low by a similar amount.

The second is a repeat on a retained sample. Keep one stable, clean oil — a sealed reference bottle of new mineral oil — and measure it at the start of each session. A drift of more than 2 mN/m against its established value is a signal to stop and re-clean, not a signal about the retained oil.

5.3 Uncertainty

The budget below is representative of a well-run laboratory measuring a 40 mN/m oil with the ring method at controlled temperature, with the ring flame-annealed before each of three replicates.

Contribution	Type	Standard uncertainty (mN/m)	How it is controlled
Repeatability (n = 3)	A	0.60	Three replicates; median reported
Ring cleanliness and wetting	B	0.50	Flame annealing before every measurement
Water purity	B	0.30	Fresh water; blank 70–74 mN/m
Temperature equality of phases	B	0.30	Both phases equilibrated 30 min
Operator and interface placement	B	0.40	Training; annual reproducibility check
Combined standard uncertainty uc		0.97	Root sum of squares
Expanded uncertainty U (k = 2)		1.9	95 % coverage; ≈ 5 % at 40 mN/m

Table 3 — Example uncertainty budget for IFT by the ring method. The expanded uncertainty of about 1.9 mN/m at 40 mN/m is consistent with the 5 % day-to-day agreement reported for the ring method in IEC 62961.

The practical reading of that number is important for alarm setting. With U ≈ 1.9 mN/m, a single result that falls 2 mN/m below the previous one is not evidence of anything. A fall of 5 mN/m is outside the noise by a factor of two and a half, and a fall that crosses a band boundary is worth investigating even when small.

5.4 Records and traceability

For an accredited laboratory the record set is fixed by the quality system, but three items are specific to this method and are often missing: the ring identifier, the water blank value for the session, and the equilibration time actually used. Add the oil temperature at sampling if the sample travelled, because a sample taken hot and analysed cold has a thermal history that may have changed the interface.

6 Sampling: where IFT results are lost

A low IFT result has three possible causes: the oil is degraded, the sample is contaminated, or the measurement is wrong. Separating them starts at the sampling valve. The practices below follow the sampling guidance for electrical insulating liquids (ASTM D923) and the wider testing guide (ASTM D117).

> **THE THREE-CAUSE RULE**
>
> When a result is unexpectedly low, test the same bottle twice before drawing any conclusion about the transformer. If the two results differ by more than the expanded uncertainty, the problem is in the laboratory or the bottle. If they agree, the oil is telling you something — and the next question is whether acidity moved with it.

- **Use a clean, dry, dark-glass bottle** with a cap that seals without a grease film. Silicone grease on a stopcock or a thread is a polar contaminant that will show up as a low IFT and no change in acidity.
- **Flush the valve** before filling, and fill the bottle completely to exclude headspace. Dissolved oxygen and light both act on the sample between the transformer and the laboratory.
- **Do not filter or centrifuge** the sample before the test. Removing particulate matter changes what reaches the interface and can move the result by several mN/m.
- **Keep the sample dark and cool** in transit, and analyse within the laboratory’s validated holding time. IFT is not a conserved quantity in a half-full bottle on a window sill.
- **Record the sampling point** — main tank, conservator, cooler circuit, tap changer — because mixing histories differ and a trend line cannot be built across compartments.

- **Never re-use a bottle** that held a different fluid, and never sample an ester into a bottle previously used for mineral oil without an approved cleaning record. Cross-contamination in either direction is small in volume and large in effect.

7 Measurement data and condition limits

The datasets in this section are the ones a programme actually runs on: the band a result falls into, the probability of sludge behind that band, the relationship with acidity, the expected rate of change, and the repeatability that decides whether a change is real. The condition limits are reproduced from the current standards; the fleet table at the end is synthetic and is labelled as such.

7.1 Typical values and condition bands

New, healthy mineral oil sits between 40 and 50 mN/m against water. ASTM D3487 specifies a minimum of 40 mN/m for new mineral oil used in electrical apparatus. In service, the classification depends on the fluid, and the 2024 edition of IEC 60422 is the first to separate inhibited from uninhibited mineral oil.

Fluid	Good	Fair	Poor	Reference
Mineral oil, inhibited	> 28 mN/m	22–28 mN/m	< 22 mN/m	IEC 60422:2024
Mineral oil, uninhibited	> 25 mN/m	20–25 mN/m	< 20 mN/m	IEC 60422:2024
Synthetic ester	> 22 mN/m	16–22 mN/m	< 16 mN/m	IEC 61203:2025
Natural ester	> 20 mN/m	14–20 mN/m	< 14 mN/m	IEC 62975:2021
New mineral oil, acceptance	≥ 40 mN/m	—	—	ASTM D3487

Table 4 — IFT condition limits by fluid type. The bands are progressively lower for esters because their new-fluid values are lower; applying mineral-oil bands to an ester flags healthy fluid as degraded.

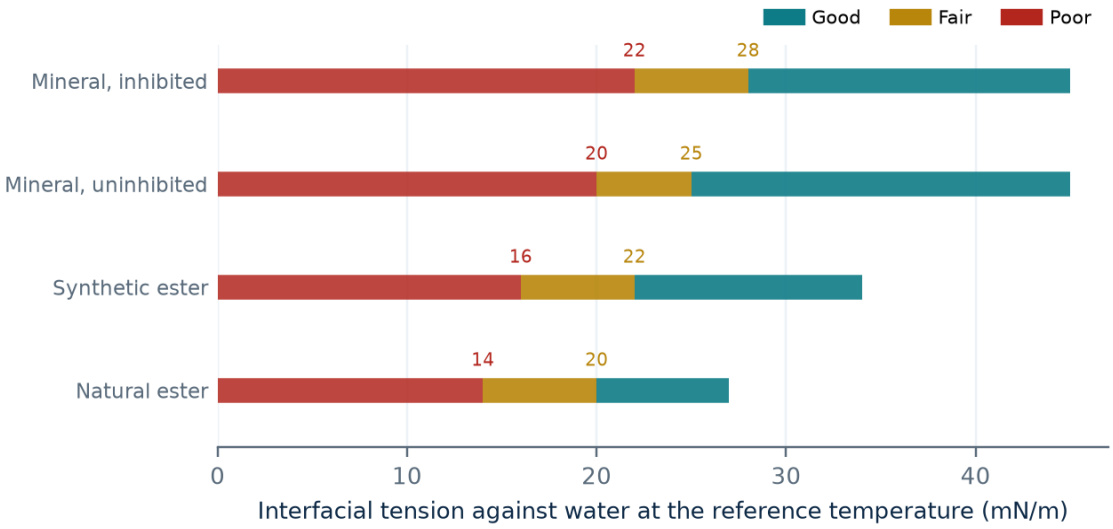


Figure 2 — The same limits as bands. The coloured segment runs from zero to the typical new-fluid value, which is what makes the relative width of the Good band visible: an ester has roughly 13 mN/m of usable range from new to Poor, a mineral oil about 23.

Two practical consequences. First, a mixed fleet needs the fluid type on every report line, not in a separate asset register: the analyst cannot choose the band otherwise. Second, the narrower dynamic range of esters means each millinewton carries proportionally more diagnostic weight, and the same absolute change is a stronger signal.

Older criteria remain in circulation — for example acceptance at ≥ 32 mN/m, questionable at 28–32 and unacceptable below 28, which is stricter than the current IEC bands. Where a utility's internal standard is

stricter than the international one, that is a legitimate engineering choice, but it should be a documented one, because it will generate reclamations that IEC 60422 would not require.

7.2 What a band means in terms of sludge

The band boundaries are not arbitrary. They descend from field work relating IFT to the presence of sludge in transformers, and the relationship is steep at the bottom.

IFT band (mN/m)	Transformers with sludge	Reading
> 24	0 %	No sludge observed in the dataset
22–24	30 %	Sludge begins to appear
20–22	33 %	Plateau; the boundary is not sharp here
18–20	35 %	Still moderate
16–18	69 %	Steep transition
14–16	85 %	Sludge is the norm
< 14	100 %	Universal in the dataset

Table 5 — Sludge incidence against IFT, from the AIEE-era field study as reproduced in the secondary literature. The dataset is old and the population is not described in the summary, but the shape — flat above 24, steep between 18 and 14 — has informed the limits ever since.

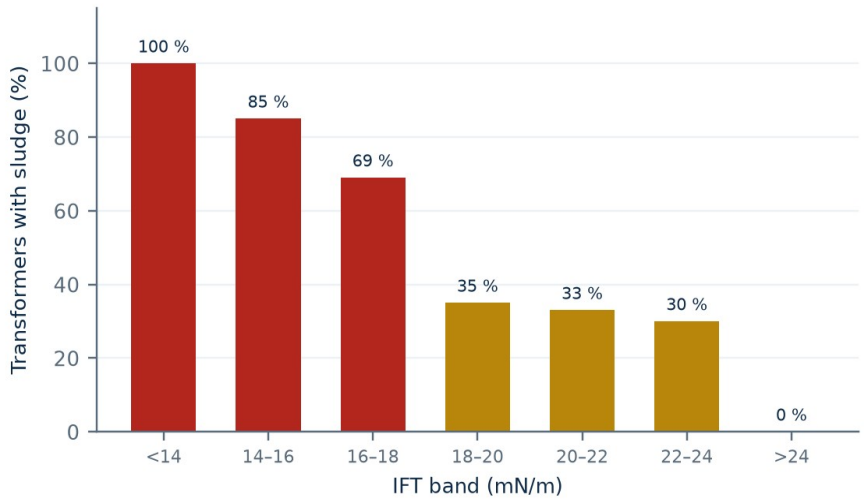


Figure 3 — The same data. Between 24 and 18 mN/m the probability changes slowly; below 18 it climbs steeply, which is why a result just inside the Fair band deserves attention rather than reassurance.

The operational reading is that the absolute number and its position on this curve are different questions. An oil at 26 mN/m in the inhibited band is Good and roughly four years from the steep part at 1.5 mN/m per year; an oil at 23 mN/m is Fair and one year from it. The band tells you what to call it; the slope tells you when to act.

7.3 IFT and acidity: two clocks running at different speeds

The classic inverse relationship between IFT and total acid number is the most documented pairing in transformer oil analysis. Its practical value is in the shape: at low acidity the curve is nearly vertical, so IFT falls measurably while acidity is still barely moving. In the fitted relationship derived from 25 power transformers, acidity is still only about 0.03 mg KOH/g when IFT has reached 22 mN/m.

The two tests also fail in different ways, and that difference is diagnostic. Low IFT with low acidity points away from normal oxidation and towards an external polar contaminant — a solvent, a gasket leachate, a silicone grease. A rise in acidity with a modest fall in IFT points to conventional ageing.

CIGRE combines the two into the oxidation index, IFT divided by acidity, and lists a value below 300 as one criterion for considering reclamation (TB 413). The index is a mineral-oil construct: ester fluids have a different acidity baseline, and applying the index to them without adjustment produces meaningless numbers.

7.4 Rate of change, and the furfural link

A decline of 0.5–1.5 mN/m per year is commonly observed in service for uninhibited mineral oil, with the rate depending on loading, temperature, oxygen access and copper content. That range is wide enough that the absolute value alone says little about time: from 45 mN/m, an oil falling at 0.5 reaches the Fair boundary in 34 years, one falling at 1.5 in 11.

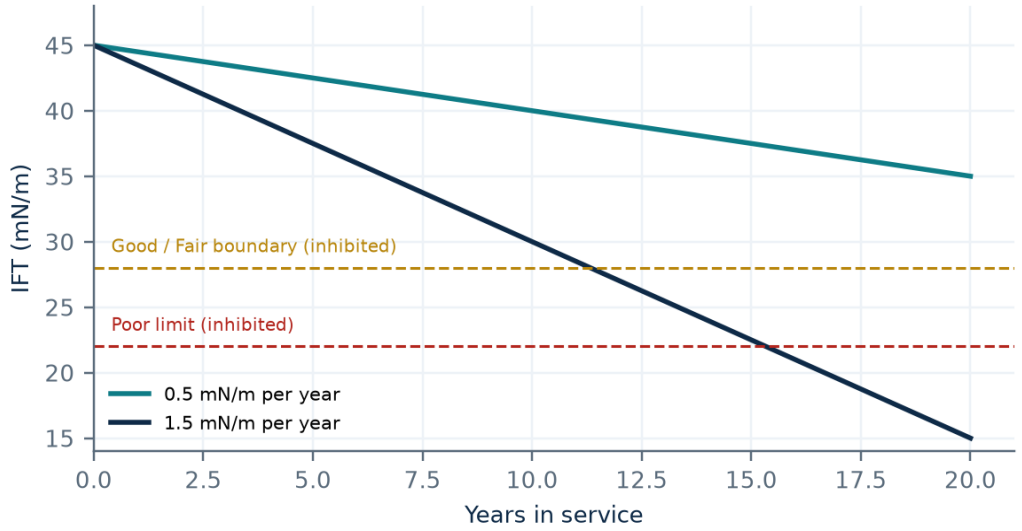


Figure 4 — Projected decline from a typical new-oil value at the two ends of the reported rate range, against the inhibited-oil boundaries. The projection is arithmetic, not a model of oxidation: its purpose is to show how much the rate matters, and why an acceleration is more informative than a level.

There is also a link to paper ageing. In a 2022 regression study of transformer oil parameters, furfural — the primary marker of cellulose degradation — had the largest single effect on IFT among the measured parameters, with a 1 ppm increase corresponding to a fall of about 0.64 mN/m in the fitted model. IFT therefore carries a signal from the solid insulation, not only from the oil.

Neither of these relationships should be used in reverse. One cannot read a furfural value from an IFT result, and a projection of years-to-limit is only valid while the mechanism stays the same. Their value is in deciding when an acceleration deserves a second sample and a wider test panel.

7.5 Repeatability: what counts as a real change

IEC 62961 reports that two results from the same operator may differ by up to 5 % of the value. At 40 mN/m that is 2 mN/m, which is the same order as the expanded uncertainty in Table 3 and the same order as two years of ageing in a healthy oil.

Three rules follow for anyone setting alarms. Do not alarm on a single result that differs by less than about 2 mN/m from the previous one. Do alarm on a fall of 5 mN/m or more between consecutive samples, whatever the absolute value. And when a result sits close to a band boundary, re-run the sample before changing the maintenance decision — a boundary crossing driven by 1.5 mN/m of noise is a paperwork event, not an engineering one.

7.6 A fleet review: worked example

The dataset below is **synthetic**. It is constructed to show how the bands, the ratio and the discordance rules combine into decisions on a mixed fleet; the values are not measurements of real units.

Unit	Fluid	IFT (mN/m)	TAN (mg KOH/g)	IFT / TAN	Band	Action
T-01	Mineral, inhibited	41	0.02	2050	Good	Routine
T-02	Mineral, inhibited	30	0.03	1000	Good	Routine; watch trend
T-03	Mineral, uninhibited	27	0.04	675	Good	Routine
T-04	Mineral, inhibited	24	0.05	480	Fair	Investigate; add DDF
T-05	Mineral, uninhibited	19	0.08	238	Poor	Reclaim; re-inhibit after
T-06	Synthetic ester	18	0.05	360	Fair	Monitor; ester band applies
T-07	Mineral, inhibited	15	0.02	750	Poor	Suspect contamination, not ageing

Table 6 — Illustrative fleet review. Bands are applied per fluid type; the ratio is computed for mineral oils only and read against the CIGRE criterion of 300.

Four of the seven rows are routine. T-04 is the interesting middle case: still inside its band, but one step from the steep part of the sludge curve — the right response is more information, not action. T-05 crosses both criteria at once (Poor band, ratio below 300) and is the only row where reclamation is clearly indicated. T-06 shows the ester band doing its job: at 18 mN/m a mineral oil would be called Poor, an ester is Fair. T-07 is the discordance case — a Poor result with an acidity barely above detection, which points to a contaminant and to a sampling investigation rather than to oxidation.

8 Three interpretation case studies

8.1 The unit that looked fine until the slope was plotted

A 132 kV transformer, twelve years in service, inhibited mineral oil. The annual results read 41, 39, 37, 36, 34, 31, 29, 27, 26 mN/m — every one of them inside the Good band until the last, and every one signed off as normal.

Plotted against time, the decline is about 1.9 mN/m per year, above the reported 0.5–1.5 range but not dramatically so; what makes it worth investigating is that it is steady rather than decelerating, and that acidity has moved from 0.01 to 0.04 over the same period. A steady, near-linear fall with slowly rising acidity is the signature of inhibitor depletion: the oil is oxidizing at a rate its additive package no longer suppresses.

The action is not a reclamation yet — 26 mN/m is comfortably in the Good band. It is to measure the inhibitor content, confirm the depletion, and plan re-inhibition before the oil reaches the steep part of the curve, because re-inhibition slows the decline but does not restore the IFT that has already been lost.

8.2 The ester that was condemned by the wrong table

A distribution transformer filled with natural ester reports 21 mN/m at its first annual sample. The utility’s internal procedure, written for mineral oil, treats anything below 25 mN/m as a trigger for investigation and anything below 20 as requiring reclamation. On that basis the fluid is one millinewton from a reclamation.

Under IEC 62975:2021 the Good boundary for natural ester is 20 mN/m, so 21 is Good — the lower absolute value reflects the fluid, not its condition. The correct response is to record the baseline and start a trend, with the ester-specific bands attached to the asset. The cost avoided is a reclamation of healthy fluid; the risk avoided is the more serious one, of a reclamation that strips the fluid’s own additives and leaves it worse.

The general rule: the band belongs to the fluid, not to the transformer, and a fluid change requires a new baseline. Any unit that has been topped up, reclaimed or converted needs its trend restarted with a documented note.

8.3 Low IFT with almost no acidity

An oil reports 15 mN/m and an acid number of 0.02 mg KOH/g. The band says Poor and the natural reflex is to schedule reclamation. The discordance says something else: oxidation produces acids, so a strongly depressed IFT with no acidity is unlikely to be ageing.

The usual candidates are external and all polar: residues of cleaning solvent, plasticiser or adhesive from a gasket, silicone grease from a sampling point, or carry-over from a previous fluid. The investigative sequence is cheap and fast — repeat the measurement on a fresh sample from a different valve, check the sample bottle and the valve for grease, look at the infrared spectrum for silicone or ester carbonyl bands, and review recent maintenance.

Only when contamination is excluded does the result become a statement about the oil. Reclaiming on a contaminated sample treats the symptom and leaves the source in the transformer.

9 Pitfalls and troubleshooting

Symptom	Probable cause	Corrective action
Every result in the session is low, including the water blank	Contaminated water or a contaminated ring	Discard the water, flame-anneal the ring, re-run the blank
Scatter between operators above 3 mN/m	Ring handling, interface placement, raising speed	Standardise the sequence; annual reproducibility test
Result drops sharply after a sampling change	Grease, solvent or bottle residue	Resample from a different valve in a new bottle
New oil reads well below 40 mN/m	Wrong fluid identification, or a dirty reference	Check the certificate of analysis and the fluid type against the bands
Low IFT with normal acidity	External polar contamination, not oxidation	Contamination screen: FTIR, valve and bottle inspection, resample
A step change appears in a long trend	Laboratory changed method or equilibration time	Record method edition; re-baseline with parallel samples
Ester fluid flagged Poor at a normal value	Mineral-oil bands applied to an ester	Apply IEC 61203 or IEC 62975 bands to that asset
Duplicates differ by more than 5 %	Ring not annealed; phases at different temperatures	Re-anneal, equalise both phases, repeat in triplicate

Table 7 — Diagnostic table. The first two rows account for most of the between-laboratory disagreement on the same sample.

10 Specifications, validation and accreditation

10.1 Setting an alarm that survives an audit

An alarm threshold is a decision rule, and it needs three components to be defensible: the band from the correct standard for the fluid, a minimum change that exceeds the measurement uncertainty, and a defined action for each level. The bands in Table 4 supply the first. The expanded uncertainty of about 1.9 mN/m supplies the second — a change of 2 mN/m is inside the noise, 5 mN/m is outside it. The third is a matter of maintenance policy and should be written down before the first alarm occurs, not after.

10.2 Validating the method in your laboratory

For an accredited laboratory the validation package normally contains accuracy against a certified reference or a proficiency-testing sample, repeatability and reproducibility, robustness against the variables that matter here (equilibration time, temperature, water quality, ring batch), and evidence that the correction is implemented correctly.

Two of those deserve emphasis for this method. **Robustness against equilibration time** is easy to demonstrate and frequently skipped: measure the same oil at 60 s and at 180 s and record the difference. If it is larger than the band width, the laboratory cannot mix protocols across a fleet. **Ring-to-**

ring reproducibility matters because rings are replaced; two certified rings should agree within the expanded uncertainty on the same oil, and the check takes an afternoon.

10.3 Proficiency testing and control charts

Participation in a proficiency-testing scheme for insulating-liquid IFT is the most direct evidence of competence, because the method's failure modes are preparation failures that a round robin exposes. Between rounds, a control chart on the retained reference oil — one measurement per session, plotted against its established value — detects drift in the ring, the water supply or the operator before a customer sample is affected.

10.4 What the result does and does not establish

An IFT result characterises the polar chemistry of the liquid at the interface. It does not measure moisture, breakdown voltage, dissipation factor, dissolved gases or the condition of the paper, and it does not locate a fault. In a maintenance decision it is one input, and its particular value is timing: it is usually the first of the chemical indicators to move.

For regulatory or contractual purposes, quote the result with its method, its edition and its temperature. A number without those attributes cannot be compared with a limit, and a limit without the fluid type cannot be applied.

11 Reporting checklist

- **Result** in mN/m at the measured temperature, to 0.1 mN/m.
- **Method and edition** — ASTM D971-20 or IEC 62961:2018 — and the equilibration time used.
- **Fluid type** — mineral inhibited, mineral uninhibited, synthetic ester, natural ester — with the band applied and its source standard.
- **Water blank** for the session, in mN/m, against the 70–74 mN/m acceptance range.
- **Ring identifier** and the date of its last verification; whether it was flame-annealed before the measurement.
- **Temperature** of both phases at measurement, and the sampling temperature if recorded.
- **Replicates** and the statistic reported (median of three is the common convention).
- **Sample identity** — unit, compartment, sampling date, bottle identifier — linked to the chain of custody.
- **Comparison with the previous result**, including the interval, so that the rate can be read without reopening the file.
- **Acidity and any companion tests** on the same sample, since the interpretation depends on the pair.

> **ONE-SENTENCE RULE FOR REVIEWERS**
>
> If a report gives an interfacial tension without the fluid type, the method edition and the water blank, the number cannot be placed in a band — and an unplaceable number is not a condition assessment.

12 References

[1] ASTM D971-20. *Standard Test Method for Interfacial Tension of Oil Against Water by the Ring Method.* ASTM International.

[2] IEC 62961:2018. *Insulating liquids — Determination of interfacial tension — Ring method.* International Electrotechnical Commission.

[3] IEC 60422:2024. *Mineral insulating oils in electrical equipment — Supervision and maintenance guidance.* International Electrotechnical Commission.

[4] IEC 60296:2020. *Fluids for electrotechnical applications — Mineral insulating oils for electrical equipment.* International Electrotechnical Commission.

[5] ASTM D3487. *Standard Specification for Mineral Insulating Oil Used in Electrical Apparatus.* ASTM International.

[6] IEC 61203:2025. *Synthetic esters — Guidance for maintenance and use in electrical equipment.* International Electrotechnical Commission.

[7] IEC 62975:2021. *Natural esters — Guidelines for maintenance and use in electrical equipment.* International Electrotechnical Commission.

[8] ASTM D923. *Standard Practices for Sampling Electrical Insulating Liquids.* ASTM International; ASTM D117, *Guide for Sampling, Test Methods and Specifications for Electrical Insulating Liquids.*

[9] Vinther J. *Interfacial tension: the most underrated test in your transformer oil programme.* TriboTech ApS technical guide, 2026. Secondary source for the IEC 60422/61203/62975 limits, the AIEE sludge table, the decline-rate range and the IEC 62961 repeatability statement.

[10] Gulf Star Laboratory. *Interfacial tension (IFT)* service note. Secondary source for the ASTM D3487 minimum and the 32/28 mN/m assessment criteria attributed to SDMyers.

[11] Saeid S, Zeinoddini-Meymand H, Kamel S, Khan B. Interaction of transformer oil parameters on each other and on transformer health index using curve estimation regression method. *International Transactions on Electrical Energy Systems* 2022. doi:10.1155/2022/7548533

[12] CIGRE TB 413 (reclamation of insulating fluids) and TB 962, cited for the oxidation index criterion of IFT/acidity below 300.

Appendix A Symbols and constants

Symbol	Meaning	Value / unit
γ	Interfacial tension, oil against water	mN/m (= mJ/m²)
F	Maximum force before lamella detachment	mN
R	Mean radius of the ring	mm
f	Harkins–Jordan correction factor	dimensionless, 0.9–1.0 typical
ρ_o, ρ_v	Density of oil and of water	g/mL
	Typical new mineral oil	40–50 mN/m
	Reference temperature window	18–25 °C
	Water surface tension acceptance	70–74 mN/m
	Expanded uncertainty of a result	≈ 1.9 mN/m (k = 2)

Table A1 — Symbols and working values used throughout this note.

Appendix B The standards landscape

Six documents are routinely confused in tenders and laboratory reports. The table below separates them by function: what a fluid must be, how it is measured, and how a result in service is classified.

Document	Function	What it gives you
IEC 60296	Specification, new mineral oil	Required properties, inhibitor content classes
ASTM D3487	Specification, new mineral oil	Acceptance limits including IFT ≥ 40 mN/m
ASTM D971	Test method	Ring method, 60 s equilibration
IEC 62961	Test method	Ring method, 180 ± 30 s equilibration
IEC 60422	Maintenance guidance, mineral oil	Good/Fair/Poor bands; test groups 1 and 2
IEC 61203 / 62975	Maintenance guidance, esters	Fluid-specific IFT bands
ASTM D923 / D117	Sampling and testing guide	How to take and handle the sample
IEEE C57.166	Acceptance and maintenance guide	Supersedes C57.106 and C57.147

Table B1 — Which document answers which question. A specification limit, a method and a condition band are three different things and cannot be substituted for one another.

— End of document —