TECHNICAL APPLICATION NOTE

Contact Angle Measurement in Food Packaging

Wettability and surface energy as release parameters for printing, lamination, sealing, anti-fog performance and food-contact compliance

A flexible pack is a stack of interfaces that must each be won: ink on film, adhesive on film, film on food, and condensate on the inside of a lid. Contact angle turns each of those interfaces into a number in seconds, on the line, without destroying the sample. This note covers the physics, the logic for choosing a method, a protocol written for films, and five datasets that show how the measurement behaves in production: corona dose, seal strength, adhesion at equal dyne level, treatment ageing and process capability.

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Data provenance: Sections 7.2, 7.3, 7.4 and 7.5 reproduce values published in the peer-reviewed literature and in an equipment manufacturer's technical paper, cited in place. Section 7.6 gives engineering targets, not measured values. Section 7.7 is a synthetic dataset built to demonstrate a capability study and is labelled as such.

1 Summary for decision-makers

Food packaging is where surface science meets a printing press at 300 m/min. A polyolefin film leaves the extruder at 29–32 mN/m; a solvent-based ink needs 40–42 mN/m to wet it, a water-based ink 46–48, a laminating adhesive 46–56. The gap between what the polymer offers and what the process demands is closed by a corona or plasma treater — and the contact angle is the cheapest way to prove that the gap has actually been closed, on this roll, today.

The measurement also has hard limits, and the data in Section 7 shows them clearly. Contact angle tells you whether a surface is energetically ready for a liquid. It does not tell you whether the bond will hold, whether the seal will peel, or whether the pack complies with food-contact law. Used as a process control it is excellent; used as a substitute for adhesion or seal testing it is misleading.

Six conclusions that shape a specification

- **The treatment gap is the specification.** Untreated PP at 29 mN/m and untreated PE at 31–32 are two to three times further from the process requirement than the measurement uncertainty. That is why the method works: the signal is enormous compared with the noise.
- **Contact angle is continuous, dyne pens are discrete.** A pen gives the highest liquid that wets within a dwell time — a pass/fail in steps of 1–2 mN/m, dependent on operator and ink age. A goniometer gives a number with an uncertainty you can calculate. Use the pen for the supplier certificate, the angle for trending and capability.
- **Equal dyne level does not mean equal adhesion.** On BOPP treated to the same 40 dyne by four methods, peel strength ranged from 321 to 369 N/m against one tape — a 15 % spread with no difference in the pen result (Section 7.4).
- **The window is two-sided.** At 300 W the water angle on OPP rises again (53.1° → 56.8°) and seal strength falls: BOPP loses 33 % at the highest power. Over-treatment is a real failure mode, not a theoretical one (Sections 7.2 and 7.3).
- **Surface energy does not predict seal strength.** Across six films and three treatment levels the correlation between surface free energy and seal strength was r = −0.19 — statistically indistinguishable from zero. Sealing is a rheological process; keep the seal test.
- **Contact angle is not a compliance test.** It supports process control and troubleshooting; migration and food-contact compliance are demonstrated by the tests defined in Regulation (EU) No 10/2011, not by a wetting measurement.

> **RULE OF THUMB FOR A PRINTING LINE**
>
> Specify the treated side as a water contact angle at a fixed time after treatment: typically 55–65° for a surface that will accept a solvent-based ink, and 45–55° for water-based inks and solventless laminating adhesives. Treat the specification as two-sided — an angle below about 35° usually means over-treatment and a risk to seal strength. Always state the age of the sample, because the number moves (Section 7.5).

2 The four interfaces of a food pack

2.1 What has to be wetted, and by what

Every flexible pack presents at least four interfaces, and each one is decided by the balance between the surface energy of the substrate and the surface tension of the liquid that must spread on it.

1. **Ink on film.** A printing ink wets and anchors only if the substrate surface energy exceeds the ink surface tension, with a margin. The literature convention is a margin of 2–10 mN/m; below 2 the ink beads or dewets, above roughly 10 there is no further gain and the extra treatment only adds over-treatment risk [1].

2. **Adhesive on film.** Solvent-based, solventless and water-based laminating adhesives each have their own surface tension, and each needs a different treatment level. Solventless polyurethane adhesives are the most demanding in practice because they are applied hot and thin, with little time to wet out.
3. **Food on film.** Product residue, fat release and clean emptying depend on the contact angle between the food and the sealant layer. A fatty sauce at 30–33 mN/m wets almost anything; a aqueous product does not. This is the interface that decides whether a yoghurt pot empties cleanly.
4. **Condensate on film.** In a chilled display, water condenses on the inside of the lid. If the angle is high, it forms discrete droplets that scatter light and obscure the product; if it is low and the hysteresis is small, it sheets into a transparent film. This is the whole engineering basis of anti-fog packaging (Section 7.6).

2.2 Where the measurement earns its place

Application	Question answered	Metric normally specified
Flexo, gravure, digital and UV printing	Will the ink wet and anchor on this roll?	Water angle on the treated side; SFE vs ink tension
Lamination (solvent, solventless, water-based)	Is the adhesive wetting out before it cures?	SFE, water angle, peel strength
Barrier and functional coatings (SiOx, AlOx, PVOH, acrylic)	Will the coating lay down uniformly?	SFE before coating; angle after each pass
Heat sealing	Is the seal layer clean, or over-oxidised?	Water angle plus seal strength
Anti-fog lidding and produce films	Will condensate sheet rather than bead?	Receding angle; captive bubble; hot-fog test
Paper and board, grease barriers	Will the coating hold out, and will fat penetrate?	Washburn or angle; Kit test for grease
Recycled-content and mono-material films	Is the incoming lot consistent?	Angle trend by lot, with capability index
Rigid containers, caps and closures	Will the label or print adhere after filling?	Angle on the moulded surface, away from gates

Table 1 — Where contact angle is used as a decision parameter in packaging. The common thread is a liquid that must spread on a polymer whose surface energy is too low without treatment.

2.3 What the number does not measure

Four confusions recur in supplier discussions and are worth stating explicitly.

- **It is not a barrier measurement.** Oxygen and water-vapour transmission depend on the whole structure and on crystallinity; a contact angle says nothing about either.
- **It is not an adhesion test.** Adhesion depends on wetting, on interfacial chemistry, on the cured adhesive’s cohesion and on the mechanical interlocking at the interface. Section 7.4 shows four surfaces that read the same dyne level and deliver different peel strengths.
- **It is not a seal test.** Seal strength is a rheological property of the seal layer at temperature and pressure. Across the dataset in Section 7.3, surface free energy and seal strength were uncorrelated.
- **It is not a compliance test.** Food-contact compliance is a matter of composition, migration and good manufacturing practice (Section 10.4). A wettability result can support a process validation; it cannot demonstrate compliance with a migration limit.

3 Physical basis: from surface energy to wetting envelopes

3.1 The Young balance, applied to a film

For a drop at equilibrium on an ideal solid, the three interfacial tensions balance along the contact line:

$$\gamma_{sv} = \gamma_{sl} + \gamma_{lv} \cdot \cos\theta_Y$$

with γ the solid–vapour, solid–liquid and liquid–vapour tensions and θ_Y the ideal contact angle. Two practical consequences follow for packaging. First, the angle is a property of the system, so the same film measured with water, with an ink and with a food simulant gives three different numbers — and the one that matters is the one measured with the liquid the process actually uses. Second, a polymer film is not an ideal solid: it carries slip agents, antioxidants, oligomers and low-molecular-weight fragments that migrate to the surface during extrusion, storage and winding. What the drop sees is not the polymer, but whatever has bloomed onto it.

3.2 Why films behave differently from machined parts

A BOPP film is smoother than most machined surfaces (Ra typically a few nanometres), so the roughness amplification described by Wenzel is small. What dominates instead is chemical heterogeneity at the scale of the additive bloom: patches of erucamide or stearamide slip agent, residues of antistatic, and oxidised fragments left by the treater. The result is a surface with a wide hysteresis window and a contact angle that drifts upward over the first days after treatment as low-energy species re-cover the oxidised layer.

This is the single most important difference from other industries: in packaging, **the surface is not stable**. A measurement without a timestamp is not a measurement.

3.3 Hysteresis, and which angle you actually need

Advancing and receding angles bracket the states a surface visits in use. In packaging the choice is dictated by the process:

- **Advancing** for printing and lamination, because the ink or adhesive front advances over dry film and must not be pinned by low-energy patches.
- **Receding** for anti-fog and product release, because the question is whether a liquid retracts and sheets, or stays pinned as a droplet. A surface can have a low static angle and a high receding angle, and it will still fog.
- **Hysteresis** as a proxy for surface heterogeneity and additive bloom: a film with Δθ above about 25° is chemically patchy, whatever its static angle says.

3.4 Surface free energy and its components

Contact angles of two or more probe liquids are combined to split the surface energy into dispersive and polar parts. The Owens–Wendt–Rabel–Kaelble (OWRK) model is the industrial default and the basis of ISO 19403-2:

$$\gamma_l\,(1 + \cos\theta) = 2\,[\,(\gamma_s^{d} \cdot \gamma_l^{d})^{\wedge}½ + (\gamma_s^{p} \cdot \gamma_l^{p})^{\wedge}½\,]$$

Water (21.8 dispersive / 51.0 polar mN/m) and diiodomethane (50.8 / 0.0) are the conventional pair. The split matters more in packaging than the total, because a corona treatment raises the polar component almost exclusively: it converts a 29 mN/m polyolefin into a 45–52 mN/m surface whose dispersive term is nearly unchanged. That is the signature of oxidation, and it is what distinguishes a genuinely treated surface from one that has merely been contaminated with a surfactant.

The Zisman critical surface tension — obtained from the intercept of a cos θ versus γ_l plot for a homologous liquid series — is the other common currency and is codified in ASTM D7541. It is a single number and easier to communicate, but it is not the same quantity as the OWRK total and the two should not be quoted interchangeably.

3.5 The wetting envelope: the picture that prevents arguments

Plotting liquids in the plane of dispersive versus polar surface tension, and drawing the locus on which the contact angle is zero for a given solid, produces a wetting envelope (Figure 1). Everything inside the curve wets; everything outside beads. The practical value is that it converts a vague requirement (“the

film must be printable") into a geometric one: the ink's coordinates must lie inside the film's envelope, with margin.

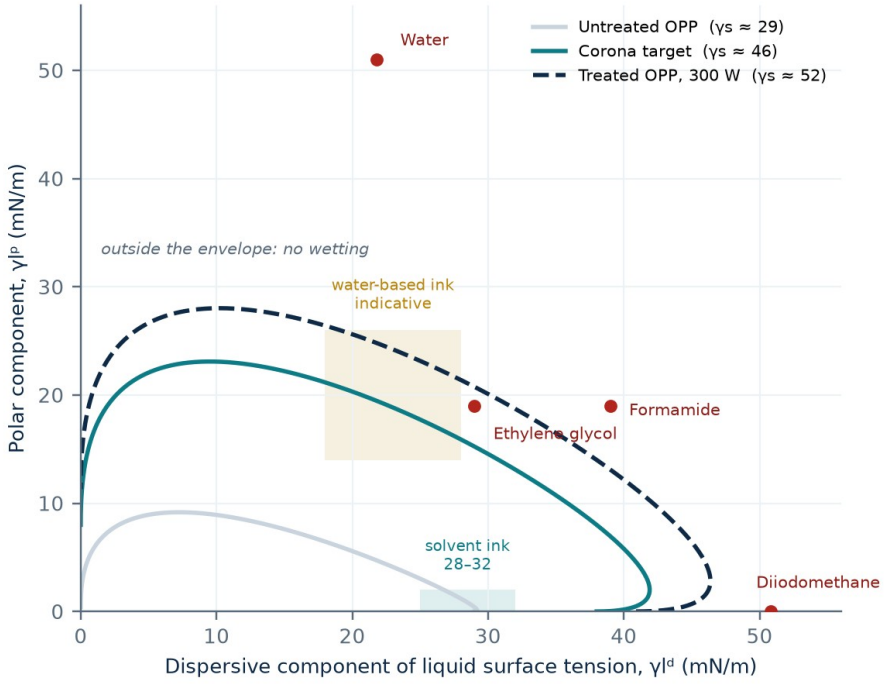


Figure 1 — Wetting envelopes calculated from the OWRK relation for three substrate states, with four characterised probe liquids and indicative bands for solvent-based and water-based inks. Water lies far outside all three envelopes: an untreated or corona-treated polyolefin is hydrophobic, and the treatments discussed here do not change that — they only move the envelope far enough to enclose the ink.

Three observations follow from the geometry, and they explain most day-to-day confusion on a printing line.

- The envelope of an untreated polyolefin encloses almost no real liquid: its total energy (29–32 mN/m) is below the surface tension of every common ink and adhesive.
- Corona treatment expands the envelope mainly upward, into the polar direction — which is why it helps water-based inks and polar adhesives far more than it helps purely dispersive solvents.
- A liquid can sit inside the envelope of a treated film and still fail to anchor, because wetting is necessary but not sufficient for adhesion. That distinction is the subject of Section 7.4.

3.6 Why a dyne level and a contact angle are not the same number

A dyne pen reports the surface tension of the highest test liquid that wets the film within a defined dwell time. It is a threshold measurement, quantised by the liquids in the set (typically 2 mN/m steps), and it carries an implicit assumption about the surface's polarity. A goniometer reports an angle, from which a surface free energy is calculated with an explicit model.

The two agree in ranking but not in value, and the discrepancy is systematic rather than random: a surface of 40 mN/m reads 75° with water if only 15 % of its energy is polar, and 67° if 30 % is polar (Appendix B). Any conversion factor between "dyne" and "degrees" is therefore valid only for one family of surfaces. This is why the two methods should be correlated locally, on your own substrates and inks, and never converted with a constant.

4 Measurement methods, including dyne pens

Six methods cover the practical range. The first two are the ones a converter will actually use; the rest solve specific problems.

4.1 Sessile drop on film

A 2–5 µL drop is deposited on the treated side and imaged from the side; the angle is extracted from a profile fit. It is fast, non-destructive and gives a continuous number, which makes it the right tool for trending, capability studies and troubleshooting. On thin film the practical difficulties are flatness (film curls), static (the drop is repelled or attracted), and knowing which side was treated.

Capture at a fixed time — two seconds is a common convention — and state it. On a treated film the angle can fall several degrees in the first ten seconds as the surface reorients under the drop, and rise over days as additives bloom.

4.2 Dyne pens and wetting-tension solutions

A series of liquids of known surface tension is drawn across the film with a pen or swab; the highest value that remains a continuous film for the specified dwell time (commonly about two seconds) is reported as the wetting tension. The method is codified for polyolefin films in ASTM D2578 and ISO 8296 and remains the contractual language of the industry for good reasons: it is portable, cheap, and directly tied to the printing process.

Its weaknesses are equally clear. Resolution is limited by the liquid set; the result depends on dwell time, stroke pressure and operator; the pens age and become contaminated; and the answer is a threshold, not a measurement, so it cannot detect a drift of two or three mN/m that precedes a print failure. Used alone it tells you whether the film passes today, not whether the process is in control.

4.3 Wilhelmy plate and film tensiometry

A strip of film is suspended from a microbalance and immersed and withdrawn through the liquid; the wetting force gives cos θ through $F = \gamma_{lv} \cdot p \cdot \cos\theta$, with p the wetted perimeter. It gives advancing and receding angles in one cycle and works on curved or narrow samples. Two cautions apply to single-side-treated film: the untreated face must be masked or the sample floated so that only the treated side is wetted, and the buoyancy correction must use the true cross-section.

4.4 Captive bubble

The sample is immersed and a bubble is pressed against its underside; the angle is read through the liquid. For anti-fog work this is the only configuration that resembles the service condition, because the condensate is on the inside of a pack in a humid atmosphere, not a drop in laboratory air. It also removes the evaporation problem entirely.

4.5 Washburn and capillary rise

For paper, board, coatings and powders, the liquid is drawn into a strip or a packed bed and the mass uptake is recorded against time. The Washburn equation converts the slope into an effective contact angle. It is the standard route for paper and board because a sessile drop on a porous substrate is absorbed before it can be measured.

4.6 Portable and in-line instruments

Handheld goniometers (ASTM D8597) and in-line systems that measure at the treater exit are increasingly common. They trade some optical quality for proximity to the process, which is usually the right trade: a measurement taken 30 seconds after treatment, on the machine, is worth more than a perfect measurement taken a week later in a laboratory.

Method	Output	Resolution	Suits packaging when…	Main limitation
Sessile drop	Static angle, continuous	±1–3°	Trending, capability, troubleshooting	Film curl, static, additive bloom
Dyne pen / wetting tension	Highest wetting liquid	1–2 mN/m steps	Supplier certificates, quick line checks	Operator-dependent; no drift detection
Wilhelmy film	θ_a, θ_r from force	±2°	Narrow or curved samples; hysteresis	Single-side masking; buoyancy
Captive bubble	Angle through liquid	±2°	Anti-fog, immersed service conditions	Immersion cell required
Washburn	Effective angle	±5°	Paper, board, coatings, powders	Packing-dependent; comparative
Portable / in-line	Static angle	±2–4°	At the treater, on the machine	Vibration, web movement

Table 2 — Method selection for packaging substrates. The dyne pen and the goniometer are complementary: the pen answers “does it pass”, the angle answers “is it drifting”.

5 Instrumentation and uncertainty on thin films

5.1 The four things that go wrong on film

The optical chain of a goniometer is the same whether the sample is a titanium implant or a 12 µm BOPP film. What changes is the sample. Four artefacts account for most of the bad data produced on packaging substrates.

- **Curl.** A film that is not flat changes the apparent baseline. Flatten the sample on a clean glass slide under its own weight, or hold it flat with a vacuum plate; never press it down with tape, because the adhesive migrates.
- **Static.** Corona-treated film holds charge for minutes to hours. The drop is attracted or repelled, and small drops can jump. Use an ionising bar or a grounded antistatic brush for two seconds before dosing, and verify by measuring the same spot twice.
- **Wrong side.** Single-side-treated film is common, and the untreated face reads 90–105° on a polyolefin. Confirm the side with a dyne pen or a quick water-break test before running a series, and record which face was measured.
- **Additive bloom.** Slip agents and antifog additives migrate to the surface over hours to days. A film measured on the day of extrusion and again after a week can differ by 10–20°. State the age of the sample in every report.

5.2 Calibration and verification

Verify daily with a reference surface and two liquids. A polymer reference is more relevant than an inorganic one here: a clean, freshly corona-treated PET film characterised in-house, or a certified polymer reference if one is available. Note the limitation of the reference — a check at 100° does not prove accuracy at 50°, and the packaging window sits at 45–65°.

5.3 Environment and drop size

Work at 23 ± 2 °C and 50 ± 10 % RH, and condition the film for at least two hours in the same room. Evaporation from a 2 µL drop is fast; capture the angle at a fixed time, preferably two seconds, and keep the enclosure closed. On film the drop should be 1–4 µL: large enough for a stable baseline, small enough that gravity and the film’s compliance do not distort the profile.

5.4 Uncertainty budget

The budget below is representative of a well-run laboratory measuring a 60° water angle on a treated film with a 2 µL drop and ten replicates. It is an example of the arithmetic, not a claim about a specific instrument.

Contribution	Type	Standard uncertainty (°)	How it is controlled
Repeatability (n = 10)	A	1.10	Median of 10 drops, 3 web positions
Drop volume 1 µL vs 4 µL	B	0.70	Fixed volume; volume-independence check
Baseline and fit model	B	0.60	Manual baseline below 30°; one fit model
Film flatness and curl	B	0.40	Vacuum plate; reject visibly curled samples
Temperature and humidity	B	0.50	Conditioned room; record T and RH
Operator and placement	B	0.70	Training; annual Gage R&R
Combined standard uncertainty uc		1.72	Root sum of squares
Expanded uncertainty U (k = 2)		3.4	95 % coverage

Table 3 — Example uncertainty budget for film measurement. The film-specific terms (flatness, static-driven placement) are the ones that separate a packaging laboratory from a general surface-science one.

A single drop therefore carries about ±3.4° at 95 % confidence and a mean of ten about ±1.1°. Since the useful process window for printing sits between roughly 45° and 65°, the window is 6σ wide: adequate, but only if the ten-drop protocol is followed.

5.5 Sampling across the web

Treatment varies across the web width, and the edges are usually the problem. Sample at three positions — drive side, centre, operator side — and at least two positions along the machine direction, preferably from different rolls. Report the median and the interquartile range: a mean hides the edge that will fail on the press.

6 A protocol for films

The following sequence transposes into an SOP for a converter’s laboratory or a film supplier’s quality department. The acceptance criteria are the ones that make a result defensible in a customer claim.

Step	Action	Parameter / acceptance criterion
1	Identify the treated side	Dyne pen or water-break test on a scrap piece; mark the face
2	Condition	23 ± 2 °C, 50 ± 10 % RH, 2 h minimum; record age since treatment
3	Neutralise static	Ionising bar or grounded brush, 2 s; verify by repeat measurement
4	Mount flat	Clean glass slide or vacuum plate; no adhesive tape on the test face
5	Verify the probe liquid	Water 72.8 ± 0.5 mN/m at 20 °C; discard after 7 days open
6	Dose	2 µL at 1 µL/s; needle withdrawn before capture
7	Capture and fit	At t = 2.0 s; Young–Laplace fit; manual baseline below 30°
8	Replicate	5 drops × 3 web positions; median and IQR; discard the first drop
9	Record	Instrument ID, calibration, liquid lot, T, RH, side, sample age, operator

Table 4 — Minimum protocol for a defensible film measurement. Steps 1, 3 and 9 are packaging-specific and are the ones most often omitted.

Two points deserve emphasis. The first is that the **age of the sample** belongs in the result, not in a footnote: the same film reads 55° on the day of treatment and 70° three weeks later, and both numbers are correct. The second is that the **method must match the contract**. If the specification is written in

dyne, report dyne; if it is written in degrees, report degrees with the method statement. Converting one into the other after the fact is where most disputes begin.

7 Measurement data

Five datasets follow. The first four are published or manufacturer-published measurements and are cited in place; the fifth is a synthetic capability study, labelled as such. Together they cover the questions a packaging technologist actually asks: how far the substrate is from the process, what treatment does to the angle, what it does to the seal, whether the dyne number predicts adhesion, and how long the effect lasts.

7.1 The treatment gap: supply versus demand

The natural surface energy of commodity packaging polymers sits far below what any printing, coating or laminating process requires. The values below are the ones used in equipment specification for corona and plasma treaters [2].

Material or process	Surface energy (mN/m)	Comment
PP, untreated	29	Natural dyne level of the base resin
PE-LD, untreated	31	Natural dyne level
PE-HD, untreated	32	Natural dyne level
BOPP, untreated	32–33	Natural dyne level; the most commonly treated film
Printing, solvent-based ink	40–42	Requirement on the treated side
Printing, water-based ink	46–48	Higher because the ink itself is more polar
Coating (functional, barrier, heat-seal lacquer)	44–54	Range spans the coating chemistry
Lamination (adhesive wet-out)	46–56	Highest requirement; solventless systems at the top

Table 5 — Natural surface energies and process requirements for packaging films, after Vetaphone [2]. The gap between the supply rows and the demand rows is what the treater has to close, and it is typically 10–25 mN/m.

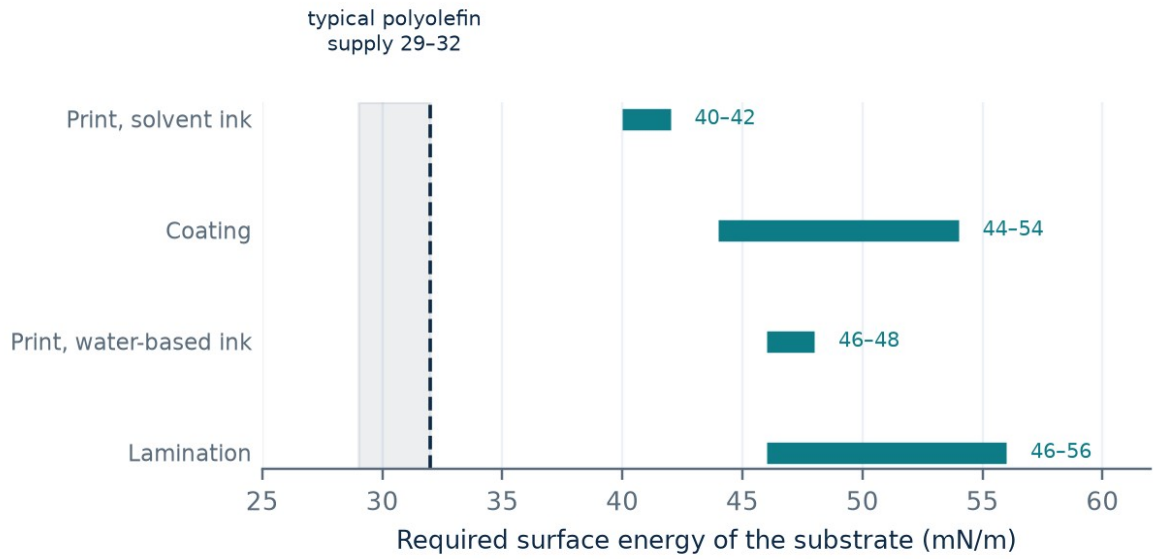


Figure 2 — The same data as a gap chart. No untreated polyolefin reaches even the least demanding process; the treater has to add between 8 and 24 mN/m depending on the application.

Two consequences follow for specification. First, because the gap is large compared with the measurement uncertainty, a treated-versus-untreated check is robust even with a dyne pen — this is why the pen survives in an industry that otherwise measures everything. Second, because the gap differs by

process, a single “treated” specification is meaningless: a film treated to 38 mN/m is adequate for some solvent inks, marginal for coatings, and unacceptable for solventless lamination.

7.2 What corona treatment actually does to the angle

Published data: six commercial packaging films treated on a laboratory corona unit at two power levels (100 W and 300 W, approximately 99 and 297 W·min/m²), with static water contact angle measured by drop-shape analysis (2 µL, 5 s after deposition, six replicates) and surface free energy calculated by OWRK from water and diiodomethane [1].

Film	Untreated	100 W	300 W
PE	93.9 ± 3.1°	62.0 ± 4.5°	55.7 ± 2.2°
OPP	100.7 ± 2.2°	53.1 ± 3.4°	56.8 ± 2.6°

Table 6 — Static water contact angle versus corona power, mean ± SD, n = 6, after Żołek-Tryznowska et al. [1]. The same study reports a minimum at 100 W followed by a rise at 300 W for the other four films (OPP2, BOPP, BOPP2 and PET).

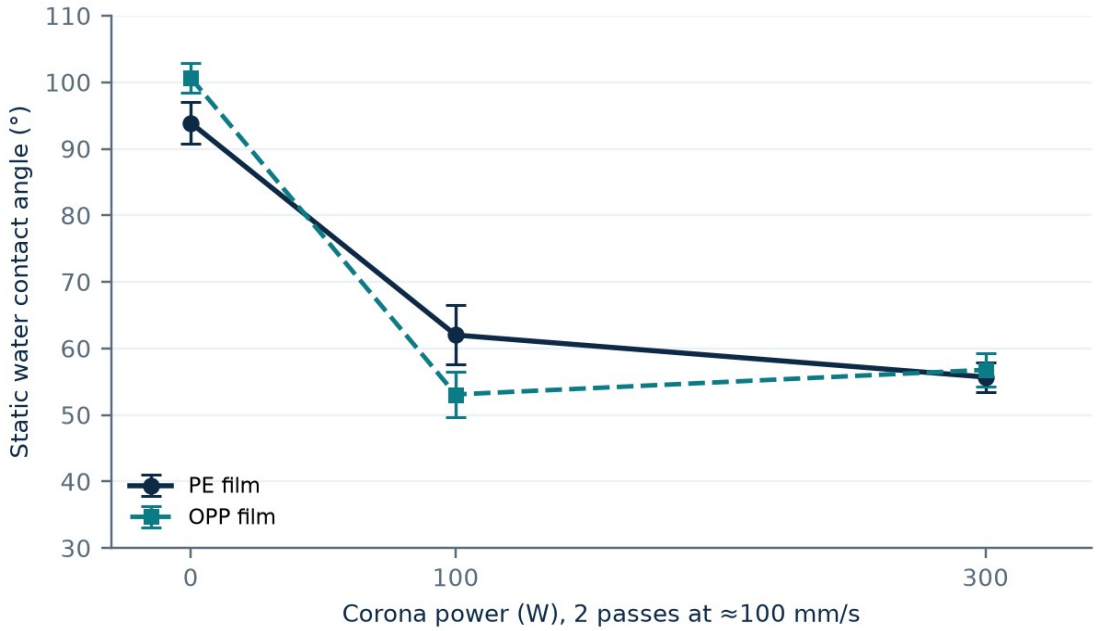


Figure 3 — The two behaviours visible in one plot. PE keeps improving up to 300 W, while OPP reaches its minimum at 100 W and then reverses — the signature of over-treatment.

The PE curve is the textbook result: 94° falling to 56° as polar groups are incorporated. The OPP curve is the more instructive one. It falls to 53° at 100 W, then rises to 57° at 300 W, and the authors attribute the reversal to surface degradation and crosslinking in the uppermost monolayer rather than to a loss of oxygen. Total surface free energy still rises — from about 29 mN/m untreated to more than 52 mN/m at 300 W — but the wetting behaviour no longer follows it, because the layer the drop touches has been mechanically and chemically altered rather than simply oxidised.

WHAT THIS MEANS FOR A SPECIFICATION

A one-sided specification (“angle below 65°”) cannot detect over-treatment, and over-treatment is the failure mode that damages seals. Write the window on both sides: for OPP-based films, 45–65° measured at 2 s is a defensible starting window, with 40° as the lower alarm.

The same dataset shows why “more corona is better” is a dangerous operating habit: the treater can be turned up until the angle stops improving and the seal is already compromised. The seal test, not the angle, is the arbiter.

7.3 The seal-strength trade-off

The same study measured seal strength after heat sealing the treated faces together (120 °C for PE, 130 °C for PP, 5 s, 2 mm bar) and T-peel testing after seven days [1]. The result is the most important caution in this note.

Film	Untreated (N/mm)	100 W (N/mm)	300 W (N/mm)	Direction
PE	0.549 ± 0.080	0.609 ± 0.073	0.513 ± 0.034	Up at 100 W, down at 300 W
BOPP	0.231 ± 0.068	0.267 ± 0.041	0.202 ± 0.034	Up at 100 W, down at 300 W

Table 7 — Seal strength versus corona power, mean ± SD, after Żołek-Tryznowska et al. [1]. Polypropylene-based films other than this grade lost strength at every treatment level: the study reports −29 % and −23 % for two OPP grades at 100 W, and −33 % for the most sensitive BOPP grade at 300 W.

Three findings matter. First, the effect is **material-dependent**: PE and one BOPP grade gain strength at the lower power, while the other polypropylene films lose it at every level. Second, the effect is **non-monotonic**, so an optimum exists and can be found. Third, and most important for anyone hoping to use wettability as a proxy: across the six films and three treatment levels, the correlation between surface free energy and seal strength was $r = -0.186$ (Pearson) and $\rho = 0.109$ (Spearman). Surface energy did not predict seal strength, and if anything the relationship ran slightly the wrong way.

The physical reason is that sealing is a rheological process. What matters is how the seal layer flows, wets and interdiffuses under heat and pressure — governed by molecular weight, comonomer content, the presence of a low-melting sealing layer, and the thickness and brittleness of any oxidised skin. A heavily oxidised surface is a barrier between two polymer melts, not a help to them. That is why the seal test cannot be replaced by a wetting measurement, and why an over-treated film can pass the dyne pen and fail the seal.

7.4 Equal dyne level, unequal adhesion

Manufacturer data: BOPP treated to the same 40 dyne/cm by four different methods, then peel tested with two tapes against an untreated control [2]. The dyne reading is identical in four of the five rows. The adhesion is not.

Treatment	Dyne level	Peel, Tesa 7445 (N/m)	Peel, 3M 610 (N/m)
Untreated	30	281	162
Corona	40	321	254
Plasma	40	369	284
Plasma, advanced gas 1	40	359	301
Plasma, advanced gas 2	40	358	292

Table 8 — Peel strength on BOPP at equal dyne level, after Vetaphone [2]. Tapes differ by a factor of 1.2–1.4 on the same surface, which is why peel results are only comparable within one tape and one test method.

The lesson is that a dyne level is a threshold, not a predictor. It tells you that a liquid of that surface tension will wet; it says nothing about the chemistry of the layer that will form the bond. Plasma in a controlled atmosphere deposits amine, amide and imide functionality that corona in air cannot, and those groups react with the adhesive or ink. Two surfaces can therefore wet identically and bond differently.

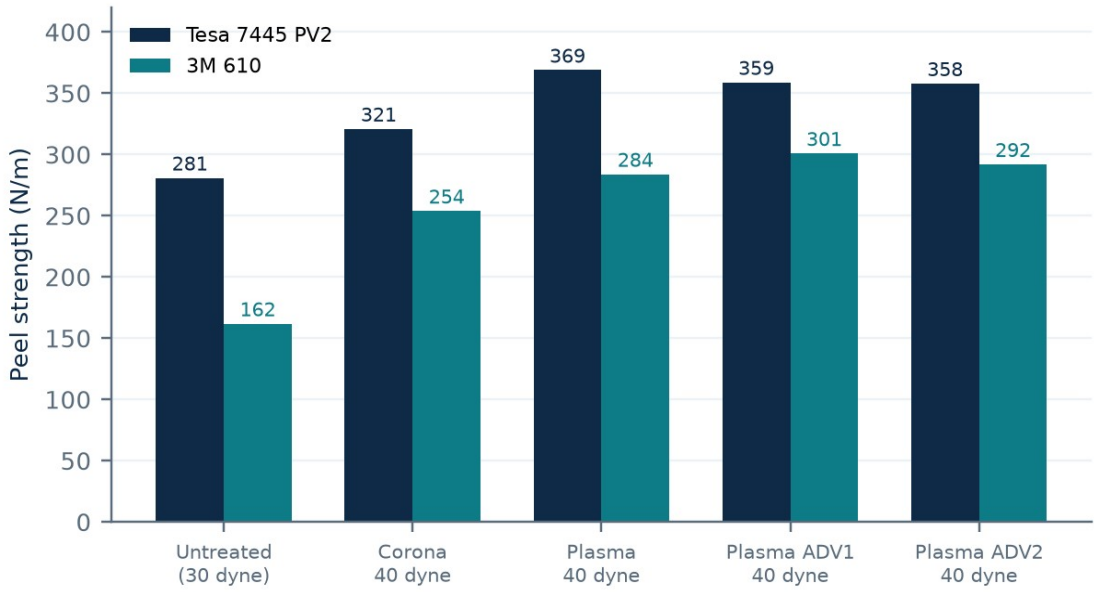


Figure 4 — The same data plotted. Between corona and plasma at an identical 40 dyne, peel rises by 15 % (Tesa) and 12 % (3M); between the two plasma recipes the two tapes rank the surfaces differently.

The same source reports a second, related effect: reaching 42 dyne on PE required twice the dose with plasma (20 W·min/m²) as with corona (10 W·min/m²), yet the plasma-treated film delivered higher peel (291–376 N/m against 265–323 N/m). Energy per square metre, not dyne level, is the process variable that should be logged.

7.5 How long the treatment lasts

Corona treatment decays. The mechanism is a combination of reorientation of polar groups away from the surface, migration of low-molecular-weight species from the bulk, and reaction of the radicals left by the discharge. Manufacturer data for BOPP illustrates the practical range [2].

Treatment	Initial (dyne/cm)	After storage (dyne/cm)	Behaviour
Corona	≈ 47	≈ 37	Falls quickly, then plateaus below the print threshold
Plasma, medium power	≈ 57	≈ 47	Falls, then stable for many months
Plasma, high power	≈ 60	≈ 60	Stable for more than a year in the reported case

Table 9 — Ageing of BOPP treatment, after Vetaphone [2]. The decay of a corona-treated surface can take it from comfortably printable to marginal within weeks.

The operational consequence is a shelf-life limit that must be written into the specification. Two practices make it manageable. Measure and record the angle at a defined age (commonly 24 h after treatment, once the initial reorientation has settled), and set a second, lower limit for the age at which the film will actually be printed. A film specified at 55–65° at 24 h and printed four weeks later needs a demonstrated value at four weeks, not an assumption.

For recycled content the decay is often faster and more variable, because the recyclate brings its own low-molecular-weight species and surface-active contaminants. Section 8.3 treats this case.

7.6 Anti-fog: targets rather than measurements

Anti-fog performance is the one application where the relevant angle is the **receding** angle, and where the target is set by appearance rather than by adhesion. When water condenses on a surface with a high

receding angle, the droplets pin and grow until they scatter light; when the receding angle is low, the condensate retracts and sheets into a continuous film that remains transparent.

The targets below are engineering rules derived from that mechanism, not values taken from a single published study. They should be validated on the finished pack with a hot-fog test: film suspended over a water bath at 60 °C, assessed at 20 cm for the time to first fog and for droplet size, at 4 °C and at 23 °C.

Property	Target	Why it matters
Static water angle	< 20°	Indicates a hydrophilic, high-energy surface
Receding angle	< 20° (ideally < 10°)	Governs whether condensate retracts or pins
Hysteresis	< 15°	Large hysteresis means droplets pin even at low static angle
Angle after 7 days at 23 °C	Within 5° of day 1	Allows for additive bloom; checks the additive is still available
Angle after 24 h at 4 °C	Still < 25°	Cold storage is the service condition for chilled retail
Hot-fog test	Clear film, no droplets > 1 mm at 60 s	Functional confirmation on the finished pack

Table 10 — Anti-fog design targets. These are engineering rules, not literature values; they must be confirmed with the hot-fog test on the actual pack and product.

Two practical notes. Anti-fog additives work by blooming to the surface, so the angle **improves** over the first days after extrusion and then degrades as the additive is consumed or washed away — measure at two ages, not one. And because the additive is a surfactant, it can interfere with printing and with seal strength if it reaches the outside face; the treated side and the anti-fog side are usually different faces, and confusing them is a common source of unexplained print defects.

7.7 Production capability: an illustrative lot study

The dataset in this section is **synthetic**. It demonstrates how contact angle data become a release decision for a printed film; the numbers are not measurements of any real product. Specification: 60° ± 10° on the treated side, measured at 2 s, n = 10 per lot, three web positions.

Lot	Mean (°)	SD (°)	Cpk	Decision	Comment
A	58.2	2.4	1.36	Release	Centred; normal production
B	61.9	3.1	0.87	Release, monitor	Drifting toward the upper limit
C	64.8	4.2	0.38	Investigate	High mean and high spread: treater or additive issue
D	52.1	3.8	0.69	Release, monitor	Low mean: approaching over-treatment
E	59.4	1.9	1.41	Release	Recovered after electrode cleaning

Table 11 — Illustrative capability study. Cpk = min(USL − mean, mean − LSL) / 3σ, with LSL 50° and USL 70°.

Lot D is the interesting one. Its mean is comfortably inside the specification, so a pass/fail check would release it — yet at 52° it is close to the over-treatment boundary where seal strength begins to suffer, and its spread of 3.8° suggests the treater is not stable. A capability index computed against a two-sided window catches this; a single-sided limit does not.

8 Three production case studies

8.1 Printed snack film: controlling a corona treater

A three-layer BOPP laminate is corona treated on the print side, printed flexo with a solvent-based ink, and examined for ink adhesion by tape test at the end of the line. The historical control is a dyne pen at the treater exit, read once per roll by the operator.

The failure that motivates a change is intermittent: one or two rolls per shift fail the tape test, always toward the drive side, and always on rolls that have been in storage for more than three weeks. A pen reading taken at the treater cannot see a decay that happens in the warehouse.

The fix is a two-point protocol. At the treater, the pen remains the operator's check. In the laboratory, a water angle is measured at 2 s on three web positions, on a sample retained from each roll, at day 1 and at the age of actual printing. The specification is written as 45–65° at day 1 and 50–70° at the age of use, with the edge positions required to be within 8° of the centre. The tape test is retained as the functional confirmation, run at the same frequency as before. Within a quarter the intermittent failures were traceable to two causes: an electrode that had drifted out of gap on the drive side, and a batch of film whose slip agent bloomed faster than the standard grade.

8.2 Anti-fog lidding for fresh produce

A PET/PE lidding film for tomato punnets carries an anti-fog masterbatch in the sealing layer. The customer complaint is condensation obscuring the fruit in chilled display, on packs that passed the supplier's incoming checks.

The incoming check is a static angle on the outside face — the wrong face, measured in the wrong condition. The relevant measurement is the receding angle on the inside face, immersed, after the film has been stored long enough for the additive to bloom. A captive-bubble measurement at 20 °C, after 7 days at 23 °C and after 24 h at 4 °C, separates good from bad lots where the static angle does not.

The corrective action has three parts: specify the inside face and the receding angle; add a hot-fog test on the finished pack as the functional gate; and control the masterbatch loading by lot, because the additive is consumed at the surface and a low loading passes on day 1 and fails on day 30. The static angle remains useful as a quick check, but only as a screen.

8.3 Mono-material PE laminate with recycled content

A mono-PE laminate for a dry-food pouch uses 30–50 % post-consumer recyclate in the core layer. Print adhesion and seal strength both become more variable, and the customer asks for a single incoming test that predicts both.

No single test does. What works is a small set: water angle on the treated print face (predicts ink wetting), seal strength on a laboratory sealer (predicts the seal), and a visual check for gels and contamination. The recyclate raises the angle variability because it carries surface-active residues and because its molecular weight distribution broadens the bloom behaviour; the angle trend by lot is therefore a useful early warning, while the seal test remains the release criterion.

The specification that emerges is asymmetric: an upper limit on the angle (printability) and a lower limit set by the seal result rather than by the angle, because the correlation between the two is weak (Section 7.3). Where a supplier proposes a single number, the right question is which failure it is intended to prevent.

9 Pitfalls and troubleshooting

Symptom	Probable cause	Corrective action
Angle rises steadily over days with no process change	Additive bloom; reorientation of polar groups	Fix the sample age in the method; measure at day 1 and at the age of use
Every sample reads 90–105°	Untreated face measured	Confirm the side with a dyne pen or water-break test; mark the film
Drop jumps or sits asymmetrically	Static charge on corona-treated film	Ionise for 2 s; ground the stage; repeat the measurement
Angle varies by more than 10° across the web	Treater gap or electrode wear; edge effects	Map drive side, centre and operator side; service the electrode
Dyne pen says pass, tape test fails	Equal dyne, different surface chemistry (Section 7.4)	Add a peel test; specify the treatment method as well as the level
Seal strength falls while the angle looks ideal	Over-treatment: brittle oxidised skin on the seal layer	Set a lower angle limit; reduce power; re-run the seal test
Values fall continuously during capture	Evaporation from a 2 µL drop; surfactant migration	Capture at 2.0 s; enclose the sample; use 4 µL
Anti-fog film fogs although the static angle is low	High receding angle; additive not bloomed or depleted	Measure receding angle or captive bubble; run a hot-fog test
Results differ from the film supplier's certificate	Different method: dyne versus angle, or different dwell time	Compare method statements; re-measure both samples in one laboratory
Sessile drop disappears on paper or board	Absorption into a porous substrate	Use Washburn or a captive-bubble configuration

Table 12 — Diagnostic table for packaging substrates. The first four rows account for most of the disagreement between a converter's laboratory and a film supplier's certificate.

10 Specifications, validation and food-contact context

10.1 Writing a specification that can be met

Three rules make a contact angle specification workable in a converting plant. Set the window at least six times the expanded uncertainty wide — with U = 3.4°, that is about 20° for single-drop testing or 7° if ten drops are averaged. Make the window two-sided, because over-treatment is a real failure mode (Section 7.2). And anchor the target to the process liquid rather than to a generic "treated" state: the requirement for solventless lamination is not the requirement for a water-based ink.

Where the customer insists on a dyne specification, keep it — but correlate it locally. Measure both on twenty production rolls, plot angle against dyne, and record the relationship. It will not be a constant offset, and the exercise is the evidence that the two specifications describe the same process.

10.2 Method validation and Gage R&R

Treat the method like any other test in a quality system: accuracy against a reference film, precision by repeated measurement of one film, repeatability within operator, reproducibility between operators, and robustness against drop volume, capture time, humidity and fit model. A Gage R&R with ten samples, three operators and three replicates is the standard design; a gauge contribution below 20 % of total variation is generally acceptable, and 20–30 % acceptable with justification.

One packaging-specific validation is worth adding: the **same-roll repeatability across a week**. Cut ten samples from one roll, measure five on day 1 and five on day 7, and record the drift. If the drift is comparable to the specification window, the method is measuring ageing rather than treatment, and the sampling plan needs to change.

10.3 Standards to cite

Standard	Subject	Use it for
ISO 19403-2	Wettability — surface free energy of solid surfaces from contact angle	SFE reporting; liquid set and model
ASTM D7334	Surface wettability by advancing contact angle	Advancing angle on flat substrates
ASTM D5946 / ISO 15989	Water contact angle of corona-treated polymer film	Incoming and in-process checks on film and web
ASTM D2578 / ISO 8296	Wetting tension of polyethylene and polypropylene film	Dyne-pen method; the contractual language
ASTM D7541	Critical surface tension by the Zisman method	Ranking low-energy surfaces with a liquid series
ASTM D8597	Contact angle with portable goniometers	Line-side measurement on large or installed parts

Table 13 — Method standards. Cite the one that matches the measurement actually made: a D2578 wetting-tension result is not an ISO 19403-2 surface free energy, and the two are not interchangeable in a specification.

10.4 Food-contact regulatory context

Contact angle sits **beside** the food-contact framework, not inside it. The relevant instruments in the European Union are the framework Regulation (EC) No 1935/2004, the plastics Regulation (EU) No 10/2011 as amended — including by (EU) 2020/1245 — and the good manufacturing practice Regulation (EC) No 2023/2006. Compliance with 10/2011 is demonstrated by composition checks, by specific migration testing against the substance list, and by overall migration testing against a limit of 10 mg/dm² of surface area (conventionally 60 mg/kg of food) using the food simulants defined in the regulation.

A contact angle measurement has no role in those determinations. What it can do is support the process validation around them: demonstrating that a coating is continuous, that a surface treatment is stable over shelf life, or that a change of supplier has not altered the interface. Written that way in a design or validation file, it is useful evidence. Written as a compliance claim, it is not defensible.

In the United States the corresponding instruments are the Federal Food, Drug and Cosmetic Act and the Title 21 CFR parts covering adhesives (175), coatings (175.300) and polymers (177), with the appropriate food-contact notifications where required. The same distinction applies: wettability is a process characteristic, not a regulatory status.

10.5 When to add a second technique

Contact angle reports the outermost layer, averaged over the drop footprint, with no chemical specificity and no mechanical information. Add the following when the question moves beyond wetting:

- **Peel or bond strength** whenever the claim is adhesion — always, if the answer will be used to release product.
- **Seal strength and hot-tack** whenever the claim involves sealing, since Section 7.3 shows the two are uncorrelated.
- **OTR and WVTR** whenever the claim is barrier performance.
- **XPS or ToF-SIMS** when the question is what the treatment actually deposited, particularly when comparing corona with plasma or two plasma recipes.
- **Migration testing** whenever the claim is food-contact compliance.

11 Reporting checklist

A contact angle result is only as useful as its method statement. The following items should appear in any report, specification or supplier certificate that quotes one.

- **Angle type** — static, advancing, receding or captive bubble, with the value reported for each.

- **Probe liquid and its surface tension** — grade, lot, measured or certified value, temperature.
- **Face measured** — treated or untreated side, and how it was identified.
- **Sample age** — time since extrusion or treatment, and storage conditions.
- **Capture time** after deposition, and drop volume.
- **Fit model** — Young–Laplace, polynomial or circle — and whether the baseline was automatic or manual.
- **Environment** — temperature, relative humidity, and any antistatic treatment applied.
- **Replication and statistics** — number of rolls, web positions and drops; median and IQR.
- **Instrument and calibration status** — identifier, last verification, reference value obtained.
- **Surface free energy details**, if reported — model, liquid set and the literature values used.

> **ONE-SENTENCE RULE FOR REVIEWERS**
>
> If a certificate quotes a contact angle without stating the face, the sample age and the capture time, the number cannot be compared with anything — including another number from the same supplier.

12 References

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[10] ASTM D2578 / ISO 8296. *Wetting tension of polyethylene and polypropylene film.* ASTM International and ISO.

[11] ASTM D7541. *Estimating critical surface tension of coatings, substrates and pigments by the Zisman method.* ASTM International.

[12] Regulation (EC) No 1935/2004 of the European Parliament and of the Council on materials and articles intended to come into contact with food.

[13] Commission Regulation (EU) No 10/2011 on plastic materials and articles intended to come into contact with food, as amended by Regulation (EU) 2020/1245.

[14] Commission Regulation (EC) No 2023/2006 on good manufacturing practice for materials and articles intended to come into contact with food.

Appendix A Symbols and constants

Symbol	Meaning	Value / unit
θ	Contact angle	degrees
θ_Y	Young (ideal) contact angle	degrees
θ_a, θ_r	Advancing and receding angles	degrees
$\Delta\theta$	Contact angle hysteresis, $\theta_a - \theta_r$	degrees
γ_{lv}	Liquid–vapour surface tension	mN/m (= mJ/m²)
γ_s^d, γ_s^p	Dispersive and polar components of solid surface energy	mN/m
γc	Zisman critical surface tension	mN/m
W_a	Work of adhesion	mJ/m²
	Water at 20 °C: γ = 72.8 (21.8 dispersive / 51.0 polar)	mN/m
	Diiodomethane at 20 °C: γ = 50.8 (50.8 dispersive / 0.0 polar)	mN/m
	Ethylene glycol at 20 °C: γ = 48.0 (29.0 dispersive / 19.0 polar)	mN/m

Table A1 — Symbols used in this note, with the liquid constants applied in Section 3.4 and Appendix B.

Appendix B Dyne level, contact angle and polar fraction

A dyne level and a water contact angle describe the same surface but not the same quantity, and there is no single conversion factor between them. The table below makes the reason explicit: it computes the water angle, by OWRK, for a range of total surface energies and polar fractions. Read a row across and the angle changes by up to 18° at constant surface energy.

Total surface energy (mN/m)	Polar 5 %	Polar 15 %	Polar 30 %	Polar 45 %
30	94°	86°	80°	76°
34	91°	82°	75°	71°
38	88°	79°	71°	67°
42	85°	75°	67°	62°
46	82°	72°	63°	58°
50	79°	68°	59°	53°

Table B1 — Calculated water contact angle as a function of total surface energy and polar fraction, using OWRK with water at 72.8 mN/m. These are model values, not measurements; expect ±5° against a real film.

Two readings of the table are useful in practice. First, a surface at 40 mN/m reads 75° if it is 15 % polar and 67° if it is 30 % polar — which is why a converter's dyne pen and a supplier's goniometer can both be right and still disagree. Second, the sensitivity to polarity is greatest in the middle of the range, exactly where the printing window sits, so the polar fraction should be reported alongside any surface energy used in a specification.

The practical conclusion is not to convert, but to correlate. Measure both on the same twenty rolls, plot angle against dyne, and use the resulting relationship — with its scatter — as the local translation between the two languages.

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