

Exposure Verification in Industrial Photopolymer Operations

Air and Dermal Sampling, Analytical Methods, Barrier Performance and Control Confirmation

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Statement of Significance

An enclosure, extraction system or glove specification is not evidence that exposure is controlled. Control must be demonstrated against the actual resin, task, operator position, sampling method and operating state. ER-177 provides a bounded verification framework for vat-photopolymerisation operations. It separates screening instruments from compound-specific measurements, printing from short manual tasks, and nominal glove material from measured chemical-barrier performance. The central rule is simple: a control claim is valid only for the exposure routes and operating conditions that the measurement strategy can detect.

Abstract

Vat photopolymerisation uses liquid reactive formulations and usually requires pouring, printing, resin recovery, washing, drying, post-curing and finishing. Direct chamber studies show that particle and organic-vapour releases occur during SLA and DLP operations, that emission magnitude varies by printer technology and task, and that printing is not necessarily the highest-concentration phase [1,2]. The same studies also show why total volatile organic compound readings and particle counts cannot identify every relevant constituent. Separate permeation studies demonstrate that glove performance depends on the challenged acrylate or methacrylate, formulation, solvent, material, thickness and test method; a generic material name does not establish a universal breakthrough time [3,4]. ER-177 translates this evidence into a tiered verification strategy combining task mapping, direct-reading instruments, time-integrated compound-specific sampling, dermal-contamination checks and barrier-performance evidence. It does not prescribe universal exposure limits, sampling durations, glove-change intervals or control efficiencies. Those decisions require substance-specific criteria, validated methods and measurements representative of the actual operation.

Keywords: vat photopolymerisation; occupational exposure; air sampling; dermal exposure; glove permeation; acrylates; methacrylates; control verification

1. Scope and ownership

ER-177 addresses verification of airborne and dermal exposure controls in industrial photopolymer operations, with vat photopolymerisation as the direct evidence core. It owns task-resolved sampling design, selection and interpretation of screening and analytical methods, evaluation of glove-barrier evidence, placement of measurements relative to worker and source, and confirmation that controls perform under defined operating conditions.

It does not re-author the toxicology, sensitisation, hazard classification or regulatory obligations of individual substances. Those remain with ER-091 to ER-095 and the applicable legal framework. ER-176 retains reactive-process safety and abnormal-event prevention. ER-178 retains solvent, wash-water and contaminated-waste management. ER-177 asks whether exposure controls work; it does not decide whether a formulation is safe, biocompatible or environmentally acceptable.

The evidence core comprises two full primary chamber studies of SLA and DLP processes, one EPA permeation study available through its complete project summary and journal abstract, and one full primary

glove-permeation article [1-4]. These sources justify a verification framework but not universal numerical acceptance criteria.

2. Exposure is a task sequence, not a printer state

A printer can be enclosed while the operation around it remains open. Resin pouring, vat access, part removal, resin recovery, washing, transfer, drying, post-curing, support removal, sanding and spill response involve different source geometries and different degrees of worker proximity.

Bowers et al. measured task-specific releases from SLA and DLP workflows in controlled chambers and found particles and gases during every evaluated task [1]. The highest organic-vapour readings were associated with IPA rinsing, soaking and drying rather than automatically with the longest task. 2-Hydroxypropyl methacrylate was reported during both pouring and resin recovery; the study reported a statistically significant difference only between recovery and curing, and only for the DLP process [1]. These results establish that sampling only during the print cycle can miss important exposure opportunities.

The finding is not a ranking that transfers to every facility. Only one resin and defined equipment and task methods were studied. It supports a design rule: decompose the local workflow into tasks before selecting measurements or declaring control.

3. Define the claim before selecting the method

“Exposure is controlled” is incomplete unless it identifies the route, agent or indicator, population, task, averaging period, operating state and acceptance basis. A defensible claim might address peak solvent vapour during open washing, task-average airborne methacrylate during resin recovery, ultrafine particle release during printing, or dermal transfer after a defined handling task. Each requires different evidence.

The verification plan should state:

1. the substance, class or operational indicator being measured;
2. the task and duration represented;
3. whether the question concerns a peak, task average, shift average, surface contamination or barrier breakthrough;
4. the worker location and relevant breathing-zone or contact geometry;
5. the control configuration and its operating state;
6. the analytical sensitivity needed to support the decision;
7. the criterion against which the result will be interpreted.

A method that cannot detect the relevant agent below the decision threshold cannot verify the claim, even if it returns a numerical result.

For European programmes, the applicable normative framework should be identified explicitly. EN 689:2018+AC:2019 addresses strategies for comparing inhalation exposure with occupational exposure limit values, while ISO 374-1:2024 addresses terminology and performance requirements for chemical protective gloves [5,6]. Naming these standards does not import a universal acceptance criterion into this review.

4. Screening instruments and specific analysis answer different questions

Direct-reading particle counters and photoionisation detectors can reveal timing, peaks, decay and task-to-task change. Stefaniak et al. used real-time particle instruments and a photoionisation detector alongside filter, impinger and off-line chemical analyses [2]. Bowers et al. similarly combined real-time particle and total-VOC monitoring with filters, sorbent media, canisters and laboratory analysis [1].

This combination matters because a total-VOC value is an instrument response to a mixture, not a complete chemical inventory. Photoionisation response depends on lamp energy, compound ionisation potential and calibration convention. Particle number concentration does not identify chemical composition, and an

instrument size range excludes particles outside that range. Conversely, a time-integrated sorbent sample can identify or quantify selected compounds but may conceal a short peak.

The off-line analyses in Stefaniak et al. also identified elemental constituents in individual particles and quantified specific carbonyl compounds [2]. Those results illustrate that particle counts and total-VOC signals require complementary chemical analysis; they do not establish composition for another printer or formulation.

Screening and specific analysis should therefore be paired when both timing and identity affect the decision. Screening locates events and compares operating states. Compound-specific sampling determines whether named agents were captured and quantified with an appropriate method.

5. Background, blanks and detection capability are part of the result

Both chamber studies established background conditions before the evaluated operations [1,2]. This is essential where room solvents, cleaning products, outdoor particles, adjacent processes or instrument drift can produce signals unrelated to the photopolymer task.

A verification study should include the applicable combination of field blanks, media blanks, instrument zero and span checks, pre-task background, flow calibration, recovery checks and laboratory quality controls. Results below a limit of detection are not zero. A non-detect supports a control claim only when the method detection capability is sufficiently below the relevant decision level and the sample represents the operating state of interest.

Background subtraction can be useful, but it should not erase an actual worker exposure merely because the same contaminant exists elsewhere in the room. The report should preserve both measured and background values and state the calculation used.

6. Sampling location determines what is being verified

Chamber measurements characterise source behaviour under controlled mixing and ventilation. They do not equal personal exposure in an occupied workplace. Area samples near a vat, washer or cure unit can diagnose sources and control leakage, while breathing-zone samples better represent inhalation opportunity for a defined worker. Neither substitutes automatically for the other.

Stefaniak et al. used a characterised 12.85 m³ chamber with controlled air exchange and high mixing [2]. Bowers et al. used separate controlled chambers and a glove box for different tasks [1]. These designs support comparisons within their experiments, but the values should not be copied into a facility risk assessment as if room volume, ventilation, operator position and duty cycle were unchanged.

For control confirmation, fixed-location measurements should be positioned to test capture, containment or migration. Personal measurements should follow the worker through the actual task sequence. The relationship between source, control, sampler and worker should be documented.

7. Printing technology and formulation remain explicit variables

Stefaniak et al. evaluated five desktop vat-polymerisation printers and reported higher mean particle and total-VOC emission yields and smaller mean particle sizes for the studied DLP printers than for the studied SLA printers [2]. Bowers et al. also observed differences between SLA and DLP task results [1]. These are direct observations from specified systems, not a universal ordering of technologies.

Formulations were proprietary and differed among machines in the earlier study [2]; the later task study used one resin, which bounds the generalisability of its task comparisons [1]. A verification result must therefore retain printer, resin, lot or formulation identity, exposure settings, temperature, job geometry, resin age and reuse state, wash solvent, cleaning procedure and post-cure conditions. Changing any of these may change the source term or the method response.

8. Controls must be tested in the configuration in which they are claimed

An enclosure can reduce release to the room only if doors, lids, seals, exhaust flow and access practices maintain the intended boundary. Local exhaust can capture one source while leaving transfer, washing or waste handling uncontrolled. General ventilation can dilute room concentration without preventing a worker's short near-field peak.

A control-verification sequence should include at least:

1. baseline measurement with the normal control configuration;
2. confirmation of airflow, pressure relationship or other engineering parameter where applicable;
3. task-resolved monitoring during normal operation;
4. a defined challenge representing credible high-use or high-emission conditions;
5. observation of worker interaction, including lid opening and transfers;
6. repeat measurement after maintenance or material/process change;
7. documentation of conditions under which the control claim no longer applies.

Control efficiency calculated from upstream and downstream concentrations is meaningful only when sampling positions, mixing, flow and time alignment support that calculation. A lower room reading after a change does not by itself prove capture efficiency.

Where respiratory protective equipment is part of the control strategy, verification must also cover device selection for the identified hazard, fit, condition, maintenance and the operating circumstances in which it is required. It does not substitute for source control, and ER-177 does not prescribe protection factors or universal respirator types.

9. Dermal verification requires contact-path evidence

Air sampling does not measure liquid contact. Dermal exposure can arise from contaminated container surfaces, tools, build platforms, vats, drips, wipes, wash equipment and glove removal. A dermal programme should map these contact paths and distinguish direct resin contact from secondary transfer.

Useful methods may include fluorescent-tracer exercises with a non-hazardous surrogate, surface wipes, glove exterior/interior wipes, absorbent patches, structured observation and task-specific contamination mapping. The selected approach must be validated for its intended interpretation. A visible tracer can demonstrate transfer pathways but cannot quantify a specific acrylate unless its behaviour has been shown to represent that chemical and surface system.

The practical endpoint is not merely “gloves worn”. It is whether contamination reaches skin or clean surfaces under the defined task and whether removal and replacement practices preserve the barrier.

10. Glove material names are not universal performance specifications

Renard et al. challenged butyl, natural-rubber and nitrile materials with TMPTA, HDDA and HDDA/EHA mixtures using a modified ASTM F739 method suitable for low-volatility, low-water-solubility permeants [3]. No permeation through the tested butyl or nitrile materials was detected under the stated conditions and sensitivity, while permeation through natural rubber was observed for defined challenges [3]. This finding is bounded by material thickness, temperature, challenge composition, duration, collection medium and detection limit.

Munksgaard tested five latex and five nitrile examination gloves against HEMA and TEGDMA, both concentrated and diluted with ethanol or acetone [4]. Nitrile generally produced longer breakthrough times than latex for concentrated monomers, but the advantage was reduced with solvent and disappeared in the acetone mixtures; large differences also occurred among glove brands [4]. These dental-material conditions

are not identical to industrial vat-resin handling, but they directly demonstrate that polymer family alone does not determine barrier performance.

These results are not in conflict: the permeants, glove constructions, thicknesses, mixtures, exposure conditions and detection limits differed, which is precisely why a generic material name is not a performance specification.

The correct engineering conclusion is not that one generic glove material is universally sufficient. Selection requires permeation evidence for the actual formulation or a defensible worst-case challenge, including solvents and other carriers.

11. Breakthrough time is not a glove-change interval

Laboratory breakthrough depends on the test definition, temperature, membrane thickness and stretching, challenge concentration, contact area, collection medium, analytical interval and detection sensitivity. Real gloves may also be punctured, abraded, flexed, contaminated internally or degraded by mixed chemicals.

Munksgaard's measured breakthrough times changed substantially when HEMA/TEGDMA mixtures contained ethanol or acetone, and the study found high post-breakthrough permeation rates for some nitrile conditions [4]. Renard et al. showed that a collection method had to be adapted for low-volatility acrylates and that results were material- and challenge-specific [3].

A laboratory breakthrough time should therefore be treated as one input to a conservative change rule, not copied directly as permitted wear time. Immediate replacement after visible contamination, tearing or uncertain integrity remains a separate operational rule. Reuse requires evidence that decontamination does not damage the barrier or drive permeant into it.

12. Verification must include abnormal but credible states

Normal print cycles are not the only states that matter. Credible challenges include a prolonged open vat, blocked extraction, a saturated filter, a warm wash bath, a resin spill, removal of a failed print, manual scraping, extended resin recovery, maintenance inside an enclosure and finishing that generates dust.

The later chamber study found that task method influenced release and that short tasks could dominate selected measurements [1]. This supports including abnormal states that change source strength, worker distance or control boundary. It does not justify deliberately creating an unsafe release. Challenges should be planned, bounded and stopped if predefined conditions are exceeded.

13. Interpretation must preserve uncertainty and method limits

Measured concentration is conditional on sampling efficiency, analytical recovery, calibration, environmental conditions and temporal representativeness. A facility comparison is valid only when the methods and operating states are comparable. Apparent improvement smaller than combined measurement and process variability should not be treated as confirmed control performance.

Repeated runs are important where manual task execution varies. Bowers et al. performed five replicates per task and identified manual handling and resin reuse as sources of variability [1]. Stefaniak et al. repeated a common artifact across printers and reported substantial printer-dependent differences [2]. A verification plan should predefine the number of repeats or explain why the evidence is adequate without them.

14. Change control and reverification

Reverification triggers include resin or supplier change, formulation or lot change, new pigment or filler, printer or light-engine change, altered exposure or temperature, changed job geometry or throughput, different wash solvent, changed enclosure or extraction, filter replacement strategy, altered task sequence,

new glove make or thickness, maintenance affecting seals or airflow, spill history and any unexplained rise in screening signal or contamination.

Not every change requires a complete study. A bridging assessment is acceptable when retained methods are sensitive to the changed source or barrier mechanism and the old and new states are measured under comparable conditions. Supplier statements alone do not demonstrate unchanged emissions or permeation.

15. Minimum reporting set

A reusable verification report should identify the facility area, date, process, printer, resin and lot, task sequence, operator position, control configuration, room ventilation, job and duty cycle, wash and post-cure conditions, sampler type and location, media, flow, duration, calibration, blanks, analytical method, detection and quantification limits, background treatment, replicate structure, raw and processed results, uncertainty, acceptance basis, deviations and change-control triggers.

For dermal controls it should also identify glove manufacturer, product, material, thickness, cuff and layering configuration, challenged chemicals, relevant permeation data, replacement rule, observed contamination, removal procedure and any interior-glove or skin-transfer result.

Where respiratory protective equipment is used, the report should identify the device, filter or cartridge, fit-verification status, inspection and change criteria, and the task or abnormal state that triggers its use.

16. Evidence limitations

The two direct VPP studies were controlled chamber investigations, not comprehensive personal-exposure surveys [1,2]. They do not represent every resin, printer, room, task method or production scale. Their emissions values must not be converted into universal exposure factors or claims of compliance.

The glove studies tested defined acrylates or methacrylates and specific materials under laboratory conditions [3,4]. They do not qualify every commercial glove against a complete proprietary photopolymer formulation. Neither non-detection nor a reported breakthrough time can be transferred without accounting for detection limits, thickness, temperature, mixture composition and physical damage.

The evidence supports measurement architecture and conservative interpretation. It does not establish universal occupational limits, control efficiencies, glove materials or replacement intervals.

17. Conclusions

Exposure verification in photopolymer operations must follow the workflow rather than the printer label. Direct studies show releases during SLA and DLP printing and during surrounding tasks, with material, technology and task method affecting the observed results [1,2]. They also demonstrate the value of combining real-time screening with compound-specific sampling.

Dermal control requires separate evidence. Glove-permeation studies show that chemical identity, mixture, solvent, material and product construction affect barrier behaviour [3,4]. “Nitrile” or “latex” alone is therefore not a sufficient specification, and laboratory breakthrough is not automatically a workplace change interval.

The defensible rule is to define the exposure claim, map tasks and contact paths, use methods capable of resolving the relevant agent and time scale, test controls in their actual configuration, and repeat the evidence after material or process change. Absence of odour, an enclosed printer, a low total-VOC reading or nominal glove use does not independently demonstrate control.

Related Engineering Review boundaries

ER-177 owns verification of air and dermal exposure controls in industrial photopolymer operations. ER-176 retains reactive-process safety and abnormal-event prevention. ER-178 retains solvent, wash-water and

contaminated-waste management. ER-091 to ER-095 retain hazard, sensitisation, toxicology and regulatory scopes. ER-177 does not qualify a resin, workplace, glove or control system for universal use.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. This review does not claim that any 3Dresyns resin, process, workplace control or protective glove is qualified for a specific occupational or regulated use.

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Data availability

No new experimental dataset was generated for this review.