PCBA Cleaning and Conformal Coating: Process Qualification and Compact Facility Design

Kyle M. LeClair
Independent Research
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Abstract

Reliable conformal protection depends on surface preparation, controlled application, and the facility conditions that sustain both. This study develops an integrated engineering framework for PCBA cleaning, rinsing, drying, bakeout, protected transfer, coating selection, cure, inspection, and storage. A two-zone flux-removal process provides the operational basis. Primary technical sources and analytical models establish the process requirements, while a STEP assembly provides a compact-facility case study. The geometric analysis preserves component placements, measures analytic boundary geometry, and exposes concealed equipment and services through selective wall and roof suppression. The circuit card assembly (CCA) cell has an internal rectangular area of $8.299\,\mathrm{m}^2$, a floor-to-roof height of $2.1844\,\mathrm{m}$, and local opposing-fixture intervals of approximately $0.926\,\mathrm{m}$. External water-treatment vessels, overhead exhaust, electrical and electrostatic-discharge controls, and thermal equipment extend the functional footprint beyond that rectangle. The analysis identifies a roof/riser interference and defines the significance of modeled access, equipment envelopes, and exhaust continuity. These are nominal geometric results; installed performance is assessed through the commissioning criteria. Worked calculations address fluid renewal, ventilation, thermal burden, capacity, measurement uncertainty, and release decisions. The resulting framework connects material compatibility, process control, facility design, and verification, providing a reproducible basis for professional electronics-processing capability in constrained space.

Keywords: PCBA cleaning; conformal coating; contamination control; bakeout; process qualification; local exhaust ventilation; compact facility design.

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Reading guide. Sections 2 and 3 establish the requirements and manufacturing sequence. The cleaning and coating chapters develop the material and process controls; the facility chapter and section 8 connect them to the physical work center. Section 9 defines qualification and release evidence. Appendices A–D provide operating and verification procedures, while section E contains independent worked calculations.

1 Introduction

Conformal coating protects an assembly through the combined effects of surface preparation, film formation, and controlled handling. Residues beneath components, moisture retained in a laminate, inadequate source capture, and excessive delay between cleaning and coating can compromise an otherwise satisfactory process. The engineering problem therefore extends from the board surface to the work center, its utilities, and the evidence used to release finished assemblies.

This study develops an integrated design basis for printed circuit board assembly (PCBA) cleaning and conformal coating in a compact work center. Cleaning, drying, preparation, application, cure, inspection, storage, and waste handling each impose conditions on the adjacent operation. Professional capability depends on controlling these interfaces and providing the operating, maintenance, and removal space required by each function.

1.1 Research question and objectives

The research question is: *How can a constrained electronics-processing area sustain a chemically compatible and repeatable cleaning and coating process while meeting electrical, environmental, and maintenance requirements?* The objectives are to:

1. connect contamination mechanisms and material selection to an explicit sequence of manufacturing controls;
2. define the facility functions, including concealed services and access envelopes, needed to sustain that sequence;
3. establish complementary inspection, cleanliness, cure, and electrical qualification evidence;
4. demonstrate the consequences of spatial, ventilation, thermal, and capacity assumptions through reproducible calculations.

1.2 Evidence basis and scope

The evidence comprises the original two-zone cleaning study, a STEP facility assembly, primary technical literature, manufacturer instructions, and analytical calculations [1, 2]. The case-study results are measurements of nominal CAD geometry. Production measurements, commissioned airflow, and completed reliability trials are outside the present dataset. The independent examples in section E use declared assumptions, and the defect photographs are attributed external reference images. Throughout the paper, these evidence classes remain distinct from demonstrated operating performance.

The detailed coating-preparation workflow begins with receipt of assembled, electrically screened hardware and approved process materials. In-process bench cleaning is treated as an upstream controlled interface: its flux history, local cleaning operations, and cumulative exposures form part of the incoming record. The workflow ends with coating verification, final functional testing, protective packaging, and preservation of the manufacturing record. Rework returns through controlled inspection and cleaning gates. Board fabrication, solder-joint formation, product-specific environmental qualification, building structural design, and permitting are interfaces to this system rather than processes fully specified here.

The framework applies primarily to controlled, low-to-moderate-volume electronics work. High-volume lines, parylene deposition plants, and specialized chemical processes add equipment-specific

requirements. The controlling process baseline includes component restrictions, product drawings, technical data sheets (TDS), safety data sheets (SDS), and applicable contractual requirements.

2 Technical Basis and Requirements Architecture

2.1 Separate material, process, assembly, and facility evidence

Qualification addresses four distinct subjects: the coating material, the manufacturing process, the finished assembly, and the facility. Material evidence establishes formulation suitability; process evidence establishes repeatable application; assembly evidence establishes performance in service; and facility evidence establishes the conditions under which production remains controlled. Table 1 relates each subject to its verification basis.

IPC-CC-830C qualifies electrical insulating compounds using standardized test vehicles. Its public scope distinguishes those material tests from end-use assembly performance. The editions used here—J-STD-001J, IPC-A-610J, IPC-CC-830C, and IPC-HDBK-830A—correspond to the IPC revision register consulted for this study. The product or procurement baseline identifies the controlling edition and amendments for a particular application [3, 4].

Table 1: Evidence layers and their distinct engineering questions.

Layer	Engineering question	Representative evidence
Material	Is the identified formulation suitable for the selected environment and process?	Controlled TDS/SDS; lot and shelf-life records; applicable qualification evidence; compatibility assessment.
Process	Can the actual combination of flux, cleaner, substrate, coating, and cure produce repeatable outputs?	Representative test vehicles; cleaning and coating trials; bounded settings; approved work instructions.
Assembly	Does the completed hardware retain function and insulation under its specified loads?	Functional tests; humidity–bias and environmental exposure; inspection before and after exposure; failure analysis.
Facility	Can the work center sustain the process under normal and degraded operating conditions?	Airflow and exposure measurements; utilities verification; oven mapping; interlock tests; maintenance and access review.

2.2 Use standards according to their scope

NASA-STD-8739.1B, Change 2, is an active workmanship standard covering polymeric applications to electronic assemblies. It provides a useful public example of coordinated preparation, material control, application, and inspection requirements. Its acceptance limits become controlling only through their applicable program or contractual basis [5].

For a United States facility, OSHA requirements concerning ventilation, flammable liquids, spray finishing, electrical installations, and hazard communication must be assessed against the actual operations. Consensus standards, equipment listings, and locally adopted building and fire codes add requirements with their own scopes and editions. A handbook recommendation is not automatically a statutory minimum, and a current catalog edition is not automatically the locally adopted edition.

The requirements register records each requirement, its source and edition, the affected equipment or product, the verification method, the responsible discipline, and the acceptance record.

Temperature limits and material restrictions must form a compatible process baseline before a traveler is issued. Requirements that describe different tests or incompatible processes require a documented technical disposition; ranking them only by apparent stringency does not establish compatibility.

2.3 Engineering deliverables before equipment selection

Equipment selection follows a defined design basis: product family, expected contamination, permissible chemistries, board sizes, component restrictions, production demand, service environments, coating keepouts, and rework strategy. The same basis specifies the highest credible simultaneous chemical use, drying and curing loads, personnel occupancy, and maintenance activities. Together, these inputs determine the required process equipment and supporting services.

An assembly with high-impedance measurement circuitry may require stringent control of localized leakage even when its operating voltage is modest. A high-voltage assembly may require special attention to voids, field concentrations, and low-pressure exposure. An RF assembly may require a coating-specific electrical assessment. Such differences justify product-family process baselines instead of a single unrestricted "coat all boards" procedure.

3 Integrated Process and Configuration Control

3.1 The manufacturing state must be explicit

Each assembly has an explicit process state and a defined next operation. As-received, cleaned, coated, cured, and accepted work are physically segregated and identified on the traveler. Completion of an operation advances the assembly only when the required record and inspection gate are satisfied. Figure 1 shows the resulting sequence and release gates.

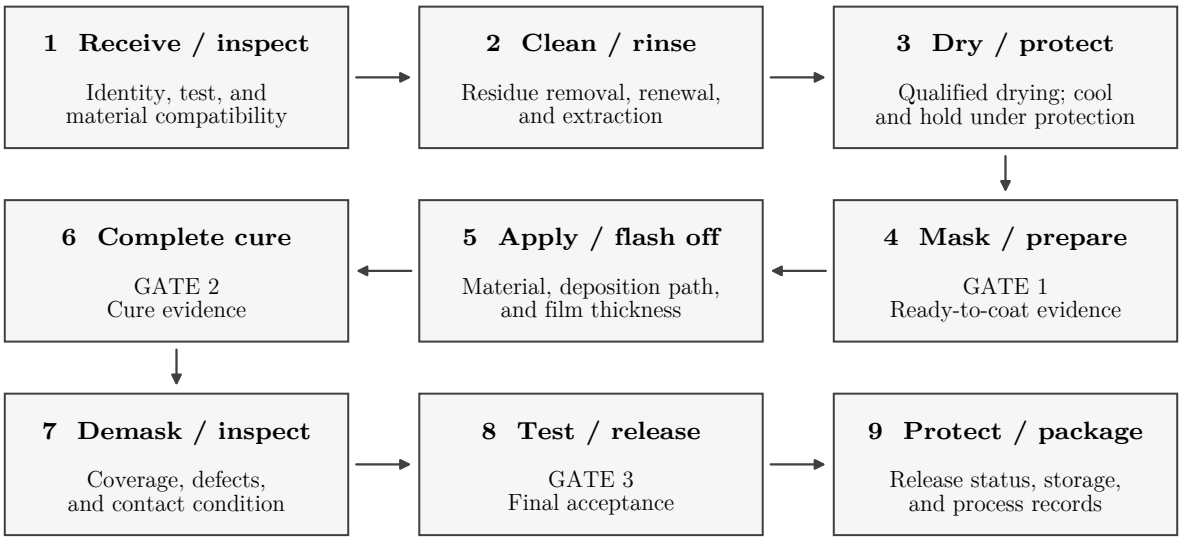


Figure 1: Integrated process and three release gates. The sequence is controlled by material compatibility and recorded assembly status; detailed drying, masking, and demasking order follows the qualified material system.

3.2 Receipt, preinspection, and compatibility review

Confirm assembly identity and revision, soldering and rework history, flux chemistry, previous cleaning, existing polymers, and storage condition. Inspect for loose components, damaged markings, visible contamination, exposed contacts, trapped debris, and evidence that a solvent or heat-sensitive item has been substituted. Complete baseline electrical tests appropriate to the product before covering features that will become difficult to inspect or probe.

Build a compatibility matrix for the complete assembly, including connectors, relay vents, switches, elastomers, sensors, adhesives, labels, cable insulation, and any fixture or tray that enters a wash or oven. Evaluate both immediate effects and delayed changes such as swelling, loss of adhesion, optical haze, embrittlement, or retained solvent. Qualification of a cleaner on a bare laminate does not establish compatibility with a populated assembly.

3.3 Three release gates

Gate 1: ready to coat. Cleaning and drying records are complete; the product satisfies the selected cleanliness evidence; allowable exposure time has not expired; handling and storage remain controlled; masks and keepouts match the drawing; any required primer or surface-activation step and its waiting limits are satisfied. Record the latest permissible coating start or the rule that determines it.

Gate 2: cure complete. Material identity, mix condition, application record, witness-coupon association, actual cure conditions, and any secondary cure are documented. Packaging release depends on the specified cure state and subsequent inspection, including where the surface is already dry to the touch.

Gate 3: ready for release. Inspection confirms specified coverage, thickness evidence, keepouts, cleanliness after demasking, and acceptable repair boundaries. Required functional and electrical tests are complete. Deviations are dispositioned and packaging is compatible with the cured coating.

3.4 Control the handoffs and hold times

Every transfer has a defined incoming condition, protective method, maximum permitted delay, and recovery route. Lidded carriers limit deposited contamination, and dry cabinets control moisture exposure; both preserve an accepted condition rather than establish cleanliness or dryness. Racks for cleaned, uncoated assemblies remain isolated from overspray, uncured coating vapor, and incompatible materials.

The traveler distinguishes wash completion, rinse completion, start and end of drying, attainment of the required assembly temperature, oven takeout, protected cooling, masking completion, first coating application, flash-off, primary and secondary cure, demasking, inspection, and packaging. Each hold-time limit has a defined starting event, such as oven exit, attainment of a specified assembly temperature, or opening of a protective container. These time stamps make queueing and cumulative exposure traceable.

3.5 Changes that reopen qualification

A new flux, cleaning formulation, concentration range, rinse sequence, coating formulation, nozzle, UV source, thermal profile, mask adhesive, fixture material, component package, or exhaust operating condition can change the process even when the board drawing is unchanged. Evaluate each change against the mechanism it can affect. Requalify the affected relationship and preserve the previous

baseline for traceability. Cosmetic document changes do not need the same evidence as a new chemistry or cure mechanism.

4 PCBA Cleaning and Control of the Coating Interface

4.1 From bench cleaning to final preparation

The original flux-removal study separates bench fabrication from pre-package preparation. The first zone controls localized residue during assembly and rework; the second prepares the completed assembly for coating, encapsulation, or packaging. Its three-stage route comprises an ultrasonic wash, a deionized (DI) water spray/soak stage, and ionized-air blow-off with collected runoff [1]. This study develops that two-zone architecture by defining the process controls and qualification evidence required at each transition.

Final preparation depends on the manufacturing history established at the bench. Record flux identity, soldering and rework operations, residue age, local cleaning chemistry, and repeated exposure of sensitive features. For each approved assembly sequence, define the points at which localized cleaning is required and the maximum permitted delay after soldering. These intervals must reflect residue behavior and component restrictions; a blanket instruction to clean immediately does not define suitable timing across a mixed product family. Improved visibility for inspection is useful, but the process must also remove dissolved material without spreading it into adjacent regions.

Final preparation must deliver the surface condition required by the next operation. Depending on the qualified route, this may involve a complete wash or another substantiated preparation sequence rather than repetition of every bench step. A record of bench completion does not replace the Gate 1 evidence required for release to coating. Subsequent solder repair reopens the contamination assessment because it introduces new residue and another chemical or thermal exposure. Table 2 summarizes the control boundaries and required evidence.

Table 2: Process controls and qualification evidence for the two cleaning zones.

Stage	Controlled boundary	Evidence before the next stage
Bench fabrication	Local flux additions, residue age, approved solvent/tool sequence, runoff, and repeated rework exposure	Assembly history; inspection access; compatibility; removal of contaminated liquid
Final preparation	Representative completed geometry, qualified wash/rinse route, retained-fluid removal, and protected transfer	Product-specific cleanliness evidence; drying record; permitted hold time; complete ready-to-coat disposition

4.1.1 Operating limits of candidate cleaners

The original process study assigns separate roles to an ambient bench solvent and an aqueous ultrasonic formulation. For the bench candidate, AXAREL 2200, the retrieved manufacturer technical sheet describes full-strength manual and immersion cleaning and advises against heating or ultrasonic use [6]. The September 2022 safety data sheet classifies the formulation as a flammable liquid and reports a closed-cup flash point of 44 °C [7]. These documents support its consideration for ambient bench work. The source sequence uses isopropyl alcohol (IPA) before and after the

cleaner; release of this sequence requires qualified dwell intervals and effective access beneath the actual integrated-circuit package. The solvent remains an ambient-process candidate, independent of the aqueous bath's settings.

For the aqueous stage, the BIOACT EC-98 technical sheet identifies ultrasonic cleaning as the intended process. Its guidance specifies 5 % to 25 % dilution in water, a 40 °C to 80 °C wash temperature, 10 min to 30 min wash time, and 50 °C to 70 °C rinse temperature. The sheet does not state whether the dilution percentage is based on mass or volume [8]. These values support screening but do not establish an operating window for the assemblies considered here. Both retrieved technical sheets are manufacturer-authored copies hosted by distributors without a visible revision date. Development trials require current supplier-controlled documents and component restrictions, with the selected wash duration justified against those limits.

Cavity cleaning requires both a compatible exposure and a route for removing contaminated fluid. Needle application and connector soaking are permitted only within the actual component's cleaning limits and with a demonstrated drainage path; protect or exclude features that cannot tolerate the exposure [5]. Qualify brush material, shedding, cleanliness, and mechanical action, since a generic "acid brush" designation specifies none of these sufficiently. Ultrasonic exposure requires the same distinction between cleaner capability and assembly compatibility, particularly for susceptible capacitors and microelectromechanical systems (MEMS) devices [9, 10].

4.1.2 Intermediate soaking, final rinsing, and collection

The original flow diagram combines a clean spray source with a reused soak and returns blow-off liquid to the water stage. This arrangement requires a clearly defined boundary between intermediate rinsing and the final clean contact. A reused bath can serve an intermediate function, but the last rinse contacting the assembly must meet the approved final-rinse requirement. Reimmersion in a dirtier collection bath can undo part of that renewal. Identify the clean supply, intermediate bath, final-rinse outlet, and collected liquid separately, even when one enclosure accommodates them all. Reuse of recovered liquid requires demonstration of its intended role and any necessary treatment.

A simple conservation model illustrates why this distinction matters. Let V_h be the liquid volume retained with the workpiece after drainage, V_r the volume added during one rinse exchange, c_n the retained-liquid contaminant concentration before that exchange, and c_b the concentration in the incoming rinse. With complete mixing and subsequent drainage back to V_h,

$$c_{n+1} = \frac{V_h c_n + V_r c_b}{V_h + V_r}. \tag{1}$$

If both volumes and the incoming concentration remain constant, repeated exchanges give

$$c_n - c_b = (c_0 - c_b)\left(\frac{V_h}{V_h + V_r}\right)^n. \tag{2}$$

This analytical model assumes a dissolved, nonreacting contaminant, no further soil release, and complete access and mixing. It illustrates the mechanism rather than reporting a measured rinse result; actual package cavities can violate each assumption. Within those limits, repeated exchange drives the retained liquid toward the incoming concentration, so a contaminated rinse imposes a

residual concentration floor. A recirculating bath with increasing contamination also requires a changing bath inventory instead of the constant-c_b model.

Rinse control therefore requires defined sampling locations, water temperature, conductivity or resistivity measurement conditions, renewal rules, and permitted bath loading. Water measurements characterize the fluid; removal from inaccessible assembly surfaces requires complementary extraction and electrical evidence. Resistivity of solvent extract (ROSE), ion chromatography (IC), and surface insulation resistance (SIR) have distinct roles in that assessment [11–13]. Select nozzles on the basis of wetted-material compatibility, particle release, cleanability, pressure and temperature capability, and electrostatic discharge (ESD) control requirements. The original suggestion of polytetrafluoroethylene (PTFE) does not establish that all metallic alternatives are unsuitable.

4.1.3 Charge neutralization and liquid removal

An ionized air jet can address electrostatic charge and displace accessible liquid, but the two functions require separate verification. The EOS/ESD Association distinguishes equipotential grounding and dissipative materials from ionization used for necessary insulators [14]. An ionizing-gun indicator therefore establishes neither dryness nor cleanliness nor complete ESD protection. Verify ESD performance at the actual working position and qualify liquid removal for the most difficult permitted geometry. Verify clean, dry process air at the outlet, after the hose, regulator, filter, and nozzle.

Equipment suitability is a separate constraint. The official Top Gun manual excludes wet environments and flammable or explosive atmospheres, making an ESD function insufficient evidence for use above a wet or solvent-bearing collection station [15]. The equipment specification must identify the exact hardware and its permitted location, splash exposure, and atmosphere. After bulk drain-down or permitted blow-off, apply the qualified drying endpoint and protected takeout and holding sequence in section 4.6. Absence of visible droplets and a surface that feels dry do not demonstrate removal of hidden liquid or absorbed moisture.

4.2 Surface condition and contamination mechanisms

Cleaning must establish an interface that supports the required electrical behavior, coating wetting, adhesion, and environmental durability. Visual appearance alone cannot establish this condition: an apparently clean assembly may retain extractable ions, thin organic films, or moisture beneath components. Conversely, a white deposit identifies a visible residue, not a particular ion or electrical failure mechanism. Process definition therefore begins with the assembly bill of materials, soldering history, flux identities, rework records, surface finishes, and intended service environment. Together, these inputs identify what must be removed, which surfaces are accessible, and which cleaning exposures the assembly can tolerate.

The behavior of a contaminant determines the evidence needed to assess it. Ionic species can contribute to leakage when sufficient moisture forms a conducting film; an applied potential can then support electrochemical reactions and metal migration. Nonionic oils or silicone-containing residues can affect wetting without producing a proportionate ionic-extraction response. Particles present a geometrical problem: they may bridge conductors, interrupt film continuity, or become embedded in the coating. The diagnostic categories in table 3 consequently require complementary measurements. The different scopes of IPC extraction and surface-insulation-resistance methods reflect this distinction between ionizable contamination and electrically harmful behavior [11, 13].

Table 3: Contamination mechanisms and complementary diagnostic evidence. Acceptance limits are specific to the product and qualified process.

Category	Potential consequence	Useful evidence
Flux activators and process salts	Moisture-dependent leakage, corrosion, electrochemical migration	Ion chromatography; biased humidity testing on representative test vehicles
Rosin, resin, oil, or handling film	Poor wetting, weak interfacial adhesion, local coating displacement	Optical inspection; targeted chemical identification; adhesion evaluation
Particles and fibers	Embedded debris, coverage interruption, conductive bridging if metallic	Controlled illumination and magnification; localized particle identification
Retained cleaner or rinse water	Residue redeposition, dilution of coating, delayed outgassing	Rinse verification, drainage assessment, validated dry-down and subsequent coating trials
Absorbed moisture	Moisture release during heating or curing; humidity-sensitive electrical behavior	Assembly-specific drying qualification and controlled post-bake exposure

The term *no-clean* describes a flux intended to leave acceptable residue within a qualified assembly process. Compatibility with a particular coating, bias condition, or humidity exposure still requires evidence. Li et al. tested three coating systems on flux-contaminated comb-pattern boards and found that the residue–coating interface materially affected adhesion and corrosion protection. Their ranking is limited to the investigated materials and exposures, rather than resin families in general [16]. An uncleaned route therefore requires substantiation of the specific soldering, residue, coating, and service combination. If cleaning is selected, demonstrate adequate removal: a partial cosmetic wipe establishes neither the qualified uncleaned condition nor the qualified cleaned condition. Figure 2 summarizes the interface mechanisms.

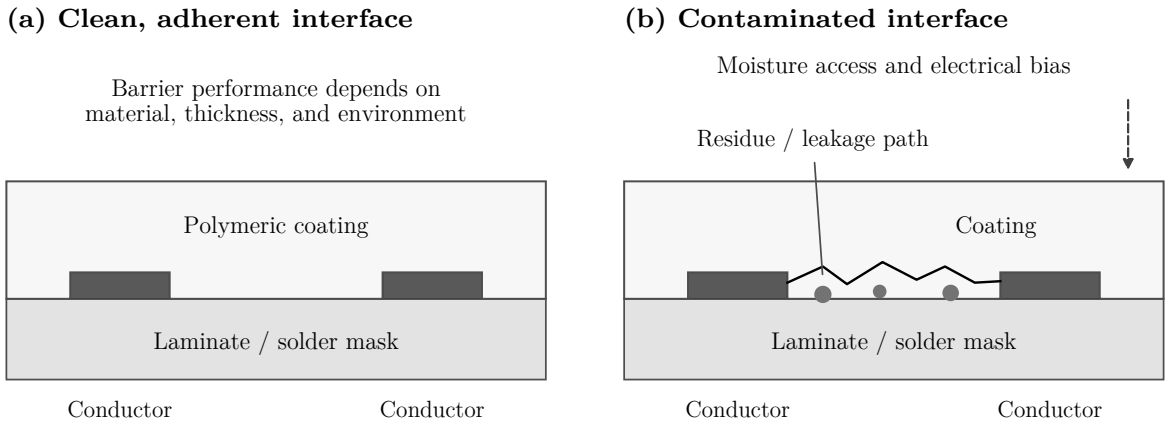


Figure 2: Clean and contaminated coating interfaces. The schematic shows how moisture, residue, and electrical bias can form a failure pathway beneath a continuous film.

4.3 Cleaning chemistry and material compatibility

Select the cleaning agent and equipment as one process, considering solubility, chemical reaction, agitation, fluid exchange, rinseability, and drying together. Evaluate actual solder-paste and flux residues produced by the intended thermal history; unused flux on a flat coupon is an incomplete surrogate for reflowed material beneath a package. Manufacturer guidance distinguishes water-soluble, rosin-based, and no-clean residues and recommends verifying their interaction with the selected process [17]. These categories provide screening inputs rather than automatic product-selection rules.

Table 4: Cleaning-chemistry screening matrix. Specific formulations, concentrations, and operating limits require material compatibility and process qualification.

Approach	Potentially appropriate application	Main qualification question
Deionized water	Residues formulated for water removal; aqueous rinsing	Can the complete residue be accessed, dissolved, transported away, and dried?
Aqueous formulated cleaner	Mixed soils, resin residues, or low-access geometries requiring selected additives	Are concentration, temperature, rinse removal, and all exposed materials compatible?
Alkaline or saponifying formulation	Soils for which chemical conversion and removal are demonstrated	Does the process remove reaction products without attacking metals, finishes, markings, or polymers?
Solvent cleaning	Compatible organic residues; qualified manual, immersion, or enclosed processes	Does the solvent remove the actual soil, avoid material damage, and remain suitable as its contamination load changes?
Semi-aqueous sequence	Organic cleaning followed by a compatible aqueous rinse	Can the wash chemistry and dissolved soil be displaced completely through the rinse and drying sequence?
Vapor-degreasing system	Assemblies compatible with the selected solvent and machine cycle	Are solvency, condensation/rinse access, materials, retained-fluid removal, and equipment suitability demonstrated?

Electronic-grade isopropyl alcohol is one candidate solvent. Its suitability depends on residue chemistry, purity, water content, application method, and removal of the contaminated liquid; concentration alone is neither a cleaning recipe nor a cleanliness criterion. A swab can spread dissolved material beyond the initially dirty area, so the method must include a final rinse or controlled collection step. Supplier benchtop guidance emphasizes fresh rinsing fluid and drainage away from the assembly [18, 19]. Exclude household cleaners, unqualified detergents, fragranced alcohol preparations, and liquids of unknown additive content from the controlled process because their constituent and residue behavior is unspecified.

Compatibility screening covers the complete assembly: solder mask, legend ink, component marking, connector housings and seals, adhesives, labels, elastomers, optical surfaces, relays, switches, acoustic ports, displays, batteries, and any pre-existing coating. Record these restrictions before selecting immersion or spraying. NASA's polymeric-application standard requires protection of unsealed parts during solvent immersion and prevention of contamination on electrical contact surfaces; it also distinguishes cleaning of coated hardware from preparation of an uncoated assembly [5]. A material coupon can establish resistance to discoloration or swelling, but it cannot establish whether

a component admits fluid. Examine the assembly physically and functionally after the specified exposure and relevant conditioning, including components that appear sealed.

4.4 Cleaning access and method selection

Low component stand-off limits fluid transport. Effective cleaning requires fluid to enter the restricted region, interact with the residue, and leave with the dissolved or detached material. An explanatory model for steady laminar pressure-driven flow between parallel plates of width w, gap h, and flow length ℓ is

$$Q_{\text{gap}} = \frac{wh^3\Delta p}{12\mu\ell}, \tag{3}$$

where μ is dynamic viscosity and Δp is the imposed pressure difference. Halving h reduces this idealized flow to one eighth when the other conditions remain unchanged. The scaling explains why external spray pressure alone cannot establish renewal beneath a component. It is not a prediction of package wash performance: solder joints obstruct the passage, wetting and trapped gas affect entry, and jets produce an unsteady flow field. Manufacturer technical literature likewise identifies package geometry and increasing footprint as cleaning constraints [20].

Manual cleaning provides local control for repair when the critical surfaces are accessible. The procedure must define brush material, application, solvent renewal, runoff collection, inspection, and operator technique, with qualification addressing operator variation and incomplete access beneath packages. Qualify brushes and wipes for particulate shedding, chemical compatibility, and their contribution to contamination. Keep dirty tools and liquid out of the clean supply, and protect the work surface so that runoff from one assembly cannot contaminate another.

Batch spray systems offer controlled recipes for economical processing of mixed, low-volume work. Their relevant variables include load position, rack orientation, shadowing, nozzle condition, and maximum approved load. Inline systems instead use staged wash, rinse, and drying zones, with conveyor speed, assembly spacing, and configuration governing exposure. Batch machines execute these stages sequentially. In either architecture, qualification must demonstrate drainage and effective rinsing around connectors and recessed features [21].

Immersion increases fluid contact, but its effectiveness still depends on renewal at the critical surface. Treat agitation, circulation, rotation, and ultrasonic energy as distinct process conditions because each changes the transport mechanism. Component restrictions determine whether an assembled PCBA can tolerate ultrasound: Murata identifies possible resonant damage to capacitors or solder joints, and MEMS devices impose additional restrictions [9, 10]. Evaluate the actual assembly arrangement. Where ultrasound is permitted, specify the equipment, frequency behavior, power setting, bath loading, temperature, duration, position, and acceptance examinations. The panel setting alone does not characterize acoustic exposure at each component.

Vapor degreasing combines a selected solvent with controlled liquid and vapor stages. Supplier descriptions establish the available cleaning, rinsing, and drying architecture; performance depends on the machine and fluid pairing [22]. Qualification must address the actual residues, trapped volumes, porous materials, component restrictions, and emissions rather than assume universal removal. Plasma treatment is a separate surface-modification process. Credit it with removal of inaccessible salts or bulk residue only when that capability is demonstrated for the relevant geometry and contaminant.

4.5 Bath condition and rinse control

Cleaning transfers material away from the assembly, making bath condition and carryover central process controls. Concentration, dissolved soil, entrained particles, and water content change with use; a bath can retain its nominal concentration while carrying excessive contamination. Establish sampling locations and chemistry-specific measurement methods before production. Titration, refractive index, density, conductivity, or a dedicated analyzer may be suitable, provided the method is calibrated and interference from dissolved soil is assessed. A pH reading alone is not a universal measure of cleaner concentration or remaining cleaning capacity.

Control the final rinse at the point of use. Specify water or solvent quality, supply maintenance, nozzle and hose cleanliness, fluid temperature, renewal, and measurement conditions. Conductivity or resistivity can indicate ionic loading but cannot alone quantify nonionic organic contamination. Acceptance also requires effective flushing of trapped regions and removal of residual wash chemistry. Repeated washing does not compensate for an inadequate rinse and can further complicate contamination in the bath or on the assembly.

Set bath replacement and maintenance limits from supplier instructions and measured process behavior. Supporting evidence includes analytical results at increasing soil load, representative assemblies processed near the replacement limit, and documented recovery after filter or fluid changes. A failed rinse, blocked nozzle, or incorrect chemical addition requires a lot hold and investigation outside routine recipe control. Authorize recleaning only after the cause, process capability, and compatibility of the additional exposure are understood. NASA likewise links recleaning after a failed cleanliness test to corrective action on the cleaning system [5].

4.6 Drainage, drying, bakeout, and controlled takeout

Drainage, drying, bakeout, and cure have different objectives and acceptance evidence. *Drainage* removes bulk liquid; *drying* removes remaining accessible liquid and vapor. *Bakeout or demoisturization* reduces retained moisture under a qualified thermal or vacuum exposure, whereas *coating cure* establishes the required material state after application. Document these operations separately even when they use the same chamber. A visibly dry surface can coexist with liquid in a blind feature or moisture in an absorbent material.

Qualify drying with the worst relevant assembly geometry and load, using controlled orientation and drainage before thermal treatment. For filtered dry gas, verify cleanliness at the actual outlet and determine whether the jet removes liquid or drives it beneath a component. Gas pressure and temperature must remain compatible with the components, fixture, and operator-protection requirements. General shop air requires this verification before use as a clean process gas. A nitrogen supply also requires controls against oxygen displacement wherever its use can affect an enclosed volume.

The bake schedule is bounded by the least tolerant exposed item and the required removal mechanism. Apply the thermal restrictions of the complete assembly, including batteries, displays, plastics, adhesives, temporary masks, labels, and fixtures. Moisture-sensitive-device handling for later solder reflow serves a different purpose and cannot be adopted directly as a coating-preparation recipe. NASA-STD-8739.1B provides example demoisturization schedules while identifying assembly construction, population, moisture history, and other influences on drying time. Its example of

90 °C ± 5.5 °C for at least four hours is specific to that standard's application, rather than a universal schedule for PCBAs [5].

Table 5: Required records and evidence for drying and protected transfer. Process-specific values are established by qualification.

Stage	Record and control	Evidence needed
Incoming wet state	Cleaner, rinse, load identity, drainage orientation, elapsed time	Defined representative worst-case retained-fluid condition
Thermal or vacuum exposure	Recipe, actual load temperatures, pressure if used, airflow, ramp, dwell	Loaded chamber mapping and compatibility; demonstrated drying endpoint
Takeout and cooling	Time out, handling tools, destination, temperature, exposure conditions	Safe handling and prevention of new particles, oils, or moisture exposure
Clean holding	Container or cabinet identity, environmental record, maximum hold and open exposure	Qualification covering the intended delay before coating
Release to coating	Cleanliness disposition, drying record, masking status, elapsed time	All prerequisites within their approved limits; deviations resolved

Thermal qualification measures assembly temperatures at representative load locations, distinguishing warm-up from the demonstrated dwell condition; the oven setpoint alone is insufficient. Record the ramps, cumulative thermal exposure, and equipment configuration. A mass plateau can support drying studies when the balance resolves the change, but chemical volatilization and desorption can also alter mass, and a plateau does not prove dryness in every hidden region. Support the endpoint with complementary evidence, including subsequent coating behavior and appropriate electrical or environmental testing. Assemblies carrying volatile solvents require equipment suitable for that solvent load. A general-purpose warming oven cannot be assumed to satisfy this requirement.

Takeout transfers the assembly from a controlled chamber to its next controlled environment. Prepare the clean receiving location before opening the chamber, use compatible fixtures, avoid contact with coating surfaces, and record the removal time. Protected cooling must preserve the qualified surface state; open room-air cooling is not equivalent, and a hot assembly must not be sealed into unsuitable packaging. Qualification establishes the maximum hold time, permitted temperature and humidity range, and cumulative open exposure. Control the storage cabinet's cleanliness, environmental performance, contents, and transfer practices. An exceeded exposure limit requires a predefined disposition, since automatically repeating a bake can accumulate unnecessary thermal damage.

4.7 Cleanliness verification and release evidence

The analytical plan must distinguish indicators of process stability from evidence of electrical performance. IPC-TM-650 2.3.25 defines ROSE as a process-control tool that does not predict reliability. The conductivity-derived result is a sodium-chloride equivalent, not an identification of sodium chloride on the assembly; insoluble, inaccessible, or nonionic material can escape the measurement [11]. A bulk result therefore cannot serve as a complete cleanliness certificate. Applying historical numerical limits to another method, geometry, or contractual requirement requires a documented technical basis.

Table 6: Roles and limits of the principal cleanliness-evidence methods.

Method	Primary question	Limitation to retain in the report
Optical inspection	Are visible residues, particles, damage, or retained liquid present?	No assurance of invisible films, ionic identity, or hidden-surface cleanliness
ROSE	Has extractable ionic response changed under a controlled method?	Bulk equivalent response; extraction-dependent; not a reliability prediction
Ion chromatography	Which targeted extractable ions are present, and at what level?	Analyte and extraction dependent; incomplete access and unmeasured species remain possible
SIR with humidity and bias	Does the representative process cause leakage or electrochemical degradation under the chosen stress?	Validity depends on test-vehicle representation, preparation, stress, and measurement integrity
Targeted surface analysis	What material causes a residue or interfacial failure?	Local sampling and method limits; diagnosis does not itself qualify a production process

Ion chromatography provides chemical selectivity. The method must specify target ions, extraction solution and temperature, duration, exposed area, collection volume, dilution, calibration, blanks, and reporting limits. IPC-TM-650 2.3.28B provides an extraction-and-analysis method with a corresponding blank [12]. For a compatible blank-corrected reporting convention,

$$q_i = \frac{(c_i - c_{b,i})Vd}{A}, \tag{4}$$

where q_i is extractable mass per reported area, c_i and $c_{b,i}$ are sample and blank concentrations, V is extraction volume, d is dilution factor, and A is the stated normalization area. Concentrations in µg/L, volume in liters, and area in cm^2, for example, yield µg/cm^2. This accounting relation does not correct unknown extraction efficiency: a low result can reflect poor access as well as low residue.

Use matching reagent and container blanks, investigate elevated blank results, and report nondetects with the relevant detection or quantification limits rather than as demonstrated zero. State the area convention explicitly: two-sided projected board area, estimated assembled surface area, and localized extraction area produce different denominators. A local measurement must not be diluted by normalization to the full-board area. Because extraction can alter the assembly, remove residue, or introduce moisture, the process plan must define the extracted article's disposition and any subsequent drying.

SIR evaluates insulation behavior under defined electrode geometry, humidity, and electrical bias. IPC-TM-650 2.6.3.7 addresses leakage and electrochemical degradation using standardized vehicles and test controls [13]. Development coupons must reproduce the relevant materials and process exposures, supplemented by assemblies or test structures when component geometry governs the response. Record current histories and inspection findings, including transient events, rather than only the final resistance. Account for fixture leakage, chamber contamination, condensation, and measurement range, all of which can obscure the result.

Release combines established material and process qualification with routine monitoring that can detect drift. Extraction alone does not establish long-term performance. Russeau's IPC-hosted

presentation explains the supporting objective evidence required when extraction testing is used in qualification; it is explanatory guidance, not the controlling text of a purchased standard [23]. Predetermine the response to failed measurements, limits on recleaning, and evidence required after a process change. Define when a new material or geometry falls outside accepted production history, particularly when one compact facility handles several product families with superficially similar assemblies.

5 Conformal Coating Selection and Functional Boundaries

A coating specification begins with the failure mechanisms that the finished assembly must withstand: moisture-assisted leakage, corrosion, conductive contamination, or loss of insulation performance in the intended environment. The required protection depends on assembly geometry, electrical bias, exposure duration, contaminants, and serviceability. Suitability must therefore be established for the assembled product. IPC-CC-830C addresses material qualification and conformance on standardized test vehicles; it does not establish application performance in the end-use environment. Its public scope also excludes treating the coating as the sole source of mechanical support [3].

5.1 Chemistry, thickness class, and cure mechanism

Record cured chemistry, deposition method, and cure mechanism as distinct attributes. The public IPC-CC-830C scope identifies acrylic (AR), epoxy (ER), silicone (SR), polyurethane (UR), paraxylylene (XY), ultra-thin (UT), and styrene block copolymer (SC) types. UT is defined by a target thickness of 12.5 µm or less, independent of chemistry; hybrid classification otherwise follows the largest cured chemistry fraction by weight. Ultraviolet (UV) exposure is a curing mechanism rather than an additional resin family in this classification [3]. Descriptions such as “UV coating” or “nanocoating” consequently leave essential purchasing requirements unspecified.

Table 7 organizes the selection criteria by coating family. Each candidate requires a controlled technical data sheet, safety data sheet, material qualification evidence where required, and compatibility evidence for the actual assembly materials. The family descriptions guide screening; performance and operating limits remain specific to the formulation.

Table 7: Coating families, selection considerations, and required evidence.

Family	Selection considerations	Evidence needed before selection
Acrylic (AR)	Practical candidate for repairable assemblies and a relatively simple liquid-coating process. A representative single-component acrylic is solvent-borne and readily repaired [24].	Resistance to the actual cleaning agents and service fluids; solvent compatibility, drying endpoint, and acceptable local-removal method.
Polyurethane (UR)	Candidate when moisture and chemical resistance are central. Products include different component counts and cure routes [25].	Complete cure before exposure, flexibility across the service range, hydrolytic behavior, and repairability after aging. Avoid treating all urethanes as equivalent.

Table 7 (continued)

Family	Selection considerations	Evidence needed before selection
Silicone (SR)	Candidate where compliance and stress relief are valuable. A representative solvent-free silicone is described as stress relieving [26].	Permeation, adhesion, abrasion, contamination transfer, and compatibility with adjacent processes. Low modulus does not establish low moisture transport.
Epoxy (ER)	Candidate for hard, chemically resistant protection where rework is limited. Epoxy coatings can be rigid and difficult to remove without affecting epoxy-based board materials [27].	Cure shrinkage, thermal stress, component loading, repair route, and the consequences of local removal on the laminate and solder mask.
Paraxylylene (XY)	Vapor deposition can cover complex accessible surfaces without a liquid coating bath. It requires specialized vacuum processing [28].	Adhesion promotion, vapor-tight masking, fixture contact effects, deposition access, batch capacity, and removal capability.
Ultra-thin (UT)	Thickness class for applications where mass, geometry, or selective surface modification motivates a thin film [3].	Actual chemistry, thickness distribution, defect sensitivity, wear, electrical performance, and whether the claimed water repellency represents the required barrier function.
Styrene block copolymer (SC)	An explicitly recognized IPC material class requiring its own candidate-specific evaluation [3].	Verified formulation data, service-fluid resistance, temperature dependence, adhesion, and process compatibility. Classification alone establishes none of these limits.

5.2 Interfacial and bulk protection

Hydrophobicity, water uptake, water-vapor permeability, and adhesion describe different properties. A water-repellent surface can still transmit vapor, while a low-permeability film can fail at a local separation, damaged edge, or poorly covered lead. Li et al. examined three coatings with no-clean flux residues and found that both moisture-barrier behavior and adhesion affected protection. Their relative ranking applies to the tested materials and exposure conditions [16].

For an ideal, continuous, one-dimensional film at steady state, an illustrative diffusion model is

$$J = \frac{D\,(c_1 - c_2)}{h}, \tag{5}$$

where J is mass flux, D is diffusivity, $c_1 - c_2$ is the concentration difference within the polymer at its boundaries, and h is film thickness. The model explains the influence of thickness on transport through an ideal film. It omits edge ingress, interfacial pathways, sorption changes, and defects, so it cannot predict assembly lifetime from material data. Increasing thickness can also increase mechanical restraint or inhibit solvent escape. Qualification must therefore establish both lower and upper thickness limits.

5.3 Environment and circuit characteristics

The selection record must distinguish continuous humidity from condensation, occasional splash from immersion, and a single chemical exposure from recurring cleaning. It must identify minimum and maximum temperatures, ramp rates, thermal gradients, vibration, ultraviolet exposure, and any low-pressure or vacuum condition. Define the electrical state during each exposure: an unbiased coupon does not reproduce a powered high-impedance node. Assess high-frequency circuitry and sensitive capacitances after coating because the local dielectric environment changes.

Mechanical assessment covers flexing regions, lead compliance, large packages, connector loads, and thermal interfaces. The coating must preserve required motion and heat-transfer surfaces. Qualify flexible regions through representative bend cycling at the intended coating location and thickness. Material screening must also address compatibility with staking compounds, adhesives, labels, solder mask, and previously applied coatings.

A first-order mechanics screen helps explain why a protective film can also impose a load. For a fully restrained, isotropic thin layer under an ideal biaxial constraint,

$$|\sigma| \simeq \frac{E}{1-\nu} \left|\alpha_c - \alpha_s\right| \left|\Delta T\right|, \tag{6}$$

where E and ν are coating modulus and Poisson ratio, α_c and α_s are coating and substrate thermal-expansion coefficients, and ΔT is a temperature change from a stress-free reference. This screening relation identifies the variables requiring evidence but excludes relaxation, cure shrinkage, substrate deformation, and local package geometry; nominal data alone are insufficient to predict component stress. Representative coating data sheets report temperature-dependent modulus and changes in expansion behavior around the glass transition [24]. Thick fillets around leads consequently require evaluation with their actual geometry and thermal history. A flat-film result cannot establish their acceptability.

Insulation coordination remains a separate design activity. IEC 60664-3 addresses the conditions under which coatings, potting, or moulding can protect against pollution and permit distance reductions within its scope [29]. A thin applied layer does not automatically authorize smaller creepage or clearance, establish hermeticity, or provide a universal immersion rating. Such claims require the applicable product standard and assembly-level evidence.

6 Controlled Application, Cure, Inspection, and Rework

6.1 Material receipt, preparation, and working life

The batch record must link material designation and revision, supplier lot, expiry, receipt condition, storage history, opening time, and assembly lot. Keep the container closed during temperature conditioning until the required material condition is reached. Record the identity, lot, and quantity of every thinner or catalyst addition, using only additions authorized for the selected coating. For multi-component systems, distinguish mixing ratio by mass from ratio by volume, verify the dispensing method, and start the working-life clock at the specified initiating event.

A storage excursion outside the permitted limits or an exceeded expiry requires documented technical disposition. Adding fresh material to an aging mixture does not reset its working life. Solvent addition can likewise restore viscosity while leaving cure chemistry or solids content

unsuitable. Record both additions and elapsed time; viscosity alone is insufficient for material release.

The material assessment must include contact with application equipment: hoses, seals, reservoir liners, release agents, and cleaning residues can alter the coating's condition. Compressed-gas pressure, moisture, and oil contamination influence application and can affect moisture-sensitive materials [30]. Control delivery conditions separately from cure conditions. A product supplied with dry delivery gas may still require controlled ambient moisture during cure.

6.2 Design for coating and masking

An annotated coating drawing must define both board faces: required coverage, permitted boundaries, thickness measurement regions, fixture contacts, and inspection access. Identify connector mating surfaces, switches, trimmers, test contacts, grounding interfaces, mounting seats, thermal-contact surfaces, optical windows, acoustic openings, pressure ports, and component vents. The component manufacturer's restrictions determine whether a package may be coated. Covering an opening with a removable mask does not itself establish a seal against ingress.

Masking qualification evaluates adhesive residue, solvent resistance, thermal exposure, release force, and cure inhibition. Verify that placement can be inspected before coating and that the removal direction preserves the adjacent film. Vapor deposition also requires control of small leakage paths that can admit deposition species. SCS identifies extensive masking and preparation as significant features of parylene processing [28].

Control masks and fixtures as process tooling, with defined revisions and inspection for wear, deformation, and contamination. Record the masking sequence relative to cleaning and drying, since placing an adhesive mask after the final cleanliness inspection can reintroduce residue. Include a representative masked-and-demasked coupon when the sequence is first qualified or materially changed.

Where a primer or adhesion-promoting treatment is required, qualify it as a distinct operation. Record primer identity and lot, substrate compatibility, preparation, application limits, required flash-off or cure, and the maximum primer-to-coating interval. Define the disposition for exceeded intervals, incomplete coverage, or contaminated primed surfaces. Plasma and other surface-activation routes likewise require a qualified configuration, geometry, and maximum delay before coating. These prerequisites belong to Gate 1 when applicable and remain separate from removal of bulk or inaccessible contamination.

6.3 Application method and controllable variables

Select the application method for the required coverage, component density, keepout complexity, batch size, and available facility. Table 8 identifies the principal control variables; establish their limits from the selected material's instructions and the equipment's operating range. Manufacturer data show that even common liquid coatings require application-specific thinning and deposition guidance [24, 31].

Table 8: Application methods and principal process controls.

Method	Appropriate process role	Principal controls and inspection concerns
Brush	Local repair, prototypes, or a qualified low-volume route.	Brush material, loading, stroke direction, pass count, access, bubbles, and edge accumulation. Demonstrate operator repeatability.
Manual spray	Flexible application to varied geometries within a suitable exhausted enclosure.	Nozzle, fluid and gas pressure, distance, angle, traverse, overlap, flash interval, and orientation. Assess overspray and shadowed surfaces.
Selective coating	Repeated placement on controlled assemblies; may reduce masking demands.	Program and fixture revision, fiducials, nozzle condition, flow, speed, height, valve timing, and recipe lock. Automation does not remove capillary intrusion.
Dip	Broad coverage when assemblies and exclusions tolerate immersion.	Bath composition, viscosity, temperature, immersion and withdrawal rates, drainage orientation, contamination loading, and masking integrity.
Vapor deposition	Specialized conformal deposition on vacuum-compatible assemblies.	Pretreatment, vacuum process, chamber loading, thickness monitor correlation, masking leakage, and fixture shadow/contact regions. Verify actual feature coverage.

Manual and selective spraying require specific attention to regions beneath overhangs, around component shoulders, and beside tall packages. Reorienting the assembly can improve access while changing drainage. Even a visually uniform planar film can leave a critical vertical lead edge inadequately covered. Qualification must therefore establish the assembly orientation and permitted pass sequence in addition to the nominal machine flow rate.

Investigate wetting problems before increasing deposited volume. Surface contamination and unfavorable wetting can create craters, fish-eyes, and film withdrawal [32]. Contact-angle or comparative wetting checks on representative coupons can support the investigation, but a single reading establishes neither assembly cleanliness nor cured adhesion. Test liquids must not contaminate production hardware. Comparing fresh, cleaned, masked, and aged surfaces helps identify the handling stage at which wetting changes.

6.4 Wet deposition, dry thickness, and measurement

Specify the allowable final film thickness with its measurement method and locations. For a uniform evaporative coating, a first-order volume balance gives

$$h_{\mathrm{dry}} \simeq \phi_V h_{\mathrm{wet}}, \tag{7}$$

where ϕ_V is the nonvolatile volume fraction of the as-applied mixture. Mass-solids percentage cannot be substituted directly. With a suitable cured-solids density ρ_s and wet-mixture density ρ_w, the corresponding ideal estimate is $\phi_V \simeq w_s\rho_w/\rho_s$, where w_s is the nonvolatile mass fraction. Added thinner changes both composition and density, while cure shrinkage and volatile reaction products require additional treatment.

For a hypothetical dry-film target of 50 µm and $\phi_V = 0.40$, the calculated wet deposition is approximately 125 µm. This conservation estimate assumes uniform coverage, no post-deposition loss beyond the accounted volatile fraction, and negligible further volume change. It is illustrative; the production setting requires measurement of the actual deposited thickness.

The thickness method must be compatible with the substrate and coating. Options include calibrated cross-section microscopy, profilometry across a prepared step, and demonstrated optical or other suitable techniques. A witness coupon represents its own substrate and exposure, so correlate it with the assembly's critical locations before adopting it for routine control. Record minimum local coverage and excessive buildup as well as the average. Mass gain can reveal gross delivery changes but cannot locate an uncoated conductor. NASA's polymeric workmanship standard distinguishes thickness assessment on representative specimens from post-application inspection of the assembly [5].

6.5 Drying, cure, and release conditions

Solvent evaporation, reaction progression, and removal of surface tack can occur on different time scales. The 1B31 and 1A33 data sheets distinguish handling, cure, and optimum-property information, illustrating why handling time cannot establish final performance [24, 31]. Define separate release endpoints for inspection, electrical testing, packaging, and service exposure. A material may tolerate handling while remaining unsuitable for sealed packaging or a chemical-resistance test.

Thermal-cure qualification requires loaded-oven mapping and temperature histories at representative assemblies. Define the start of dwell from the coldest relevant location and verify that the hottest component remains within its approved exposure. Moisture cure requires specified humidity, temperature, film geometry, and moisture access to the reaction region. A dry enclosure can change the reaction conditions of a still-curing assembly; moisture exposure in a delivery reservoir can instead initiate premature reaction. Set these controls for the selected material and process.

For light curing, radiant exposure at a surface is

$$H = \int_0^{t_c} E(t)\,\mathrm{d}t, \tag{8}$$

where E is irradiance and H has units of energy per area. Equal total dose does not necessarily produce equal conversion when spectrum, peak irradiance, oxygen exposure, temperature, or optical attenuation differ. The HumiSeal UV40 data sheet specifies spectral and irradiance considerations and

distinguishes direct exposure from secondary moisture cure in shadowed regions [33]. Record lamp type, spectral band, radiometer configuration, belt speed or exposure time, distance, temperature, and lamp condition.

Evaluate UV access in three dimensions. Tall components can shelter coating on neighboring leads, and liquid can wick beneath a package. Secondary moisture or heat cure is available only when the formulation provides that mechanism; Dymax describes these routes for its respective product families [34]. Oxygen inhibition can affect surface cure in some photopolymer systems, so a higher dose alone may not correct the defect [35]. Addition-cure silicones can also suffer chemical inhibition: Dow identifies several nitrogen-, sulfur-, and tin-containing compounds as potential platinum-catalyst inhibitors [36]. Investigate chemistry and contact materials when cure fails locally before relying on a longer cure cycle.

Cure verification must connect the production observation to a required material property. Establish that relationship by comparing bounded cure conditions on representative thicknesses and substrates. Suitable responses can include adhesion, chemical resistance after conditioning, residual reaction measured analytically, or a demonstrated mechanical-property endpoint. Selection of the measurement method must account for specimen thickness and substrate influence; a bulk hardness method is not automatically valid for a thin film. Dymax's 9451 technical guidance similarly describes assessment through the development of cured properties and qualification of parameters for the application [35].

Once the relationship is established, select routine production checks without repeating every development measurement. A batch witness verifies only the conditions it experiences. Use additional witnesses or instrumented surrogate features for distinct cure challenges, including optical shadowing and large thermal masses. Predetermine the disposition for an interrupted cure, environmental excursion, or failed witness. An additional cure cycle requires approval because it can increase thermal exposure while leaving contamination, mixing errors, or inaccessible reaction regions uncorrected.

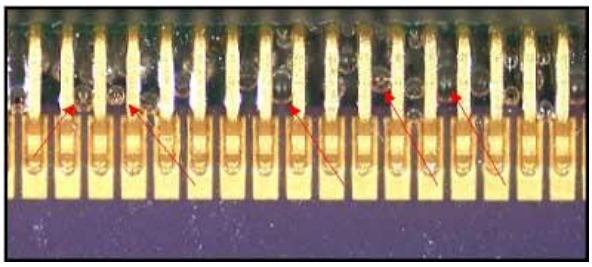
6.6 Inspection and defect diagnosis

Inspection must establish coating presence, coverage of required features, film integrity, function of restricted areas, and cure evidence supporting release. UV fluorescence helps locate compatible fluorescent coatings, but brightness depends on illumination, geometry, material, and the optical system. It cannot serve as an uncalibrated thickness measurement or proof of cure. Visible-light inspection remains necessary for particles, damaged edges, and mechanical interference.

Figure 3 illustrates excessive bubbling, exposed conductive areas, lifting, and dewetting using the cited NASA reference photographs.

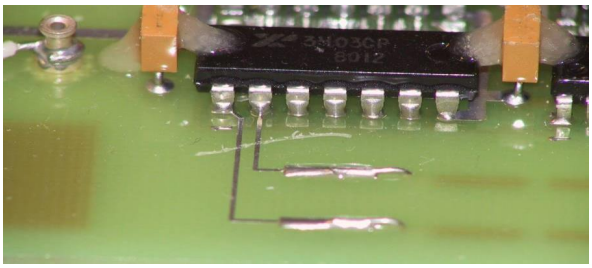
Table 9 links visible symptoms to competing causes and the observations that distinguish them. Manufacturer discussions support the wetting, bubbling, and moisture-blush mechanisms; the investigation sequence is an engineering synthesis [32, 37, 38]. Acceptance follows the controlled drawing and invoked workmanship criteria.

(a) Excessive bubbling



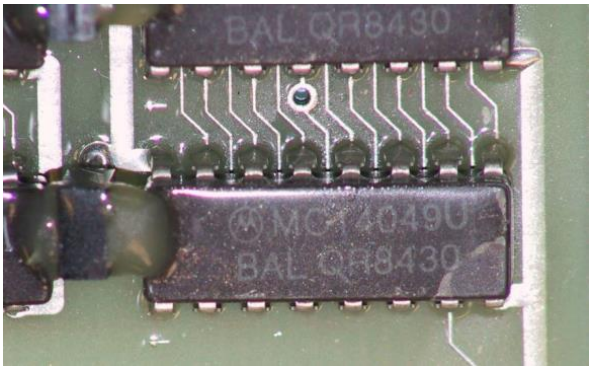
NASA Figure 10-2

(b) Exposed conductive area



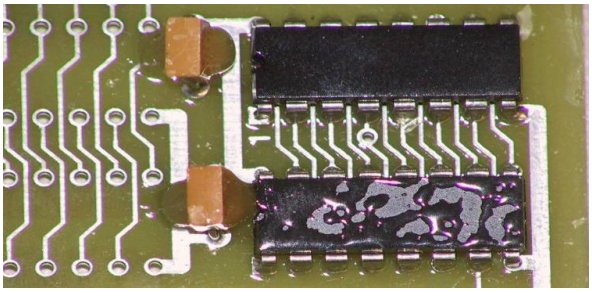
NASA Figure 10-3

(c) Lifting and peeling



NASA Figure 10-4

(d) Dewetting / loss of adhesion



NASA Figure 10-5

Figure 3: Reference photographs: (a) excessive bubbling; (b) scratch exposing conductive area; (c) lifting and peeling; (d) dewetting and loss of adhesion. Panels are reproduced without retouching from NASA-STD-8739.1B, Change 2, Figures 10-2 through 10-5 [5].

Table 9: Coating defects, competing mechanisms, and useful discriminating evidence.

Observation	Candidate mechanisms	Investigation and process response
Fish-eyes or dewetting	Local contamination; unfavorable wetting; incompatible residues.	Compare surface history and defect locations. Check handling, masks, delivery-system contamination, and matched coupons before changing thinner.
Bubbles or pinholes	Entrained gas; substrate outgassing; trapped solvent or reaction products.	Observe whether defects begin in the reservoir, during deposition, or during cure. Examine fill method, pressure, flash interval, dryness, and local film buildup.
Orange peel or dry spray	Poor leveling; premature droplet drying; unsuitable viscosity or spray conditions.	Verify the material mixture, nozzle condition, stand-off, atomization, temperature, and airflow. Change one controlled factor at a time.

Table 9 (continued)

Observation	Candidate mechanisms	Investigation and process response
Blush or whitening	Moisture interaction; evaporative cooling; incompatible material or residue.	Correlate with temperature, humidity, assembly conditioning, and solvent choice. Similar appearance can have different causes; document when whitening develops.
Lifting, peeling, or cracks	Poor interfacial adhesion; contamination; cure or thermal strain; damage during mask removal.	Map the failure relative to interfaces and high-strain regions. Examine adhesion on representative substrates and inspect before and after environmental exposure.
Bridges or excessive fillets	Excess deposited volume; drainage; capillary accumulation between features.	Measure local buildup and assess stress, cure depth, and trapped material. Do not infer acceptability from adequate thickness elsewhere.
Keepout intrusion	Mask leakage; program or fixture error; overspray; capillary transport.	Verify the boundary against the drawing and test the affected interface. Correct the process cause before applying touchup to unrelated regions.
Tack or local uncured film	Wrong ratio; expired material; insufficient light or heat; shadowing; chemical inhibition.	Compare a batch witness with the affected location. Review mixing and cure history and test suspected contact materials.
Fibers, particles, or buried residues	Airborne deposition; unclean tools; packaging debris; inadequate preparation.	Locate the contaminant relative to the coating and substrate. Determine whether repair can remove the source while preserving required insulation.

Figure 4 shows cross-sectional mechanisms that support interpretation of the diagnostic evidence. These schematics illustrate possible failure paths; they do not represent experimental observations from this study.

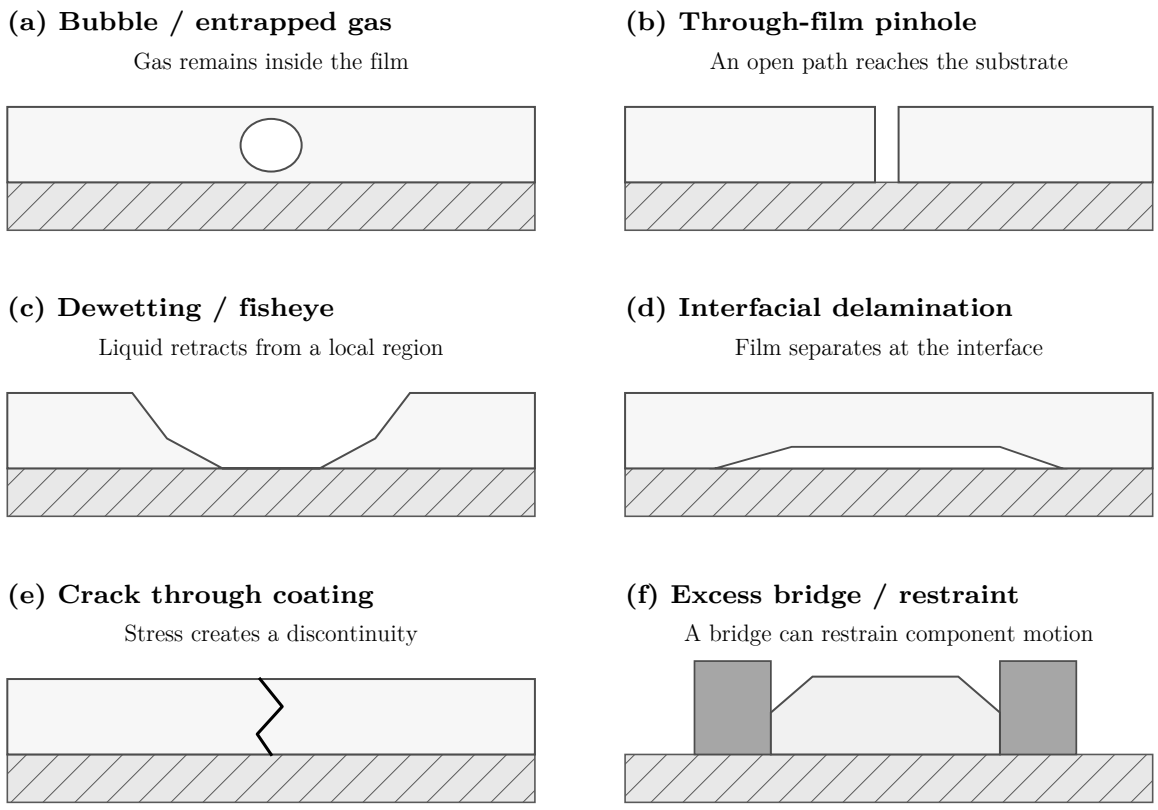


Figure 4: Schematic cross-sections of common coating defects. Hatching denotes the substrate, light gray the coating, and dark blocks adjacent features. Disposition depends on location, conductor geometry, material, and the governing acceptance criteria.

6.7 Rework and restoration of protection

Demonstrate rework capability before releasing a material for use. SCS describes chemical, thermal, and mechanical removal methods with different compatibility and damage risks; parylene removal differs substantially from dissolution of a readily soluble acrylic [39]. Each method requires compatibility evidence for the specific component, solder mask, laminate, and coating stack.

Begin repair by isolating the affected hardware, identifying the coating and defect extent, and selecting an approved local removal method. Protect adjacent features, collect removed material, inspect exposed conductors and component bodies, and repeat the applicable cleaning and drying controls. Inspect the repaired electrical connection before recoating. The governing procedure and representative compatibility demonstration must establish the required overlap and surface preparation, including adequate bonding of fresh material to the aged surface.

Recoating records must preserve the original material and process history, removed region, added material lot, cure cycle, and final inspection result. Recheck keepouts and function after demasking. The engineering disposition must address changes in local thickness, component stress, or high-voltage geometry. Assess cumulative exposure when repairs recur, because individually acceptable solvent or heat cycles can produce an unacceptable total history.

7 Facility Engineering for Constrained Process Cells

A compact cleaning and coating facility must coordinate material movement, contaminant capture, chemical inventory, thermal processing, inspection, and service access. Its usable capacity depends on how these functions operate together. Equipment may fit on a plan yet leave insufficient space for an open oven door, a filter change, or protected storage beside an emitting process. Facility design therefore evaluates the complete operating envelope, including the volumes behind walls and above the ceiling. The principles in this section provide the engineering framework for the model analysis in section 8; installation condition and measured performance require their own evidence.

7.1 Design basis and operational zoning

The operating basis links each assembly family to its cleaning chemistry, coating formulation, application method, maximum batch, expected solvent release, and required holding condition. This record establishes which operations can occur simultaneously. Changing from brush application to atomized spray, for example, changes the emission source, overspray collection, electrical assessment, and exhaust duty even when the formulation remains unchanged. The chemical inventory and current safety data sheets are controlled inputs to the hazard communication program: a familiar trade name does not establish unchanged formulation or hazards. Workplace labels, accessible safety data sheets, and personnel training complete this part of the controlled process [40].

The layout separates three flows: assemblies moving toward release, personnel and clean consumables entering the cell, and chemicals or waste leaving it. Forward movement from incoming inspection through cleaning, drying, protected holding, masking, coating, cure, and final inspection reduces unnecessary crossings. These are functional stages; several may share a physical room if their boundaries remain observable through layout or procedure. Covered transfer containers, dedicated racks, and shelves separated by work status help preserve those boundaries. They do not, by themselves, establish cleanroom performance.

Table 10: Functional zones for a compact PCBA cell, selected for the chemistry and operating modes.

Zone	Primary purpose	Boundary to preserve
Incoming and rework	Record condition; segregate returned or failed assemblies	No exposed cleaned boards beside incoming packaging or abrasive rework
Wet preparation	Contain cleaning liquid, displaced residues, rinsing and drain-down	Splash and vapor control; independent dirty-tool storage
Dry and protected hold	Drying, cooling, timed transfer and clean storage	Identified clean racks; limited exposure to room air
Coating and flash-off	Mixing, application and controlled initial evaporation	Capture at each emitting step; restricted clean-through traffic
Cure and inspection	Controlled conversion; examination and disposition	Cure status visible; unaccepted material separated from released boards
Chemical and waste	Compatible inventory, dispensing and closed collection	Separation from egress, clean holding and ignition sources

Dedicated equipment is necessary where cross-contamination cannot be reliably removed or measured. When NASA-STD-8739.1B governs, silicone operations must be segregated from other

polymeric operations, including their ovens, fixtures, tools, supplies, and garments. Scheduling silicone work last therefore does not justify a shared oven. In other applications, the governing requirements and compatibility evidence determine the segregation strategy [5]. The layout must also control paths by which masking debris, soldering fumes, lubricants, or aerosol maintenance products could reach adhesion-critical surfaces.

7.2 Spatial design beyond the equipment footprint

Each machine has four spatial requirements: installed geometry, operator envelope, service envelope, and removal route. The operator envelope includes fixture loading, tray withdrawal, visibility, two-handed handling, and space to set down a hot assembly safely. The service envelope provides access to pumps, filters, regulators, fans, electrical isolation, and removable panels. The removal route must accommodate the largest replaceable item through the door and around installed equipment without dismantling a protected partition. Storage belongs outside all of these reserved spaces.

A shared service strip along one wall can concentrate distribution and isolation points while keeping the equipment's process face accessible. Its arrangement must still accommodate any required separation of wet services, electrical distribution, chemically incompatible exhausts, and controls. Potential leakage paths must lead away from electrical equipment and clean holding, with accessible isolation upstream of flexible connections. Penetration seals, compatible supports, inspection openings, and access for cleaning concealed ledges are integral to the service design. Panel removal and the associated maintenance sequence must preserve the exit route.

Three-dimensional analysis can suppress architectural walls to expose horizontal sections, vertical sections through exhaust connections, and equipment service volumes. These views reveal hidden fittings, inaccessible isolation valves, inadequate bend radii, and conflicting withdrawal paths. Geometry establishes arrangement and access. Duct leakage, airflow, electrical suitability, chemical compatibility, fire resistance, and the quality of installed penetrations require specifications and inspection evidence.

Table 11: Design criteria and supporting evidence for concealed facility services.

Concealed element	Design criterion	Supporting evidence
Exhaust branches	Access to deposits, joints, and balance devices for inspection and service	Sections; access locations; flow and pressure design
Water and drains	Controlled leakage paths and protection of clean supply from contaminated streams	Piping schematic; containment; backflow assessment
Power and control	Accessible isolation and wiring suited to the operating environment	Electrical schedule; classification drawing; service envelope
Thermal equipment	Heat dissipation and tray withdrawal without exposing clean stock	Equipment clearances; loading and unloading study
Service chase	Filter, pump, and utility replacement with the cell safely isolated	Maintenance sequence; component removal route

Vertical storage is suitable for clean, light, closed supplies within safe reach, with appropriate shelf loading, restraints, and cleanability. Its placement must avoid lifting open chemicals over circuit

assemblies. An operating-state analysis includes the worker, transfer cart, and open equipment doors together so that efficient use of space preserves handling and service access.

7.3 Local exhaust, replacement air, and pressure relationships

Local exhaust should intercept contamination close to its source, before it passes through the breathing zone or deposits on neighboring assemblies. Sources include cleaning baths and open containers, atomized coating, mixing, flash-off, oven discharge, and solvent-bearing waste. OSHA's ventilation guidance distinguishes local exhaust, dilution, replacement air, comfort conditioning, and recirculation. Each serves a different function; satisfactory room temperature alone provides no evidence of effective contaminant control [41].

Define capture geometry before selecting a fan. In an enclosed spray process, the workpiece and atomization region must remain within the capture volume. An operator between the source and hood, a board outside the booth, or a supply diffuser disturbing the opening can defeat capture despite a high nominal duct flow. Assess airflow with the fixtures and largest intended assembly in place. Reducing the opening can lower the required flow, provided handling, sight lines, and the prescribed operating geometry remain adequate.

Select booth face velocity for the applicable booth and application configuration. OSHA 29 CFR 1910.94(c), Table G-10, differentiates operating conditions and crossdrafts; 1910.107(b)(5) separately addresses conventional dry-type overspray collectors. OSHA's interpretation explains the relationship between these provisions. There is consequently no universal face velocity for every coating process, and exposure and flammability require independent assessment [42]. Air changes per hour summarize room exchange but do not demonstrate source capture. Likewise, the solvent-dilution provisions of 1910.94(c)(6)(ii) require an emissions basis derived from solvent fraction and evaporation rate; total coating delivery rate cannot substitute for these quantities [43].

Conditioned replacement air must support the exhaust duty without drawing uncontrolled air through doors, ceilings, or adjacent dirty spaces. Distribute it to assist capture and avoid impingement on wet films. Pressure relationships must serve both containment and cleanliness: a negative chemical enclosure can coexist with protected clean storage, whereas a positive room intended solely to exclude dust may drive solvent emissions into adjacent areas. Excessive negative pressure can disrupt doors, reduce hood flow, and draw particulates into the cell. Test the balance at defined door positions and during simultaneous equipment operation.

For spray operations within the scope of 1910.107, exhausted air is not recirculated, and discharge must not contaminate replacement air or other ventilation intakes. The standard also addresses duct access and continued ventilation while sprayed articles dry [44]. Nonspray cleaning processes require their own regulatory assessment; any separate air-recirculating cleaner also needs a compatibility and exposure basis. Overspray and HEPA filters capture particles, so solvent-vapor control requires separate evidence. A carbon element alone establishes neither adequate capacity nor breakthrough control or fire suitability.

7.4 Ductwork, filtration, and maintainability

Develop an exhaust-branch schedule recording each source, operating flow, pressure loss, compatible construction, connection size, and inspection points. Account for loaded filters and all intended operating combinations when selecting fans against the complete system resistance and service conditions; a free-air rating is insufficient. Limit flexible ducting and difficult-to-clean runs to what

the equipment connection justifies. Roof discharge provisions must include structural support, weather protection suited to the discharge design, and inspection access.

For covered spray booths, 1910.107(d)(3) establishes independent exterior exhaust, subject to its limited cabinet-booth exception; chemical compatibility alone does not authorize combining ducts [44]. Other exhaust streams need separation where mixing would cause incompatibility, deposits, or unacceptable maintenance exposure. Assess aerosol loading, curing chemistry, cleaning fluids, and abnormal operation even when two machines use the same nominal solvent. Plan filter removal, the waste container, and replacement-filter storage together so that contaminated filters never pass above cleaned assemblies. Differential pressure can monitor filter loading, but its relationship to demonstrated hood performance must be established: a single pressure reading does not measure capture at every branch.

7.5 Chemical inventory, storage, and dispensing

Manage unopened stock, in-use containers, mixed working material, returnable material, and waste as distinct inventories, each with its permitted location and quantity. Keep workstation quantities within justified operating demand while preserving lot identification, expiration, opening date, and formulation-specific temperature conditions. Arrange storage by chemical compatibility and hazard. Oxidizing, corrosive, flammable, and reactive materials may need different storage and containment; alphabetical order or container size is not a sufficient basis.

OSHA 1910.106 addresses cabinet capacity, storage arrangements, handling, and industrial use in separate provisions. Allowable room or building inventory therefore depends on liquid category, use conditions, fire area, and applicable adopted codes as well as cabinet capacity [45]. Dispense in a designated controlled location using stable receiving vessels, spill retention, compatible closures, and the bonding or grounding arrangement required for the transfer operation. Keep unused mixed coating and contaminated cleaner out of the original stock.

Flammable-liquid cabinet ventilation must conform to manufacturer guidance and applicable authority requirements, including any alteration of bungs, ducts, or fittings. Manufacturer guidance explains that ventilation is not automatically required for fire protection and that a vented installation must preserve the cabinet's intended performance. An improvised exhaust connection is therefore inappropriate [46]. Cold-storage equipment must be suitable for the formulation's hazard; a temperature-controlled cabinet for dry PCBAs is not interchangeable with storage for flammable chemicals.

7.6 Electrical systems, ESD, and ignition control

Electrical design has three distinct acceptance tasks: protective earthing and fault protection, electrostatic protection of the assembly, and ignition-source control in hazardous atmospheres. ANSI/ESD S20.20 provides the ESD control-program framework for electronic parts and assemblies [47]. Hazardous-location suitability of the booth and its accessories requires separate evidence; an ESD-marked mat, wrist strap, chair, or air ionizer does not establish suitability for flammable vapor.

Under OSHA 1910.307, each area's classification depends on the materials present and the likelihood of a hazardous concentration. Record the resulting boundaries and equipment requirements [48]. The assessment must include spray controls, lights, sensors, fans, heaters, portable inspection devices, and equipment brought in for maintenance. Place ordinary switching and

instrumentation outside classified regions where the approved design allows, and distinguish normal operation from releases caused by damaged hoses, open containers, or ventilation failure.

The load schedule should record connected and simultaneous demand, startup behavior, protective-device coordination, isolation, and environmental suitability. Separate control and process power where necessary to achieve the specified failure response. Preserve electrical working space and access in accordance with the installation, labeling, environmental-exposure, cooling, and clearance provisions of OSHA 1910.303 [49]. A cabinet behind a process bench must remain serviceable without relying on that bench as temporary electrical working space.

7.7 Water, process gases, and waste interfaces

Specify water quality at the point of use, with the required attributes and sampling locations defined by the cleaning process. Distribution materials, stagnation, filters, and the final length of hose can alter quality downstream of the treatment system. Identify clean supply, recirculated wash solution, final rinse, and recovered waste separately on the piping schematic. Physical arrangement and identification should discourage misconnection, while accessible isolation and appropriate backflow protection preserve control of each stream.

Similarly, specify compressed-gas quality, pressure, flow, and filtration at the nozzle or machine inlet wherever gas contacts assemblies. An oil-free compressor designation does not establish downstream cleanliness; qualification must also consider residues from hoses and regulators. Blow-off methods require evaluation for redistribution of contamination and displacement of liquid into inaccessible features. Where nitrogen is used, assess oxygen displacement from credible leaks and operating releases. Cylinders and distribution systems introduce hazards independent of the cleaning chemistry.

Keep spent cleaner, rinse concentrates, solvent-bearing coating waste, and contaminated consumables separate until their compatibility and disposition are established. Visual clarity is insufficient evidence for liquid discharge. EPA's pretreatment provisions for nondomestic discharges to publicly owned treatment works address fire, corrosion, interference, pass-through, and other hazards; local limits and permissions also inform the design [50]. Every disposal route, including a floor drain, needs an established basis.

Closed collection and prompt removal reduce exposed evaporating area and support housekeeping. Characterize waste by its actual contents, including metals or reactive residues introduced during use. EPA's solvent-contaminated-wipes exclusions depend on waste constituents, container management, documentation, free liquids, and state adoption. Marketing a cleaner as environmentally preferable does not establish that its used wipes qualify as ordinary trash [51].

7.8 Thermal processing, UV equipment, and environmental control

Assembly drying and processing of solvent-bearing coated work impose different equipment requirements. Establish maximum solvent loading, heat release, ventilation, purge, interlocks, temperature limits, and the permitted loading sequence for each intended duty. NFPA 86 is the relevant oven/furnace standard family; record the project-adopted edition and equipment classification in the design basis. The newest catalogue edition is not automatically the governing edition [52]. A general laboratory oven must not be assumed suitable for evaporating flammable solvents, and the automobile-refinishing provisions of 1910.107(j)(4) do not define a general PCBA purge schedule.

Provide a designated location for takeout and cooling, with a clean, thermally suitable fixture and enough space for the full batch. Protection of the baked assembly must continue through unloading, cooling, and transfer. For UV equipment, use suitable enclosures and interlocks to contain accessible radiation, assess lamp-dependent ozone and heat emissions, and preserve light-source cooling and service clearances. Optical and material qualification must establish sufficient dose and shadow-region cure separately from enclosure safety.

Monitor temperature and relative humidity where materials and assemblies are processed. Set limits from the coating, cleaner, component, and process-qualification requirements, since no universal room setpoint ensures acceptable viscosity, evaporation, adhesion, or moisture control. Consider dew point when cold materials or assemblies enter the room. Lighting should support color and surface inspection without glare, shadows, or unintended heating. Cleanable finishes, controlled garments, suitable wipes, and a defined housekeeping sequence address contamination at its sources. Cleanroom classification is justified only by a defined particle-control requirement and its corresponding verification program.

7.9 Egress, emergency access, and operating states

Preserve the escape path with equipment doors open and a normal batch cart present. OSHA 1910.37 requires unobstructed exit routes and addresses travel toward high-hazard areas [53]. Storage, unattended trays, and waste containers must remain clear of this path, even temporarily. Locate emergency isolation, spill-response equipment, and first-aid provisions so they can be reached without passing through the emission source. Where injurious corrosives create an eye or body exposure risk, OSHA 1910.151(c) requires suitable immediate flushing facilities [54]. Select protective equipment and emergency provisions from the chemical assessment; a wall-mounted bottle cannot be assumed adequate for every exposure scenario.

A cause-and-effect specification translates the risk assessment into observable equipment behavior. A process stop and loss of all electrical power can have different consequences: stopping an exhaust fan while solvent continues to evaporate can worsen the condition. Define the response sequence from the selected equipment, detection, and fire strategy. Manual reset must preserve the event record and leave affected work subject to disposition.

Table 12: Cause-and-effect requirements for the selected equipment and assessed hazards.

Initiating condition	Intended controlled response	Evidence to retain
Insufficient capture flow	Inhibit new emitting work; execute the defined shutdown and ventilation sequence	Trip basis, sensor test and recovery test
Filter or duct restriction	Alarm or stop at the established operating boundary	Loaded-filter performance and alarm response
Oven overtemperature or ventilation fault	Remove heat or material feed as specified; preserve required protective functions	Independent-limit and sequence verification
UV enclosure access	Prevent hazardous accessible radiation; identify interrupted product	Interlock test and restart behavior
Liquid leak or excessive collection level	Isolate the affected source and prevent uncontained transfer	Detection, containment and isolation test
Power loss or emergency stop	Enter the documented equipment-specific safe state	Residual-hazard review and restoration sequence

7.10 Commissioning, capacity, and change control

Commissioning demonstrates the installed system under representative use and establishes the maintenance baseline. HSE's LEV commissioning guidance offers a technical model: define emissions and operating conditions, verify balance at every hood, and retain quantitative performance, qualitative observations, test points, and calibration evidence. Its United Kingdom inspection intervals are not adopted here as United States legal requirements [55].

The commissioning matrix combines maximum intended simultaneous operation, routine door movement, realistic fixtures, clean and permitted loaded-filter conditions, and relevant failure states. Airflow and pressure measurements require an appropriate exposure assessment alongside them. A harmless tracer can reveal escape, but does not measure solvent concentration. Acceptance also requires evidence of utility quality at the point of use, electrical and ESD controls, thermal uniformity with the planned load, emergency functions, and the clean transfer sequence. Deviations and corrective actions form part of the record supporting the released operating envelope.

Determine capacity from the slowest qualified operation and the buffers around it. Account for cleaning batches, bake and cure dwell, cooling, inspection, rework, and protected holding limits. More benches or a faster coater can increase congestion if the oven or inspection station cannot accept the output. Reserve space for a defined maximum work-in-process quantity and a separate failed-work position. Evaluate expansion through its effects on simultaneous exhaust demand, utility capacity, storage inventory, and service access.

Changes to chemistry, nozzles, enclosure openings, exhaust branches, filters, rack loading, material inventory, or adjacent HVAC can invalidate the operating basis. Assess them through the same interfaces used for initial qualification. A compact arrangement supports professional practice when it preserves measurable control, safe access, and repeatable work. Drawings, inspection points, and commissioning records keep the concealed infrastructure accessible to that same level of control.

8 Case Study: Compact Cleaning and Coating Work Center

8.1 Study basis and geometric method

The original flux-removal study and facility model connect process intent with spatial design. The process study defines two functional stages: residue control during bench fabrication and final assembly preparation before coating or packaging. The STEP model locates a circuit card assembly (CCA) work cell, an adjacent mechanical-washing bay, equipment, and supporting services. These physical spaces serve different purposes from the two process stages. In particular, mechanical-parts washing is a separate operation from bench fabrication of PCBAs [1, 2].

The geometric analysis preserves the STEP AP214 assembly hierarchy, component occurrences, and accumulated placement transformations. Declared inch units were converted to millimetres using the exact relation 1 in = 25.4 mm. The hierarchy contains 100 nodes, including 95 leaf occurrences representing 56 distinct leaf definitions; the exchange file contains 61 product records. Repeated instances retain their individual locations. Measurements come from the located boundary representation, planar faces, and analytic cylindrical surfaces, rather than rendered pixels.

The analysis views suppress selected walls, roof panels, and obstructing equipment while leaving the source model unchanged. A local coordinate system uses u across the CCA cell, v from the wet-process bank toward the opposing worktables, and h upward from the floor. The accompanying transformation, component inventory, visibility sets, and measurement records document how the

views and dimensions were obtained. Neutral shading carries no construction-material designation. Throughout this case study, CAD dimensions describe nominal geometry; installation tolerances, equipment certification, installed condition, and commissioned performance require separate evidence. Component names such as "drying oven" identify design intent without establishing rating or usable capacity.

8.2 Room dimensions and usable space

The CCA cell's internal wall planes define a 3403.6 mm by 2438.4 mm rectangle, equivalent to 11 ft 2 in by 8 ft. Its rectangular plan area is 8.299 m^2, with a modeled floor-to-roof-underside height of 2184.4 mm. A short separator projects from the wet-process wall beside the hood; deducting its footprint gives a floor-face area of 8.268 m^2. Both areas precede any deduction for equipment, operators, storage, or maintenance envelopes [2].

The adjacent mechanical-washing bay measures 3403.6 mm by 4673.6 mm internally, giving approximately 15.907 m^2. Together, the two interior rectangles occupy approximately 24.206 m^2. This sum excludes the wider building and supporting-service area. As figure 5 shows, the assembly also includes a much larger slab; using its overall bounding box to measure the rooms would materially overstate their area.

Table 13: Nominal dimensions from the STEP model, before deducting equipment and operating envelopes.

Quantity	Model-derived value	Interpretation
CCA internal rectangle	3.4036 m × 2.4384 m	Distances between enclosing internal wall planes.
CCA rectangular area	8.299 m^2	Gross internal rectangular envelope.
CCA floor-face area	8.268 m^2	Excludes the projecting separator footprint only.
Modeled clear height	2.1844 m	Floor to roof underside; local services reduce available space.
CCA rectangular volume	18.129 m^3	Geometric envelope, not free-air or usable working volume.
Separator	50.8 mm thick; 609.6 mm projection	Geometry does not establish fire resistance or a complete emission boundary.
Adjacent mechanical bay	15.907 m^2	Separate internal rectangular area.
Local opposing-bank interval	Approximately 0.926 m	Static fixture-envelope separation at overlapping locations; not an accepted aisle width.

8.3 Spatial arrangement, transfer, and operating envelopes

The layout concentrates the hood, rinse basin, and ultrasonic station along one side of the CCA cell, opposite the worktables and modeled drying oven. A wall-mounted sink, waste container, aerosol-storage unit, ESD provisions, and local electrical and service components complete the arrangement. The DI vessels sit outside one CCA wall, with the spill kit outside the opposite wall. This distribution keeps the working sequence close together while moving supporting functions into adjacent service space. That surrounding area remains part of the facility's space requirement.

Figures 6 and 7 show the equipment positions and their static envelopes. Where the rinse and ultrasonic stations overlap the rear-table bank, the opposing fixture envelopes are approximately

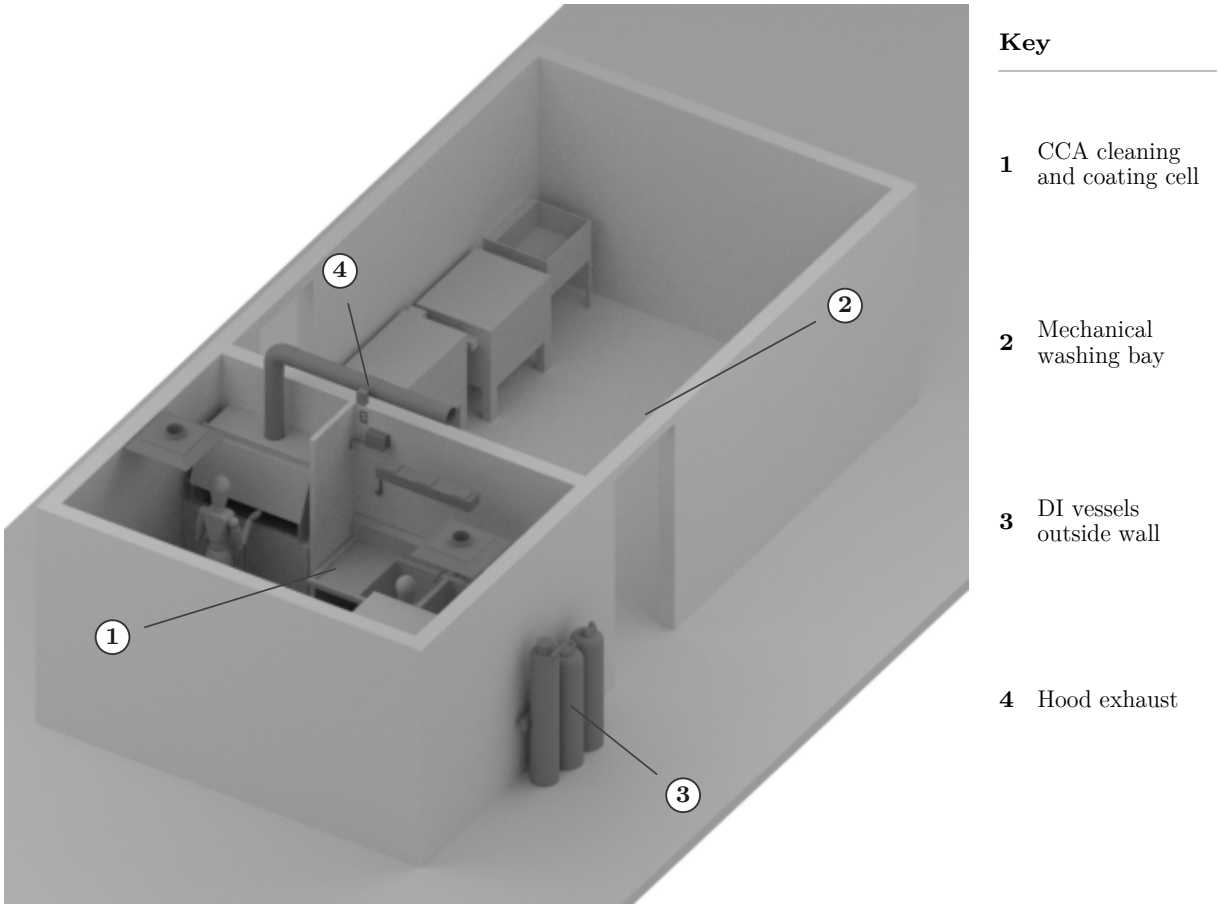


Figure 5: Facility context from the STEP assembly, with selected roof geometry suppressed. The CCA cell adjoins a separate mechanical-washing bay and external support equipment.

926.3 mm to 926.7 mm apart. The interval excludes operators, trays, hose movement, open doors, and removed equipment, so it cannot be treated as a minimum usable circulation path or accepted egress width. Two approximately 1.805 m mannequin instances convey scale and working orientation. Reach, posture, accessibility, and simultaneous occupancy are assessed under the defined operating states.

Short transfers can support control of time between washing, rinsing, and drying, while requiring movement across the shared working interval. A qualified method defines a holding position for dripping assemblies, containment of runoff, and a route from accepted dry work to masking and coating that avoids uncontrolled splash or dirty handling. Covered carriers, a designated receiving position, and separation by work status can preserve the accepted surface condition. Takeout and cooling require a reserved clean location for a full drying load, accounting for the consumables, fixtures, and other batches that may occupy the benches at the same time.

The oven component is explicitly identified as approximately dimensioned. Equipment acceptance depends on the selected supplier's dimensions, tray-withdrawal distance, usable chamber volume, ventilation connections, thermal loading, and permitted solvent burden. The adjacent isolation mat defines a layer and location; thermal and fire ratings are properties outside that geometric

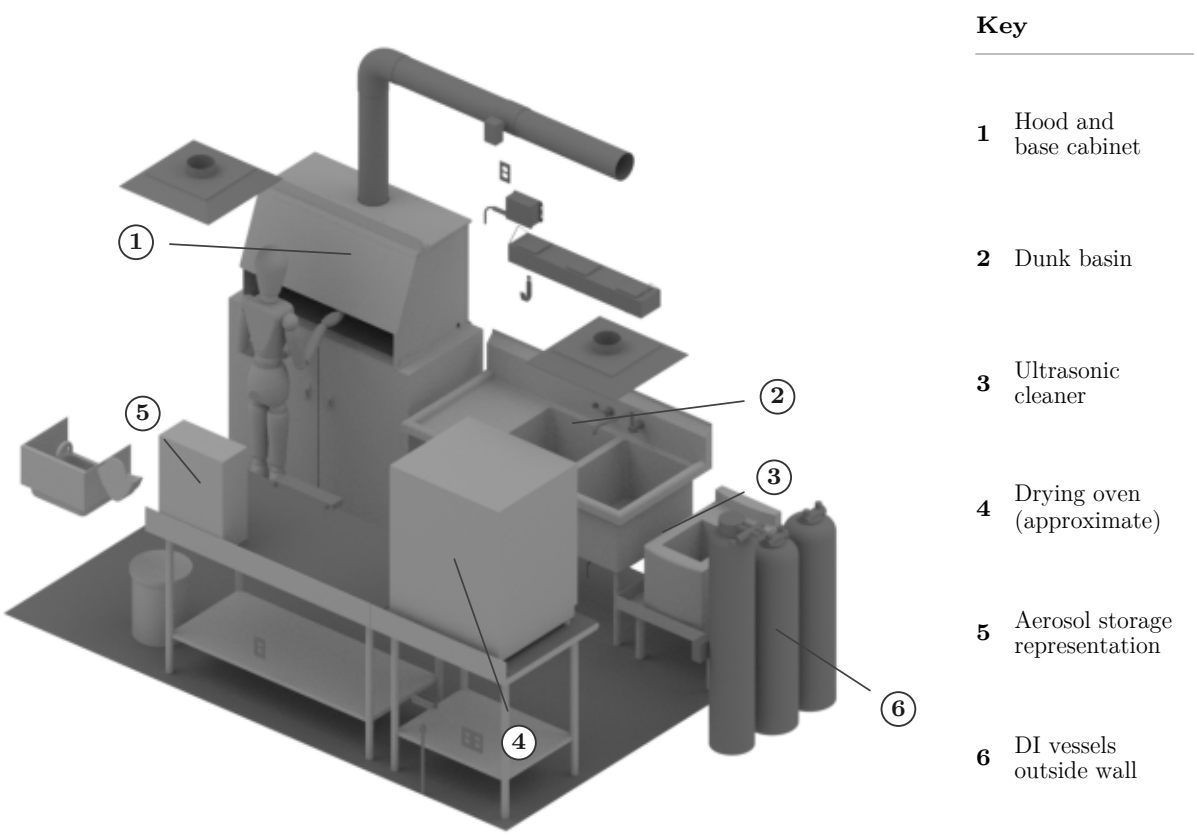


Figure 6: CCA cell with roof and enclosing walls suppressed, showing overhead exhaust, external DI vessels, opposing workbanks, and under-bench services in their modeled positions.

representation. Fit acceptance uses the selected equipment envelope together with the swept volumes required for doors, racks, access, and removal.

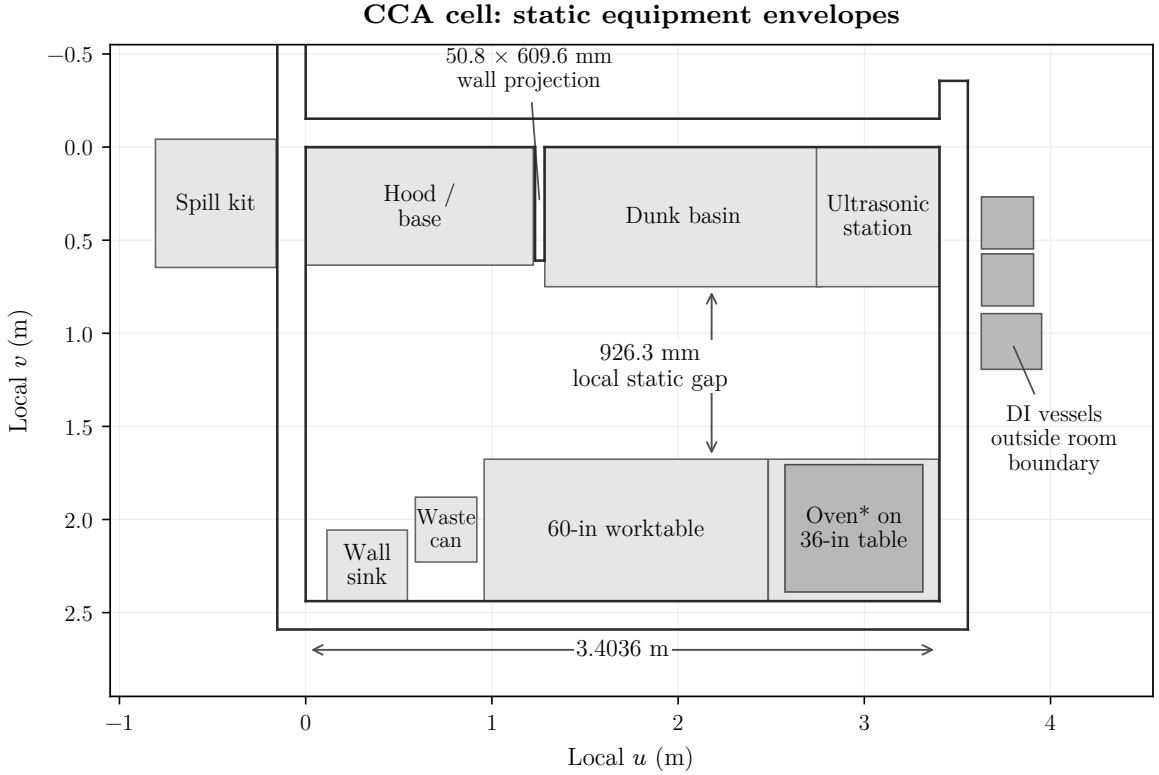


Figure 7: Dimensioned CCA plan. Equipment reservations represent static projected geometry or envelopes; the opposing-bank interval excludes operating and maintenance movement.

8.4 Concealed services and exhaust interfaces

Suppressing the walls exposes the support systems that make the compact arrangement possible. Table 14 connects each modeled system to its design and acceptance criteria. Component hierarchy and context are essential to interpretation: several pipe-and-flange components form the ultrasonic support-table legs and must not be counted as water or gas lines.

Table 14: Modeled services and the evidence required for functional acceptance.

System	Observed model evidence	Design and acceptance criteria
Hood exhaust	Hood collar, three straight-pipe instances, one elbow, and a butterfly-valve representation; route rises through and above roof.	Defined operating duty; complete fluid route; fan and capture performance; controls; treatment where required; final discharge.
Room air	Two ceiling objects named as air inlet/outlet interfaces.	Specified supply/return/exhaust roles, flow rates, throw, pressure relationships, and operating modes.
DI water	Two shorter vessels, one taller vessel, and a bracket outside the CCA wall.	Defined vessel function, resin/media, flow order, isolation, sampling, breakthrough criteria, connections, and replacement access.
Rinsing and drainage	Basin, faucet, drain-valve and flow-adjustment components.	Tagged fluid schematic separating clean supply, intermediate rinse, final rinse, collection, and authorized disposition.
ESD controls	Floor and table mats, connection-point and bus-bar components, static-neutralization-related equipment names.	Demonstrated product ESD control at working positions; separate protective-earthing and ignition-control evidence.
Electrical interfaces	Receptacle and equipment-power representations at several heights.	Load schedule, protective devices, environmental suitability, isolation, routing, and installation requirements.
Storage and waste	Aerosol-storage object, waste can, hood cabinet, worktable shelves, and external spill kit.	Approved contents, inventory limits, compatibility, containment, status segregation, and accessible response equipment.
Light and thermal equipment	UV-light object and an approximately dimensioned drying oven.	Defined inspection or cure function, applicable spectrum/dose, thermal performance, and permitted operating environment.

The hood geometry and component names are consistent with a 40-inch ducted-hood family. The manufacturer's brochure describes a six-inch exhaust collar and identifies the fan and ducting as separate provisions. The comparison supports the interface analysis at product-family level, without identifying an exact selected configuration or qualifying it for conformal coating [56]. Spray-finishing construction, ignition control, and exhaust compliance depend jointly on chemistry, deposition method, emission rate, enclosure materials, and equipment approval. A CAD designation such as "spray booth" is not evidence of those properties.

The straight exhaust-pipe surfaces define an internal diameter of 152.4 mm, compared with approximately 147.83 mm at the hood-collar bore. Their circular areas are approximately $0.018\,24\,\mathrm{m}^2$

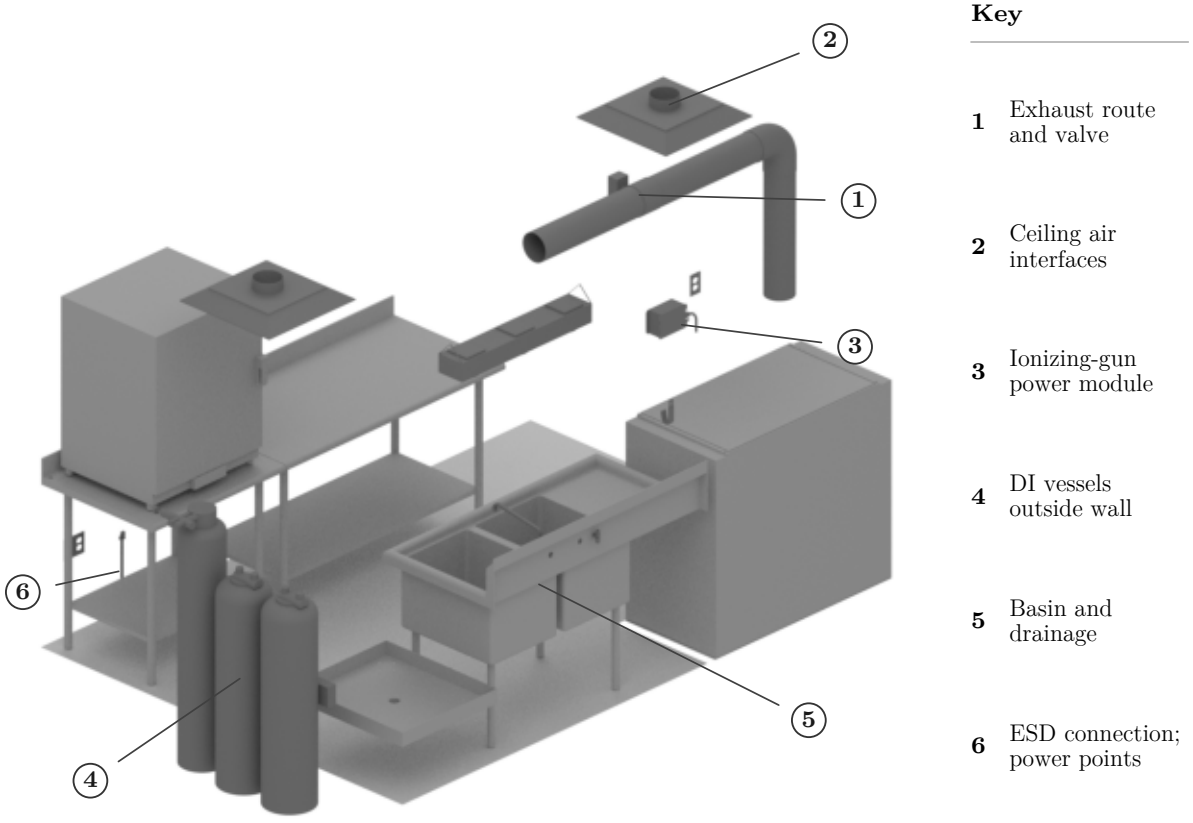


Figure 8: Concealed services exposed by suppressing selected shell and equipment panels, showing exhaust, water, electrical, and ESD interfaces in relation to process equipment.

and $0.017\,16\,\mathrm{m}^2$, respectively. At an assumed common incompressible volume flow, the collar's approximately 5.9 % smaller area would produce about 6.3 % greater mean velocity. For a specified flow, this geometric relationship follows from $v = Q/A$. The operating point is determined by the complete pressure-loss model and fan characteristic.

The modeled exhaust route ends above the CCA-cell footprint, without a fan or final external discharge termination. Its elbow is an outer swept form with no demonstrated internal passage. This arrangement-level simplification prevents direct use as a verified fluid domain; flow analysis requires connected internal geometry, defined duct interfaces, and a pressure-loss basis. The representation does not indicate a blockage in an installed duct.

The roof interface contains a quantifiable geometric interference. Its circular opening is modeled at 152.4 mm diameter, while the riser's outside diameter is 158.75 mm. The nominal difference is 6.35 mm; a Boolean intersection of the located solids confirms approximately 77.6 cm^3 of common volume, as shown in figure 9. Penetration acceptance depends on the final opening and duct geometry, sleeve or seal, installation tolerances, support, movement, and required protection for the selected construction. The calculation neither specifies the final hole size nor establishes the condition of an installed roof.

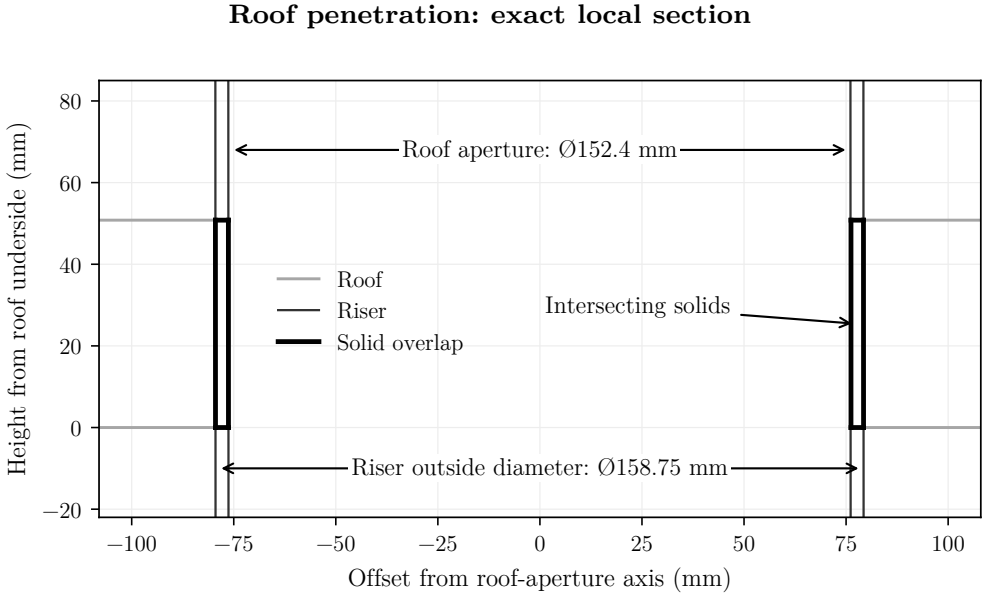


Figure 9: Roof-to-riser interface. Source-derived diameters and positive Boolean common volume identify a nominal CAD fit interference.

8.5 Wet-process, thermal, and coating interfaces

The process sequence depends on a verified boundary between used liquid and the final clean rinse. Returning runoff to a vessel does not regenerate collection or reused soak water, and the three outside-wall vessels alone do not establish either treatment sequence or purity at the workpiece. Their configuration must provide accessible point-of-use sampling and maintenance, with a service route that avoids carrying contaminated items through the accepted-product location.

The modeled ionizing-gun power module introduces an equipment-specific environmental constraint. The Top Gun manual discussed in the cleaning chapter excludes wet environments and flammable or explosive atmospheres, and restricts filter-nozzle contact with alcohols or glycols. The selected hardware's environmental rating therefore governs any use directly over wet collection [15]. Static neutralization, liquid removal, material compatibility, and ignition suitability require distinct evidence. Acceptance of cleaning air must also address applicable nozzle-pressure, guarding, and protective-equipment requirements beyond the supplier's maximum inlet pressure [57].

Coating capability requires controlled locations for material preparation, masking, application, flash-off, complete cure, and inspection. The model records equipment positions; it does not establish

every process state or simultaneous capacity. Those operating properties depend on whether drying and coating cure share equipment, whether wet cleaning and coating can run concurrently, and where full loads remain protected while waiting. A shared oven requires an approved material sequence, contamination controls, thermal capability, and equipment suitability.

Mechanical-parts washing in the adjoining bay creates a separate contamination boundary. Transfer of fixtures, brushes, containers, gloves, or reusable liquid into the PCBA process requires a qualified cleaning and release method. The boundary includes splash, handling, footwear and cart movement, and air transfer at any planned or installed connection. Control of these paths preserves each operation's function while preventing its waste and residues from becoming an uncontrolled input elsewhere.

8.6 Access and circulation requirements

The CCA cell's enclosing walls contain no modeled doorway. Analysis of face boundary loops and areas confirms that the five inner wall faces, including the front wall split by the separator, are complete rectangles without an opening or notch. The adjacent mechanical bay contains side openings of approximately 812.8 mm by 2057.4 mm and 914.4 mm by 2082.8 mm. These are findings about the model: they establish neither absent access in an existing room nor compliance of the adjacent openings with exit requirements.

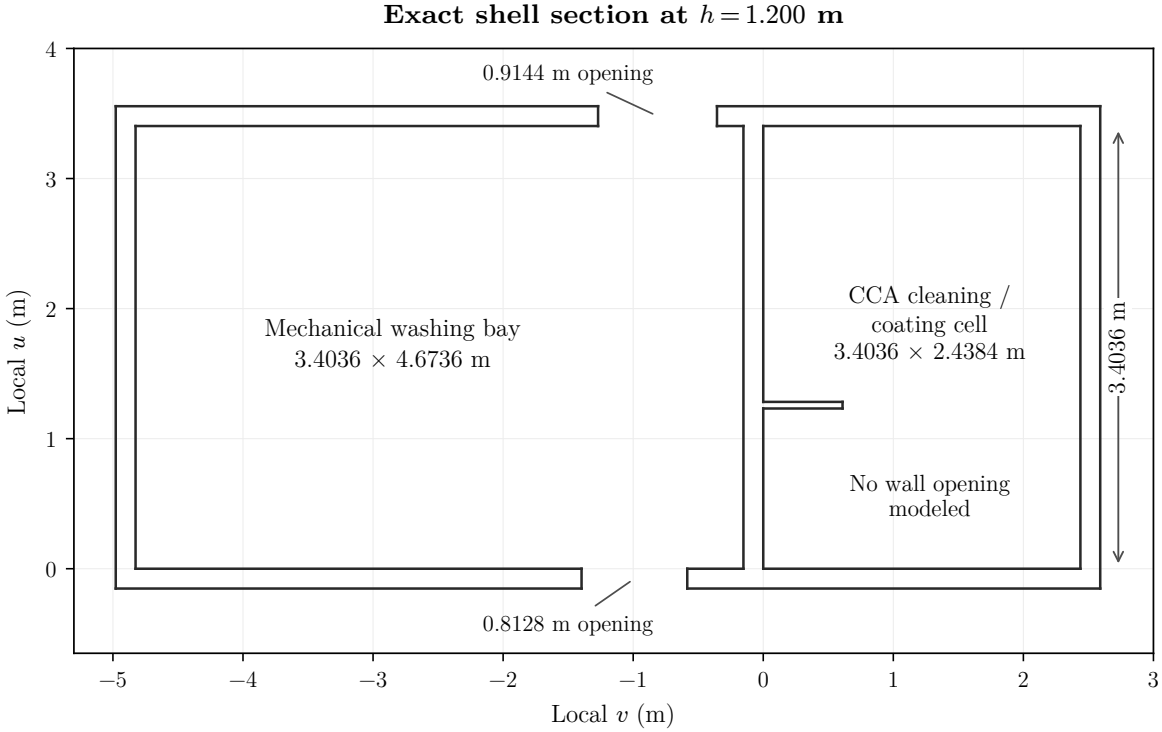


Figure 10: Horizontal section through the facility shell at $h = 1.200$ m. The section retains the modeled CCA boundaries, projecting separator, and adjacent-bay openings.

Circulation acceptance requires an access opening, door or other closure, transfer method, and equipment-removal route. The opening also affects pressure balance, crossdrafts at the hood,

contamination transfer, and storage placement, making access an integral part of the process design. The same operating-state analysis must include outside-wall DI servicing and spill-kit access.

The case study demonstrates the spatial coordination of wet processing, thermal preparation, coating-related equipment, utilities, and maintenance interfaces within an approximately $8.30\,\mathrm{m}^2$ CCA cell supported by adjoining service space. Functional performance depends on equipment and operating envelopes, access and building-service connections, controlled clean/dirty and emission boundaries, and verification under representative conditions. The worked examples in section E address a separate, explicitly assumed $24\,\mathrm{m}^2$ room; they are not calculations of the measured CCA cell.

9 Qualification, Measurement Integrity, and Release

9.1 Qualification stages

Qualification progresses from material-compatibility screening to representative process trials and service-relevant assembly evaluation. Compatibility screening establishes the permitted cleaner, coating, mask, fixture, and temperature exposures. Process trials establish bounded cleaning, drying, application, and cure windows on representative hardware. Assembly evaluation then tests the completed process against its environmental and electrical requirements. Production release rests on successful completion of the applicable stages and a documented operating envelope.

Installation verification and process validation address different outcomes. An oven may achieve its setpoint while a heavily loaded assembly remains too cool; a running fan may provide inadequate capture through a restricted duct; and a repeatable coating path may miss a critical surface. Acceptance therefore depends on the required output at the workpiece or exposure location, supported by the relevant equipment checks.

9.2 Representative test articles and controls

Use a test vehicle that contains the difficult features of the product family: the smallest relevant conductor spacing, representative solder mask and finish, low stand-off packages, component overhangs, connectors, recesses, and thermally sensitive items. Standard comb patterns are useful electrical sensors but do not automatically reproduce an assembly's cleaning access. Combine them with process-representative geometry and, where necessary, sacrificial production-equivalent assemblies.

A comparison set includes a documented clean control and the cleaned-and-coated process condition. An uncleaned-and-coated condition belongs in the set only when that route is under evaluation; an uncoated control helps distinguish coating protection from the initial surface condition. Deliberately contaminated research coupons require known contaminant identity and loading and remain separate from production hardware.

Record material lots, soldering and rework history, board position, rack loading, operator, day, and equipment condition. Randomize within feasible operating restrictions and block known nuisance factors. Independent process runs provide stronger evidence of repeatability than repeated readings of the same coupon. Ten measurements at adjacent points on one board are not ten independently manufactured boards.

9.3 Factorial screening protocol

For three bounded cleaning factors—concentration, temperature, and exposure time—a two-level factorial design contains eight combinations. Three independent runs at each of two representative residue-aging conditions give 48 process cases, before controls and additional specimens for destructive measurements. This calculation defines the experimental design size. Actual factor levels are selected within component restrictions and approved chemistry limits before testing.

The response set combines chemical, physical, and electrical evidence: selected extracted ions, a documented residual-film score, adhesion after conditioning, coating continuity, and insulation response under the specified humidity and bias. Time-series electrical measurements and time to failure retain transient behavior that a final reading can miss. Specimens surviving to test termination are right-censored observations. Test duration and environment follow the requirement or failure mechanism; a single exposure condition does not necessarily accelerate every field mechanism.

Screening identifies influential factors and interactions. Confirmation then demonstrates the defined operating window, including its limits, with different lots or other relevant sources of variation. If manual application is retained, evaluate between-operator effects and the representativeness of the training standard. Investigate failed trials and preserve them in the record; excluding them because the preferred setting performed better biases the conclusion.

9.4 Acceptance criteria and release evidence

Table 15 defines the qualification and release framework. Each criterion has a product-specific technical basis, measurement method, and decision rule established before testing. Cleanliness limits, cure conditions, and coating thickness therefore follow the applicable material and assembly requirements. Development objectives, binding release requirements, and deviation authority are recorded separately.

Table 15: Qualification and release criteria. Numerical limits follow the product and process baseline established before testing.

Characteristic	Criterion and technical basis	Evidence / decision
Material compatibility	No unacceptable physical or functional change after the approved chemical and thermal exposures.	Before/after examination and tests on representative materials and assemblies.
Cleanliness	Product-specific limits and process window supported by complementary chemical and electrical evidence.	Extraction method, blanks, normalization, reporting limits, and representative humidity–bias data.
Drying and holding	Defined endpoint and maximum delay supported for worst relevant load, geometry, and storage condition.	Loaded thermal records; appropriate moisture or retained-fluid evidence; subsequent process performance.
Coverage / keepouts	Drawing-defined surfaces protected and restricted functional features free of unacceptable coating.	Visible and appropriate UV inspection, accessible views, mask reconciliation, and functional checks.

Table 15 (continued)

Characteristic	Criterion and technical basis	Evidence / decision
Thickness	Controlled range, measurement locations, and method appropriate to the selected coating and geometry.	Calibrated method and correlated witnesses; local extremes as well as averages.
Cure	Material state demonstrated by a qualified relationship between recipe and required properties.	Actual thermal, moisture, or light exposure; appropriate witnesses and secondary-cure evidence.
Electrical behavior	Required insulation and functional performance maintained under specified electrical and environmental stress.	Defined test circuit, bias, humidity, duration, current sensitivity, and failure criteria.
Environmental durability	No unacceptable degradation after service-relevant exposures and combined sequences.	Inspection, adhesion where suitable, and electrical tests before and after exposure.
Facility capability	Required capture, exposure control, utilities, pressure relationships, and fault responses demonstrated.	Commissioning records under representative loading and credible degraded conditions.
Rework / packaging	Repairs satisfy original requirements; packaging preserves coating and product function.	Approved repair record; repeated applicable inspections/tests; storage compatibility evidence.

9.5 Uncertainty and defensible decisions

Specify what is being measured, where, and under which conditions. A thickness result at a flat coupon, an average of a face-velocity traverse, and a minimum insulation resistance during a humidity test are different measurands. Their calibration, sampling, repeatability, and interpretation require separate uncertainty evaluations.

For $q = f(x_1, \ldots, x_m)$, first-order propagation gives

$$u_c^2(q) = \sum_i \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i<j} \frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j} u(x_i, x_j). \tag{9}$$

This is the linearized framework of the GUM. The adequacy of the first-order approximation depends on the measurement model and input uncertainties; significant nonlinearity requires evaluation of higher-order effects or numerical propagation. Correlated inputs are represented by the covariance terms [58]. Report whether the uncertainty describes the mean, an individual observation, spatial sampling, or the complete measurement procedure. Repeated sampling cannot remove an uncorrected bias or unrepresented location.

For the independent illustrative spray-flow calculation in section E, assign $u(A_f) = 0.012\,\mathrm{m}^2$ and $u(\overline{v}_n) = 0.035\,\mathrm{m/s}$ as standard uncertainties, with zero covariance. Then

$$u_c(Q) = \sqrt{(\overline{v}_n u(A_f))^2 + (A_f u(\overline{v}_n))^2} = 0.0268\,\mathrm{m}^3/\mathrm{s}. \tag{10}$$

The hypothetical result is therefore $0.540\,\mathrm{m^3/s}$ with expanded uncertainty approximately $0.054\,\mathrm{m^3/s}$ at the assumed coverage factor $k = 2$. These inputs are illustrative, not instrument specifications or field measurements. The model omits correlated spatial errors and should not be used as an installed-booth uncertainty budget without refinement.

A conservative decision rule for a lower acceptance limit is $q - U \geq q_{\min}$. For an independently specified illustrative requirement of $0.500\,\mathrm{m^3/s}$, the guarded value is approximately $0.486\,\mathrm{m^3/s}$; acceptance is therefore unsupported under this rule. That decision concerns the available evidence and its uncertainty, rather than proof that the actual flow is below the requirement. JCGM 106 addresses the role of measurement uncertainty in conformity decisions [59].

9.6 Repeatability, stability, and finite-sample evidence

Use control charts or an equivalent stability assessment before interpreting process capability. A calculated capability index is meaningful only for an appropriate, sufficiently supported distribution and a stable process. NIST describes C_p and C_{pk} in that context [60]. Do not compute a reassuring index from several readings on a single board or combine different products into one artificial distribution. For a mixed-product cell, appropriate controls may be stratified by recipe, geometry, and equipment condition.

Zero observed failures provide a finite amount of evidence. Under an independent, identical Bernoulli model, the one-sided upper confidence bound for defect probability after zero failures in n units is

$$p_U = 1 - \alpha^{1/n}, \tag{11}$$

where $1-\alpha$ is the confidence level. The expression follows from $(1-p_U)^n = \alpha$ and the exact binomial approach [61]. At 95 % confidence, 30 zero-failure units give $p_U \approx 0.0950$; 60 give approximately 0.0487; and 299 give approximately 0.00997, as shown in figure 11. These sampling examples leave qualification sample size tied to the actual requirement and test design. Correlation within a bath or cure batch weakens the independence assumption, while extrapolation from a short laboratory trial to long-term field reliability requires a separate basis.

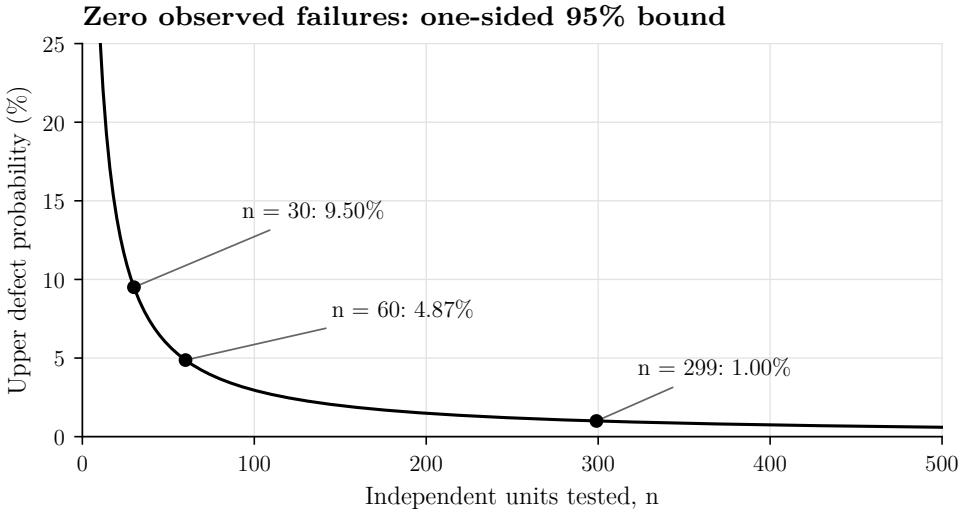


Figure 11: One-sided 95 % upper bound on defect probability after zero failures. The calculation assumes independent units with a common Bernoulli defect probability.

9.7 Data integrity and long-term control

Preserve original measurements, instrument exports, images, environmental logs, material records, and exceptions separately from calculated summaries. Link each record to the assembly or coupon, process recipe, equipment configuration, time, and operator. Keep raw failed runs; corrections should create an auditable interpretation rather than replace inconvenient observations.

A release record should permit reconstruction of the actual process. Retain the approved baseline, the records used to accept the lot, calibration status, and any deviation or repair disposition. Periodic review should examine drift in bath loading, rinse performance, material consumption, defect location, exhaust condition, oven behavior, and rework frequency. These signals connect product quality to facility maintenance instead of treating them as unrelated administrative systems.

10 Discussion and Engineering Conclusions

10.1 Integrated process and facility performance

The analysis links each manufacturing operation to the condition it establishes or preserves. Cleaning establishes the coating interface; drying and protected transfer preserve it; application and cure form the protective film; and inspection and electrical evidence support release. The facility provides the environmental, utility, handling, and maintenance conditions that make this sequence repeatable. Effective control therefore follows the mechanism at each interface.

The compact work center coordinates wet processing, hooded work, thermal equipment, worktables, storage, and electrical/ESD provisions within an $8.299\,\mathrm{m}^2$ internal CCA rectangle. External DI vessels and overhead exhaust extend the service envelope. The approximately $0.926\,\mathrm{m}$ local fixture interval represents static separation; usable operating space also accounts for personnel, trays, doors, and maintenance movement. The geometric results identify the significance of access, the roof/riser interference, the approximate oven envelope, and exhaust continuity. The independent calculations in section E quantify the corresponding relationships between access area, ventilation demand, building-service load, and process capacity.

Professional capability in a small area therefore comes from selecting compatible operations, containing emissions at their sources, preserving clean states, and planning service access. Vertical storage and overhead utilities can reduce occupied floor area only when retrieval, maintenance, inspection, and removal remain feasible. Scheduling can reduce simultaneous resource demand only when the restriction is enforceable and does not violate allowable product hold times.

10.2 Evidence and applicability

The results comprise process analysis, nominal facility geometry, and calculations with declared inputs. Production capability and installed performance are established through the qualification and commissioning methods, for which no completed dataset is presented here. Model precision describes the digital representation; equipment ratings, utility connectivity, and as-built dimensions have separate acceptance bases. Cleaner and coating selection, bakeout limits, and exhaust operating points are specific to the product, chemistry, and equipment. Manufacturer examples retain the revision and applicability limits identified in their citations.

The implementation basis consists of the product/material matrix, controlled equipment data, chemical inventory and use rates, duct and fluid schematics, access and building interfaces, and representative qualification measurements. These records connect the spatial design to material, exposure, and performance evidence. Supplier-controlled chemistry instructions, final-rinse topology, ionizer environmental suitability, and the complete drying/cure sequence are especially consequential because they determine the accepted condition at successive process boundaries.

10.3 Conclusions

1. A defensible conformal-coating process begins with a qualified surface condition and preserves that condition through drying, takeout, cooling, handling, and coating. A visually clean board or dry-to-touch film is insufficient evidence by itself.
2. Coating selection must address the actual formulation, service environment, geometry, electrical demands, cure mechanism, and repair strategy. Resin labels and material qualification certificates do not establish assembly performance.
3. The facility model coordinates multiple processing and support functions within an $8.299\,\mathrm{m}^2$ CCA-cell rectangle and adjoining service space. Its geometry demonstrates the distinction between equipment fit and the complete operating envelope, including access, utility continuity, and maintenance.
4. Release combines appropriate chemical, physical, electrical, and facility evidence with predefined decision rules. Analytical predictions, external reference images, qualification protocols, and observed production results must remain distinguishable.

Data and Reproducibility Statement

The source package contains the manuscript, bibliography, original diagrams, attributed NASA photographs, CAD-derived figures, declared assumptions, and calculated CSV/JSON outputs. The companion CAD archive contains the original process manuscript and STEP assembly, geometric inventory, measurement records, analysis scripts, and view configurations. Input checksums identify the unchanged source files. The records support reproduction of the geometric analysis and calculations; production measurements, calibration certificates, and completed qualification reports are outside this dataset. Figure provenance is documented in `FIGURE_SOURCES.txt`.

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A Operational Procedure

The operating sequence below defines the required controls, records, and release gates. Product-specific chemical mixtures, drying temperatures, and cure durations follow the qualified process baseline.

A.1 Readiness and incoming work

1. Verify the current assembly drawing, traveler, coating boundaries, material matrix, and approved process recipe, including the disposition of substitutions and previous repairs.
2. Verify personnel competency, required protective equipment, ESD controls, equipment readiness, calibration status, exhaust availability, and waste capacity. Demonstrate required permissives before introducing emitting material.
3. Identify incoming assemblies and inspect them under the defined conditions. Preserve the bench-cleaning and rework history, flux identity, residue age, and prior exposures. Record damage, residue, unsealed features, missing protection, and other exceptions. Complete the required baseline functional tests.
4. Check material identity, lot, expiry, storage condition, and container integrity. Prepare only the amount needed for the controlled work interval. Segregate incompatible material systems and tools.

A.2 Cleaning, drying, and transfer

5. Protect cleaning-sensitive items using the qualified method. Verify the load orientation, nozzle access, rack configuration, and maximum permitted loading.
6. Run the approved cleaning sequence. Record the relevant chemistry condition, temperature, exposure, mechanical settings, bath status, and observed exceptions.
7. Complete the rinse and drainage steps. Verify fluid quality at the defined sampling location, preserve the boundary between intermediate/reused liquid and the final rinse, and remove retained liquid through the qualified orientation and method.
8. Obtain the required cleanliness evidence. Hold affected work when a criterion fails; identify and correct the cause before a recleaning disposition is issued.
9. Execute the drying or demoisturization recipe, if required. Record actual load conditions and the event defining the start of the qualified dwell.
10. Prepare the protected receiving location before takeout. Record oven removal, cool the assemblies in the approved condition, and initiate the defined exposure/hold-time clock.
11. Apply and inspect masks and, where required, primer or surface activation in the qualified sequence. Verify primer identity, flash-off/cure, and permitted primer-to-coating interval as applicable. Verify that handling, mask materials, fixtures, and elapsed time have preserved the accepted surface condition. Release Gate 1.

A.3 Application, cure, and acceptance

12. Condition and prepare coating material using the specified method. Record any additions, ratios, viscosity measurement, working-life start, and authorized limits.
13. Verify nozzle or brush condition, fixture and program revision, orientation, dispensing behavior, and witness-coupon association. Apply the qualified sequence of passes or deposition stages.

14. Examine accessible uncured regions according to the process. Correct permitted local defects only with a qualified technique; repeated unplanned manipulation is a process exception.
15. Complete the qualified flash-off, cure, and demasking sequence. Demask at its specified stage, which may precede full cure; preserve the remaining cure requirements and protect exposed film edges. Record actual thermal, moisture, or optical conditions and any secondary-cure interval. Preserve the record of interrupted cycles.
16. Verify completion of all required cure and release Gate 2. Verify that demasking has occurred at its qualified stage, reconcile removable items, and inspect for adhesive residue, torn film, particles, or contact contamination.
17. Inspect coverage, local buildup, thickness evidence, keepouts, adhesion indicators, and visible defects. Use the specified illumination and appropriate magnification; identify any region that cannot be inspected directly.
18. Complete required functional and electrical tests. Route discrepancies to controlled evaluation and rework. Apply all required repeat inspections and tests after repair.
19. Release Gate 3 only when the record is complete. Package and store the assembly in a compatible condition with its status and traceability preserved.

A.4 Operator protection and competency

The work instruction distinguishes gloves used to protect the product from gloves used to protect personnel against chemicals. Selection follows the exposure assessment and qualified use conditions, including material, thickness, permeation, contact duration, and replacement practice. OSHA's PPE framework requires hazard assessment, suitable selection, and demonstrated training [62]. Personnel competency also includes controlled handling, material preparation, mask verification, defect recognition, and response to equipment faults.

Where respiratory protection is necessary, its selection and use follow the applicable respiratory-protection program. OSHA establishes engineering measures as the primary approach to atmospheric-contamination control and specifies program requirements for necessary respirator use [63]. The exposure assessment covers routine work and maintenance, because filter changes, deposit removal, and waste handling can produce different exposures.

B Facility Commissioning and Periodic Verification

The commissioning plan defines operating configurations, instruments, calibration status, measurement locations, required responses, and acceptance criteria before testing. Table 16 specifies the challenge conditions and records that support acceptance.

Table 16: Commissioning tests and retained acceptance evidence.

System	Challenge / observation	Record supporting acceptance
Layout and access	Normal loading, door movement, rack withdrawal, filter removal, maintenance tools, and maximum staging.	Dimensioned envelope review; photographs or model views; interference dispositions.
Source capture	Representative fixture, operator position, source rate, doors, and simultaneous equipment operation.	Velocity/flow traverse; suitable capture observations; exposure assessment; agreed operating boundary.
Room balance	Mechanical supply, transfer routes, exhaust modes, adjacent HVAC, and normal door states.	Flow and pressure records tied to each operating mode; acceptable door and airflow behavior.
Exhaust degradation	Allowed filter loading, branch restriction, sensor fault, and loss of protective airflow.	Alarm/trip setpoints, margins, response time, shutdown sequence, and recovery demonstration.
Water and gases	Point-of-use quality, startup, normal demand, and worst relevant simultaneous draw.	Sampling method and results; pressure/flow/quality limits; line and filter configuration.
Drying / cure oven	Empty and representative loaded mapping, heat-up, dwell, high-temperature limit, and ventilation fault.	Time-stamped load temperatures; uniformity assessment; fault response; approved loading diagram.
UV system	Source condition, access interlock, representative exposure geometry, shadowed features, and thermal effects.	Radiometric configuration; cure correlation; interlock response; secondary-cure evidence.
Liquid handling	Normal transfer, maximum collection level, leak detection, and isolation.	Containment and compatibility evidence; simulated or safely tested fault response.
Electrical / ESD	Protective functions, equipment suitability, grounding, and product-control verification.	Separate electrical, hazardous-area, and ESD acceptance records appropriate to their scopes.
Restoration	Power interruption, controlled stop, interrupted product, and restart.	Correct safe state; work segregation; authorized reset and defined product disposition.

Periodic verification intervals follow failure consequences, observed drift, manufacturer requirements, governing obligations, and maintenance history. Baseline values provide the reference for subsequent measurements. Changes to a filter medium, enclosure opening, UV lamp technology, nozzle, oven rack, or adjacent air-distribution arrangement trigger an assessment of the affected verification evidence, including replacements marketed as equivalent.

C CAD Analysis and Facility Evidence Register

The method applied in section 8 preserves the relationship between source geometry, calculated measurements, and engineering interpretation. The same evidence structure supports controlled changes to equipment and services.

C.1 Model preparation and interpretation

Preserve the original model and record its filename, revision, units, coordinate frame, and assembly structure. Generate review copies with the roof and selected walls suppressed or made transparent. Identify imported solids whose names or simplified shapes do not establish their function. Compare the model against equipment drawings and the process equipment schedule before assigning a cabinet, duct, tank, or electrical service a definitive role.

Measure internal room dimensions, equipment footprints, working heights, door openings, aisle pinch points, and service-interface clearances, including installation and removal routes. Classify each result by its basis: measured CAD geometry, a controlled specification, a geometric inference, or an unrepresented interface. Corroborating evidence establishes the engineering meaning of an inference.

C.2 Views required for a technical review

1. **Roof-off arrangement:** show the process path, work status locations, exits, door swings, and the complete operating envelopes.
2. **Wall-off services:** trace exhaust, electrical, water, gas, drainage, control wiring, and service access to their source or destination.
3. **Congested sections:** dimension vertical and horizontal clearance at ducts, racks, doors, overhead structures, and equipment withdrawal paths.
4. **Functional overlays:** identify clean/dirty interfaces, chemical segregation, assessed hazardous-area boundaries, airflow assumptions, and inspection points.
5. **Maintenance and fault states:** show replacement parts, temporary tools, waste handling, and the continued availability of emergency access.

The register connects each observation to its engineering consequence and acceptance evidence. An exhaust route is supported by a fluid-system and fan-duty basis; a transfer rack by thermal, cleanliness, and capacity criteria; and a partition by construction, penetration, and applicable regulatory requirements. This linkage keeps geometric fit and functional performance within one traceable design record.

D Minimum Manufacturing Record and Terminology

The following fields support reconstruction of a completed run. A local system may use a paper traveler or electronic record, provided identity, status, and revision relationships remain clear.

Table 17: Minimum record groups for a controlled cleaning and coating run.

Record group	Required content
Product / configuration	Assembly and revision; lot or unit identity; restrictions; approved drawing, recipe, and tooling versions.
Materials	Cleaner, rinse, primer, coating, thinner, catalyst, and mask identities; lots; expiry; storage/opening history; additions and mixture basis.
Equipment / condition	Machine and instrument identity; calibration; bath/loading state; filter and nozzle condition; operating permissives.
Time / environment	Start and finish events for each operation; protected-hold intervals; actual relevant temperature, humidity, pressure, and exposure.
Evidence	Inspection observations and images; chemistry and electrical results; witness association; cure records; acceptance decision rule.
Disposition	Deviations, failed runs, technical authorization, rework route, repeat verification, final status, and packaging.

PCBA
: Printed circuit board assembly: the populated board and its associated mounted items. PCB alone refers to the board, not necessarily the populated assembly.

CCA
: Circuit card assembly: the assembly terminology retained in the facility model and original process study.

DI
: Deionized water: process water whose ionic content is controlled; acceptance is specified at the point of use.

ESD
: Electrostatic discharge: charge transfer addressed by the product's electrostatic-control program.

ROSE
: Resistivity of solvent extract: a bulk ionic-extraction process-control method, reported on its specified equivalent and area basis.

IC
: Ion chromatography: identification and quantification of selected extractable ionic species under a defined analytical method.

SIR
: Surface insulation resistance: an electrical response measured on defined structures under specified conditions, often involving humidity and bias.

LEV
: Local exhaust ventilation: capture and transport of contaminants near their source; distinct from general room comfort conditioning.

UV
: Ultraviolet radiation: used for inspection or photochemical cure according to the equipment and material system.

TDS / SDS
: Technical data sheet / safety data sheet: different documents addressing material use/performance and hazard information, respectively.

Working life

The interval during which prepared material remains within its authorized use condition; distinct from unopened shelf life and final cure time.

Witness specimen

A specimen processed with production hardware to provide particular evidence. Its relevance is limited to the conditions and geometry it represents.

E Independent Worked Engineering Examples

E.1 Purpose and declared assumptions

This appendix develops a reference scenario for spatial reservation, ventilation, thermal load, material consumption, capacity, and inventory. The assumed room measures 6.0 m by 4.0 m by 2.7 m, giving 24 m^2 of floor area and 64.8 m^3 of volume. These analytical inputs are independent of the measured facility geometry in section 8. Equipment blocks and operating values define the calculation scenario; the accompanying script records the assumptions and reproduces the results. Figure 12 shows its functional layout.

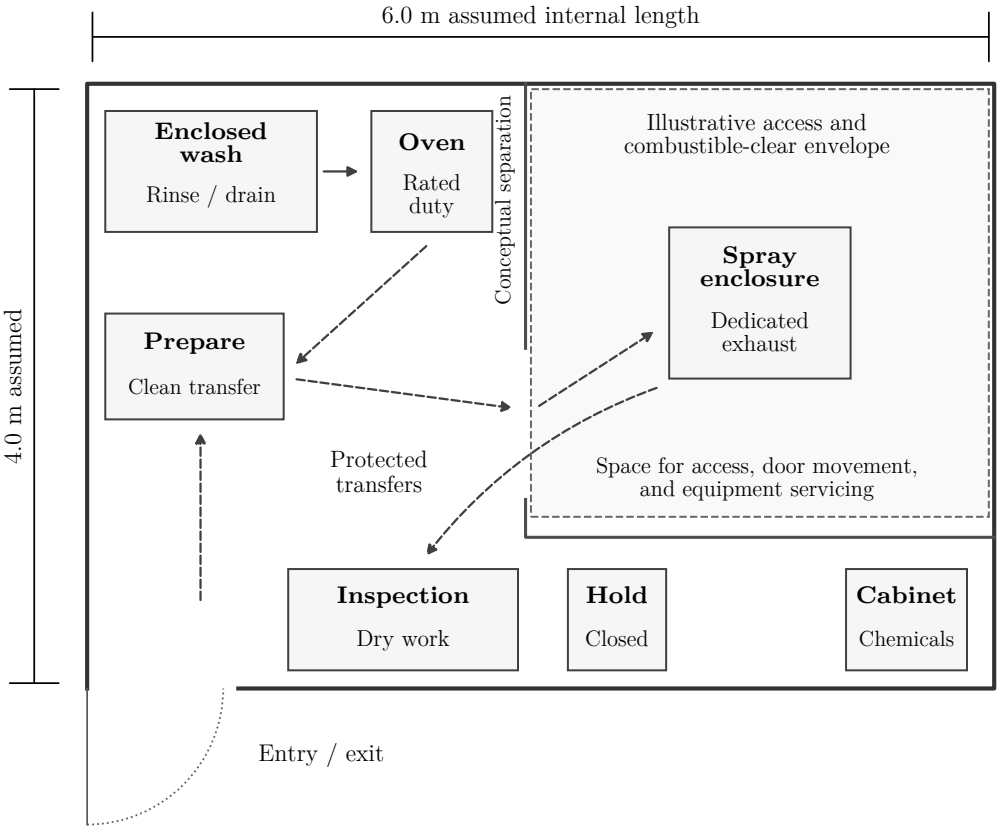


Figure 12: Functional layout for the 24 m^2 reference scenario. Dashed arrows indicate protected process transfers. The enclosure boundary represents functional separation; its construction and equipment suitability follow the operation-specific criteria in the text.

The layout assigns wet processing, protected preparation, coating, and inspection to distinct locations and reserves an enclosure interface around the coating operation. Layout acceptance

requires compatible operating, service, removal, and emergency envelopes. Spatial constraints are addressed through arrangement, qualified process selection, external service locations, or additional area, with equipment represented at its actual scale.

E.2 Equipment footprint versus usable space

Consider an illustrative spray enclosure with a 1.2 m by 1.0 m footprint. A rectangular 0.9144 m reservation on all sides occupies

$$A_{\text{reservation}} = (1.2 + 2 \times 0.9144)(1.0 + 2 \times 0.9144) = 8.57\,\text{m}^2. \tag{12}$$

This is approximately 35.7 % of the assumed room area, compared with the enclosure's $1.2\,\text{m}^2$ physical footprint. The three-foot dimension is used here to illustrate the cleaning-access and storage/combustible-clear-space provision in OSHA 1910.107(b)(9). It is not the complete separation requirement. Adjacent operations, ignition sources, electrical equipment, and exhaust arrangements have additional provisions, including twenty-foot restrictions in specified unpartitioned arrangements [44].

The shaded reservation quantifies access area; electrical and heating-equipment suitability follows a separate assessment of the operation and hazardous-area boundaries. Partition requirements include extent, construction, openings, penetrations, equipment arrangement, and effects on visibility, access, makeup air, and emergency movement. The calculation therefore exposes a support-space demand that a footprint-only fit assessment would omit.

For the complete room, form the geometrical union of equipment, service, door-swing, extraction, operator, and access envelopes. Adding rectangle areas can double-count legitimately shared space, while ignoring envelopes can hide an impossible arrangement. Assess shared areas by operating state: a maintenance position may overlap a work aisle only if the documented shutdown and access conditions permit it. A required exit path cannot become a temporary staging rack.

E.3 Concealed services and swept clearances

The geometric analysis uses four complementary views: an external arrangement, a roof-off plan, a wall-off services view, and dimensioned sections through congested interfaces. Visibility changes retain the complete underlying model, units, assembly hierarchy, object identities, and revision record. Figure 13 illustrates the functional relationships exposed by a services section.

Each utility has a traceable route from source to point of use, and each exhaust or effluent route has an identified destination. The service design includes penetrations, isolation valves, strain relief, required drain slopes, maintenance access, supports, inspection ports, filter-removal directions, and equipment-removal paths. Duct geometry is supplemented by material compatibility, leakage, pressure-loss, fan-duty, fire-protection, and discharge evidence.

Review clearances as swept volumes. Examples include a filter sliding out of its housing, a cabinet door at full opening, an oven rack passing through the doorway, and a washer being removed without dismantling a permanent partition. Check these volumes against ducts, cable trays, lighting, emergency equipment, and the neighboring workstation. Planned future equipment also consumes utility capacity and maintenance space; an unused corner is not automatically expansion capacity.

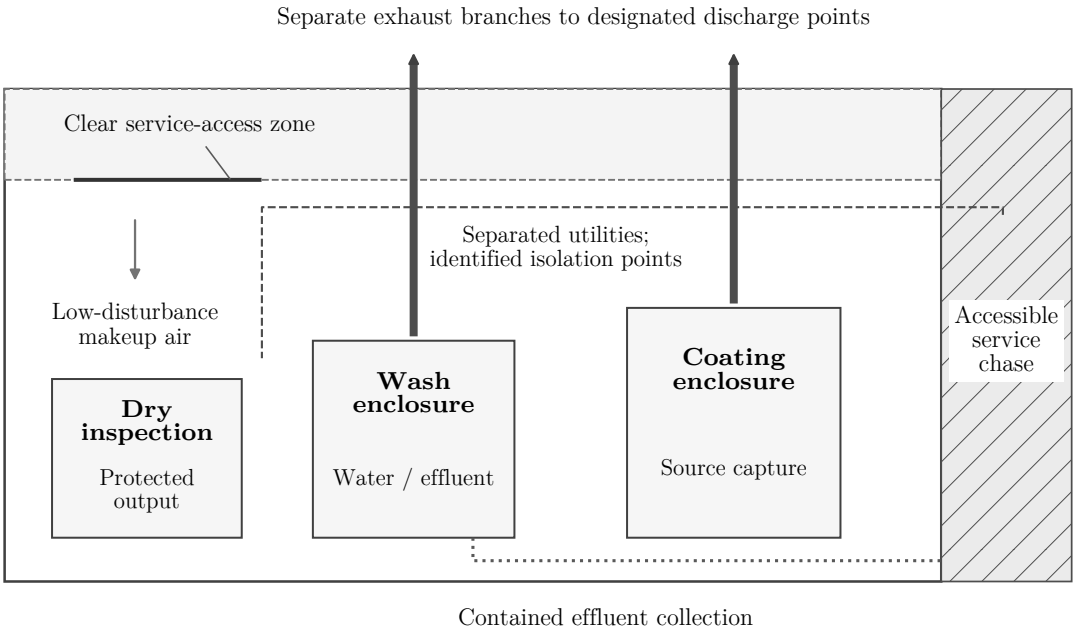


Figure 13: Functional services section showing exhaust separation, supply air, utility isolation, effluent containment, and maintenance access. The schematic is independent of the reference plan's dimensions.

E.4 Exhaust and makeup-air accounting

For a planar enclosure opening with approximately normal flow,

$$Q_{\text{spray}} = A_f \overline{v}_n, \tag{13}$$

where A_f is the free opening area and $\overline{v}_n$ is its area-weighted mean normal velocity. The traverse must characterize the spatial distribution; an average can conceal a local outward-flow region. This relation describes airflow through an opening, not capture effectiveness at an arbitrary distance from a hood.

For the declared opening area of $0.72\,\text{m}^2$ and mean velocity of $0.75\,\text{m/s}$, $Q_{\text{spray}} = 0.540\,\text{m}^3/\text{s}$. These inputs define the reference calculation; an equipment setpoint follows the applicable operating requirements. Adding separate washer and oven exhausts of 0.120 and $0.060\,\text{m}^3/\text{s}$ gives

$$Q_{e,\text{total}} = 0.720\,\text{m}^3/\text{s} = 2592\,\text{m}^3/\text{h}. \tag{14}$$

The flow corresponds to a nominal room-volume equivalent of 40/h. This derived exchange rate is a summary quantity, while capture acceptance depends on local geometry, crossdrafts, loading, filter condition, and the applicable operating category.

With no room return in this illustrative balance, a mechanical supply of $0.650\,\text{m}^3/\text{s}$ requires $0.070\,\text{m}^3/\text{s}$ of net inward transfer air to balance the exhaust. In general,

$$Q_{\text{sup}} + Q_{t,\text{in}} = Q_e + Q_r + Q_{t,\text{out}}, \tag{15}$$

where Q_r is return air and the transfer terms include relevant leakage. Volumetric flows in this balance share common reference conditions or approximately equal density; use a mass balance when density differences are material. The flow deficit alone does not establish a pressure difference. That requires the opening and leakage characteristics and must be checked with the installed doors, transfer paths, and interacting ventilation systems.

An additional mass-balance screen can compare emission generation with transport. For a well-mixed space at steady state with a net contaminant generation rate G and clean replacement flow Q, $C - C_{\text{in}} = G/Q$. This simplified relation is useful for consistency checks, but ignores near-field exposure, incomplete mixing, transient release, and source capture. It must not replace exposure measurements or the design of a local exhaust enclosure. Evaluate occupational exposure and flammability separately; meeting one criterion does not establish the other.

E.5 Pressure loss and thermal burden

For separate exhaust systems, an indicative total input-power estimate is

$$P_{\text{fans}} = \sum_i \frac{Q_i \Delta p_i}{\eta_i}, \tag{16}$$

where Δp_i is the required pressure rise and η_i is the overall wire-to-air efficiency at the operating point. If all three systems are assigned 850 Pa and $\eta_i = 0.55$, the estimate is 1.11 kW. At unchanged flow and assumed efficiency, increasing the losses to 1150 Pa gives 1.51 kW. A fixed-speed fan would move to a different operating point as resistance changes; this comparison estimates the input required to maintain the stated flow. These values do not select motors or justify combining chemically incompatible exhaust streams. They exclude the supply fan and other auxiliaries.

For mechanical makeup air, the sensible thermal load is approximately

$$\dot{Q}_{\text{heat}} = \rho c_p Q_{\text{sup}} \Delta T. \tag{17}$$

Using an assumed density of 1.2 kg/m^3, specific heat of 1005 J/(kg K), supply flow of 0.650 m^3/s, and temperature rise of 20 K gives 15.7 kW. The estimate excludes latent load, cooling duty, process heat, and conditioning of transfer air elsewhere in the building. It demonstrates why a small floor footprint can still require substantial building services.

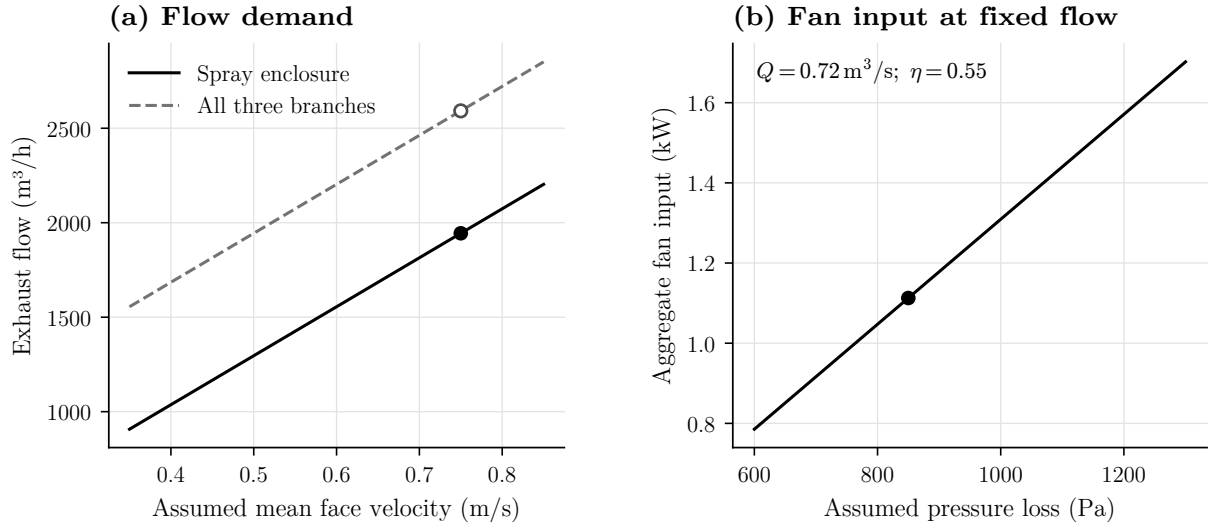


Figure 14: Calculated exhaust demand and fan input. Panel (a) varies face velocity; panel (b) varies pressure loss at fixed flow and efficiency. Markers identify the reference operating point.

E.6 Coating consumption and curing capacity

For an independently assumed developed coating area of 0.050 m^2, dry thickness of 50 µm, actual volume-solids fraction of 0.35, and transfer efficiency of 0.65, the dry-film volume is 2.50 mL. The required deposited wet volume is approximately 7.14 mL; the dispensed amount is approximately 11.0 mL. The associated uniform wet-film estimate is 143 µm. These assumptions differ intentionally from the separate illustrative example in the coating chapter. Purge volume, tubing retention, mask deposition, batch remnants, and cleaning liquid are additional material flows.

The batch capacity of a curing or drying resource is

$$r_{\text{eff}} = \frac{ab}{t_d + t_h}, \tag{18}$$

where a is operational availability, b is assemblies per approved load, t_d is the full required processing interval, and t_h is load/unload time. For $a = 0.85$, $b = 12$, $t_d = 2.0$ h, and $t_h = 0.25$ h, the effective capacity is 4.53/h. Figure 15 shows the dependence on batch size at these fixed time and availability inputs. Demand of six assemblies per hour exceeds the calculated capacity, making the drying or cure resource the bottleneck regardless of a faster coating-machine setting.

At an intended stable throughput of six assemblies per hour and mean process lead time of four hours, the inventory identity $L = rW$ gives 24 assemblies in process. This is a planning illustration, not a prediction for the capacity-constrained example: with demand above sustainable output, the queue does not remain in that steady state. Holding racks, protected carriers, and status segregation must be sized for a defensible production plan. Additional qualified parallel capacity, batch redesign, or scheduling changes can be evaluated; an unqualified reduction in cure time is not a capacity solution.

Table 18 consolidates the calculated outputs and their facility implications.

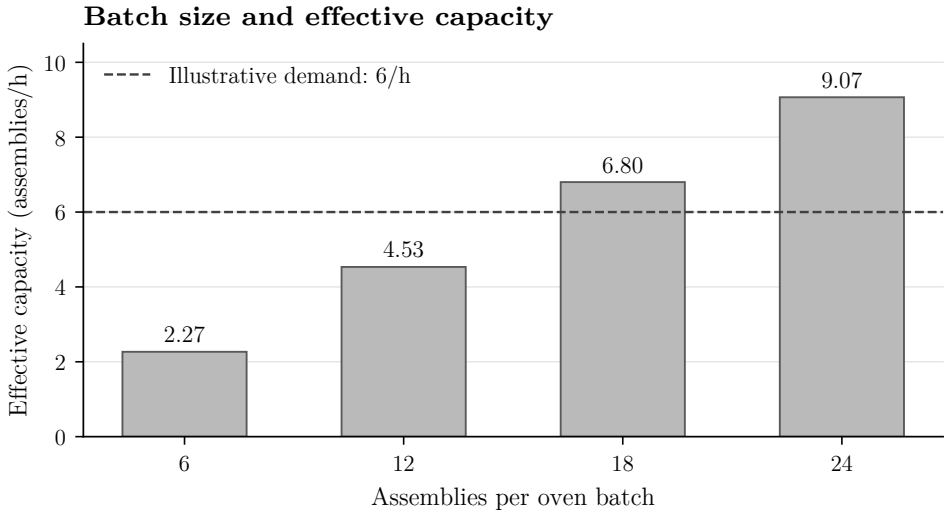


Figure 15: Calculated capacity of a batch resource at fixed availability and processing time. Batch size remains bounded by the qualified loading configuration.

Table 18: Calculated outputs for the declared reference scenario.

Quantity	Calculated value	Engineering implication
Enclosure/access reservation	$8.57\,\mathrm{m}^2$	35.7 % of gross room area before other constraints.
Total independent exhaust	$0.720\,\mathrm{m}^3/\mathrm{s}$	Makeup and transfer paths are substantial design interfaces.
Aggregate exhaust input	1.11 kW	Assumes identical pressure loss and efficiency; excludes supply.
Mechanical-supply sensible heat	15.7 kW	HVAC capacity can dominate the support burden.
Dispensed coating estimate	11.0 mL/assembly	Excludes purge, masking, residuals, and cleaning fluids.
Effective oven throughput	4.53/h	Below the illustrative six-assembly-per-hour demand.