

Top-Down Vat Photopolymerisation: Free-Surface Optics, Recoating, Buoyancy, Supports and Scale-Up

A system qualification framework from liquid surface to finished geometry

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Abstract

Top-down vat photopolymerisation exposes resin at or through an upper liquid interface while the part descends into the vat. The architecture avoids a transparent vat floor and its separation forces, but introduces a coupled free-surface system. Optical path length, meniscus and waves influence exposure; recoating must restore a usable layer; buoyancy and hydrodynamic forces act on the submerged build; supports must resist those loads; and scale-up changes both surface dynamics and resin inventory.

This review defines system-level qualification for top-down vat photopolymerisation. It consumes the qualified global-level state from ER-246 and the qualified local surface-readiness state from ER-244, then integrates those inputs with optical and mechanical consequences without redefining either upstream control problem. Qualification is non-compensatory across optical integration, buoyancy, supports, thermal state and long-build drift, with accepted surface and level states treated as required inputs. No universal support density or scale factor is supported.

Keywords: top-down vat photopolymerisation; free surface; architecture integration; buoyancy; supports; scale-up; stereolithography

1. Significance and scope

In top-down printing, the free surface is both a material boundary and part of the optical-mechanical process. Moghadasi and colleagues modelled the fluid dynamics of top-down digital light processing, illustrating the coupling among motion, geometry and surface stability [1].

ER-248 owns integration of the complete top-down architecture: upper-interface exposure, optical reference geometry, immersion mechanics, supports and scale-up. It consumes qualified recoating and global-level outputs from ER-244 and ER-246 rather than reclaiming them.

1.1 Corpus boundary

ER-010 retains dimensional metrology; ER-035 retains cure-depth interpretation; ER-174 and ER-203 retain optics and radiometry; ER-244 retains per-layer replenishment, meniscus motion, exposure-readiness settling, bubble entrainment and layer uniformity; ER-245 retains thermal control; ER-246 retains global resin inventory, liquid level, hydrostatic head and long-term free-surface drift; ER-247 retains continuous dead zones; and ER-355 retains vibration fields. ER-203, ER-244, ER-245, ER-246, ER-247 and ER-355 are planned forward references and do not supply authority here.

2. Define the top-down architecture

Document whether light enters from above through air, a cover, a liquid layer or a constrained interface; whether the part moves, the vat moves or both; and whether recoating uses passive settling, a blade, roller, jet or another device. These choices determine the qualification chain.

3. Establish the optical reference plane

Define the intended exposure plane relative to the free surface and machine axes. Measure focus or projected resolution across the build area and through the qualified liquid-height range. A fixed projector position does not prove a fixed optical path.

4. Integrate free-surface geometry inputs

ER-246 supplies the qualified global liquid reference and ER-244 supplies the qualified local meniscus and exposure-readiness state. ER-248 integrates those outputs with the optical reference plane and verifies that the resulting top-down architecture delivers the required image geometry. It does not redefine either upstream control problem.

5. Control refraction and reflection

Surface slope and curvature change ray direction and magnification. Surface contamination, foam and films add scattering or reflection. Validate delivered geometry with representative resin, wavelength, surface state and incidence angles rather than an empty-vat alignment.

6. Integrate layer-formation state

State commanded layer thickness, platform motion, overtravel, return and exposure timing. Use ER-244's qualified local liquid-thickness state as an input when comparing commanded build motion with the realised exposure geometry. ER-035 retains cure-depth interpretation; ER-248 verifies that the accepted layer-state and exposure inputs remain correctly coupled at architecture level.

7. Interface with ER-244 recoating qualification

Consume the qualified per-layer replenishment, meniscus, bubble and settling outputs owned by ER-244. At architecture level, verify that recoater envelope, exposure plane, part immersion and machine timing are mutually compatible. Pham and Ji provide architecture context for this coupling [2], not an independent ER-248 recoating qualification.

8. Interlock the exposure-readiness decision

Use ER-244's measured exposure-readiness decision as an input to the top-down sequence. ER-248 verifies correct interlocking between that decision, exposure command and platform motion; it does not set independent height, slope, velocity, bubble or settling limits.

9. Control recoater geometry

Measure blade or roller straightness, gap, parallelism, runout, wear and contamination. Challenge the extremes of vat level, viscosity and travel direction. Requalify after contact, replacement or alignment change.

10. Preserve bubble and inclusion readiness

ER-244 supplies bubble-readiness acceptance for the layer, and ER-246 supplies the global level and refill state. ER-248 verifies that the architecture preserves those accepted states through descending hardware, optical exposure and support motion, including correct stop or hold behaviour when an upstream gate fails.

11. Account for buoyancy

The submerged part experiences buoyancy equal to displaced-liquid weight, while supports and stage transmit the resulting load distribution. As the immersed volume grows, net force and moment change. Include trapped gas and hollow geometry because they can dominate apparent buoyancy.

12. Account for hydrodynamic loads

Platform and recoater motion produce drag, added-mass and transient pressure loads. Relate loads to viscosity, velocity, acceleration, gap and geometry. A static buoyancy calculation does not qualify motion.

13. Qualify supports in the liquid environment

Supports must resist cure shrinkage, buoyancy, drag, recoater disturbance and part weight while the network is green. Test representative orientations and cross-section transitions. Support density cannot be transferred solely from a bottom-up process.

14. Control part immersion and collision risk

Map the submerged build envelope, vat hardware and recoater path. Include deflection and positioning uncertainty. Establish interlocks for unexpected force, surface obstruction or part detachment.

15. Couple temperature and viscosity

Temperature changes viscosity, density, surface tension, cure response and settling. ER-245 owns thermal control; ER-248 requires optical, recoating and mechanical capability across the qualified thermal range.

16. Interface with the resin inventory balance

Use ER-246's qualified inventory, level, hydrostatic-head and long-term drift outputs. ER-248 verifies their architectural interfaces with platform immersion, optical reference and build envelope. It does not reopen the global material balance or controller qualification.

17. Long-build drift and contamination

Challenge the longest credible integrated top-down build while recording the accepted ER-244 readiness state and ER-246 level state alongside optical response, immersed-part mechanics, support condition, temperature and dimensional outcome. Any failure remains attributed to its owning subsystem rather than absorbed into an architecture-wide average.

18. Scale-up

Larger build area increases surface modes, travel distance, resin volume, recoater deflection, thermal gradients and submerged forces. Bhanvadia and colleagues demonstrated that deliberate interface constraint can improve stereolithographic control [3], but that architecture does not remove the need to qualify scale-specific mechanics and optics.

19. Non-compensatory qualification matrix

Gate	Required evidence	Shortcut prevented
Optical plane	Field-wide focus and distortion mapping	Assuming projector alignment is sufficient
Surface input	Accepted ER-244 readiness state at exposure	Requalifying local refill inside ER-248
Level input	Accepted ER-246 level and head state	Requalifying global control inside ER-248
Mechanics	Buoyancy, drag and support margin	Reusing bottom-up support rules
Thermal	Capability across temperature range	Treating viscosity as constant
Endurance	Long-build drift and contamination test	Qualifying only short coupons

Failure of any gate rejects the process point; an exposure adjustment cannot compensate for an unstable surface or inadequate support margin.

20. Minimum reporting set

Report machine architecture; resin identity and lot; vat geometry and fill range; optical path and reference plane; wavelength, irradiance and field map; free-surface measurement and uncertainty; layer-motion sequence; recoater type, gap and alignment; readiness criterion; viscosity, density, surface tension and temperature; bubble controls; inventory and refill logic; platform trajectory; part volume and projected-area history; buoyancy and dynamic-load method; support design; collision interlocks; long-build results; raw-data hashes; transfer domain; and change triggers.

21. Knowledge boundary and limitations

Reference [1] was examined at full-text depth and provides a computational treatment of top-down fluid dynamics. Reference [2] was examined at publisher-abstract depth as architecture context while ER-244 remains the owner of recoating qualification. Reference [3] was examined at full-text depth and demonstrates a constrained liquid interface. Zhang and colleagues demonstrate a distinct one-droplet continuous strategy [4], used here only as an architecture contrast. None establishes universal free-surface tolerance, layer delay, recoater gap, support density or geometric scale factor.

22. Conclusions

Top-down vat photopolymerisation is governed by integration of an exposed optical interface with the mechanics of an increasingly submerged part. Qualification must connect accepted ER-244 surface-readiness and ER-246 level-control outputs to optical delivery, buoyancy, dynamic load and support survival without reclaiming those upstream scopes. Scale-up requires new architectural evidence because travel, force, optical geometry and thermal gradients change together.

References

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