

Calibration of VPP Cure Response with Fine Tuners, Light Blockers and Curing Rate Tables

Printer-specific control of cure threshold and penetration depth with formulation-specific validation

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Highlights

- The Jacobs working curve links cure depth to exposure through the effective penetration depth D_p and critical exposure E_c [1,2].
- Curing Rate Tables translate measured, printer-specific results into a controlled starting exposure window.
- Fine Tuners can modify effective cure response, while Light Blockers can modify optical penetration and lateral overcure; their effects may be coupled.
- Every additive creates a modified formulation that must be checked for homogeneity, stability, cure and dimensional response.
- Process calibration supports manufacturing control but does not establish biological safety, regulatory conformity or suitability for a finished device.

Abstract

VPP cure response depends on the complete resin, additive, printer and exposure system. Fine Tuners can adjust effective cure response, while Light Blockers can modify optical penetration and lateral overcure. Curing Rate Tables provide a printer-specific method for selecting an exposure window from measured results.

The calibration method should be reported independently from application claims. An additive compatible with a base resin does not automatically preserve the base resin's chemical or biological evaluation. Each final formulation and processing route must be assessed for homogeneity, stability, cure, dimensional response and the requirements of the intended finished article.

For medical or dental devices, calibration data can support manufacturing-process control but do not establish biological safety, MDR conformity or FDA clearance. Those conclusions belong to the finished device and legal manufacturer.

Keywords vat photopolymerisation · Jacobs working curve · cure depth · critical exposure · penetration depth · Curing Rate Table · Fine Tuner · Light Blocker · process control · formulation validation

Source use. Working-curve theory, metrology and interlaboratory evidence are mapped in [1–2,5–10]; controlled product and process documentation in [3–4]; sustainability and general AM method context in [11–12]; biological and legal boundaries in [13–17].

1. Industrial application

Vat photopolymerisation (VPP) converts a liquid photopolymer into a solid network by selective exposure to ultraviolet or visible light. Production control requires a defined relationship among resin composition, printer spectrum and irradiance, exposure time, layer thickness, temperature, geometry and post-processing. A setting that works on one platform or batch cannot be assumed to transfer unchanged to another [1,2,7,8].

Calibration principles can be used in many industrial contexts, but application suitability does not transfer automatically. Dental, medical, aerospace, tooling, optical and consumer products have different failure modes, material specifications and conformity routes. The role of the calibration workflow is narrower: to establish and monitor a repeatable exposure window for a named formulation and printer.

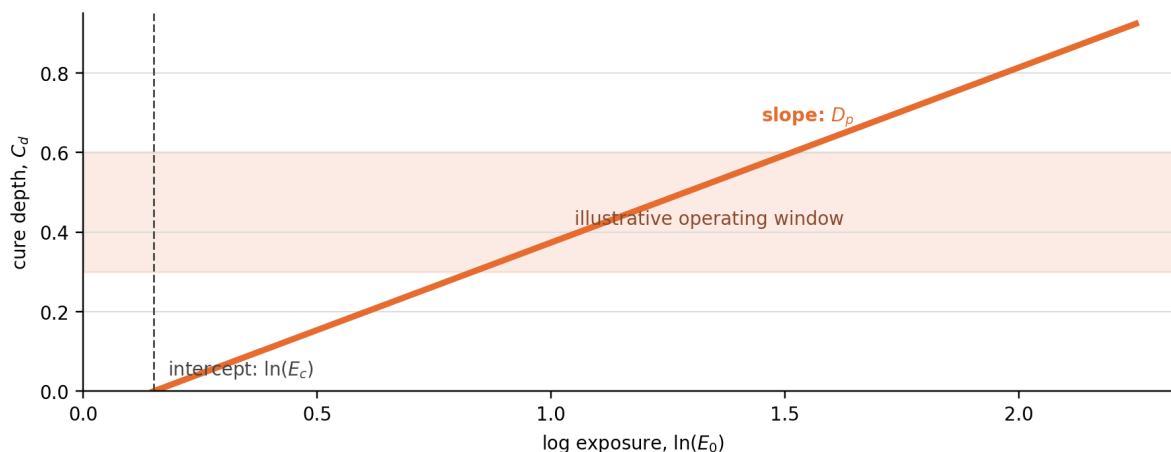


Figure 1. Schematic Jacobs working curve. On semi-logarithmic axes, the slope corresponds to effective penetration depth D_p and the intercept identifies critical exposure E_c . The plot is explanatory and contains no product-specific calibration values.

2. Engineering challenge

The Jacobs relationship is commonly written as $C_d = D_p \cdot \ln(E_0 / E_c)$, where C_d is cured depth, E_0 is the surface exposure, D_p is the effective penetration depth and E_c is the critical exposure associated with gelation under the stated test conditions [1,2]. D_p and E_c are fitted system parameters. They depend on the formulation, wavelength and spectral bandwidth, irradiance, temperature, oxygen conditions, measurement method and printer optics [5,6,9,10].

Interlaboratory studies have reported large differences in fitted working-curve parameters across systems using a common resin, including variation of up to approximately 7-fold for D_p and 70-fold for E_c under the study conditions [7,8]. These results support printer-specific measurement and reporting. They do not define universal variability factors for every resin or platform.

A practical production method must therefore combine a physical model with empirical checks. The model helps interpret cure response, while the empirical Curing Rate Table and validation specimen establish a usable local process window. Neither element eliminates the need to repeat the assessment after a material, additive, printer or processing change.

3. Controlled calibration architecture

Control element	Purpose	Required evidence	Boundary
Working curve	Describe cure-depth response	Named resin, wavelength, irradiance, exposure series and fit	Fitted parameters are not transferable constants
Curing Rate Table	Select a local starting exposure window	Measured printer irradiance and test result	Platform- and method-specific
Fine Tuner	Modify effective cure response	Current TDS starting range plus formulation-specific test	May also affect penetration, colour or cure kinetics
Light Blocker	Modify penetration and overcure	Current TDS starting range plus dimensional and cure test	May increase the exposure needed for target depth
Validation specimen	Verify layer formation and XYZ response	Documented geometry, acceptance criteria and post-cure	Does not establish application conformity

KEY INSIGHT

Fine Tuners and Light Blockers provide useful adjustment routes, but E_c and D_p cannot be assumed to vary independently. Absorption, colour, scattering, concentration and cure kinetics can couple their effects.

4. Scientific basis

For an idealised monochromatic system, Beer–Lambert attenuation gives $I(z) = I_0 \cdot \exp(-z / D_p)$. With exposure time t , the local dose is $E(z) = I(z)t$. Setting the dose at the cured boundary equal to E_c yields the Jacobs expression. This derivation is useful for process interpretation but is an approximation when scattering, broadband sources, complex photochemistry, oxygen inhibition or conversion-dependent optical properties are important [5,6,9].

A Fine Tuner used as a photoaccelerant can change the radical-generation efficiency and therefore the effective cure response of the complete mixture. The term photoinitiator should be reserved for the general reaction mechanism or a

separately identified primary cure component. A Light Blocker adds wavelength-dependent absorption or attenuation and can reduce penetration and lateral light spread. Because both additions modify the formulation, concentration-response behaviour must be established experimentally for the named system.

Fixed dosage values are not universal specifications. Starting ranges, handling instructions and compatibility statements must come from the current controlled TDS for the exact product. The working concentration is then selected with CRT and dimensional tests under the intended wavelength, irradiance, layer thickness and temperature.

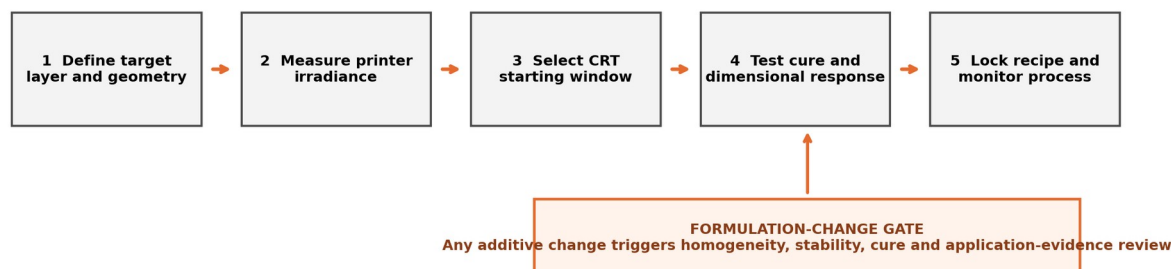


Figure 2. Controlled CRT workflow. Additive selection is followed by an explicit formulation-change assessment gate before the recipe is locked for production.

5. Recommended workflow

- Define the target layer thickness, geometry, accuracy requirement and application-specific acceptance criteria.
- Identify the exact base resin, additive product and controlled documentation revision. Record batch identifiers where production traceability requires them.
- Measure irradiance at the build plane with a suitable calibrated instrument and record wavelength or spectral information, printer, optics and temperature.
- Use the applicable CRT only as a starting window, then expose a defined test series and measure cure and dimensional response.
- If adjustment is needed, use the current TDS-controlled starting range. Mix by a documented method and assess homogeneity and stability before printing.
- Repeat cure-depth and dimensional checks after every formulation change. Do not assume that changing a Fine Tuner affects only Ec or that changing a Light Blocker affects only Dp.
- Lock the formulation and printer recipe only after acceptance criteria are met. Monitor the variables that can shift the process during production.

6. Formulation and evidence control

Documented formulation routes. For applications requiring biological evaluation, use only base-resin, Fine Tuner and Light Blocker combinations covered by current controlled documentation. Because additives alter the formulation, the final mixture and post-processed specimen may require chemical characterization and biological evaluation appropriate to the finished device. CLP classification and absence of hazard pictograms must be reported separately from biological-safety evidence.

A Safety Data Sheet describes hazards and safe handling for the supplied chemical product under the applicable classification framework. It is not a certificate of biological safety. Likewise, ISO 10993 is a biological-evaluation framework, Regulation (EU) 2017/745 is legislation and FDA 510(k) is a premarket submission pathway. They must not be presented as interchangeable material certifications [13–16].

For a finished medical or dental device, the legal manufacturer must define intended purpose, nature and duration of contact, processing, risk management and the applicable conformity route. Calibration records can support manufacturing-process evidence but cannot replace finished-device evaluation.



Figure 3. Evidence boundaries. Process calibration, formulation control and finished-article evaluation are connected, but each answers a different question and requires its own evidence.

7. Validation and reporting

7.1 Minimum calibration record

- Resin and additive identities, batch or lot information where applicable, concentrations and mixing procedure.
- Printer model and unit, wavelength or spectrum, build-plane irradiance, layer thickness and exposure settings.
- Ambient and resin temperature, elapsed time after mixing and any conditioning or degassing step.
- Test geometry, measurement method, results, acceptance criteria and operator/date.
- Post-cure and cleaning conditions used for any dimensional or property verification.

7.2 When recalibration is required

Recalibration should be considered after changes in formulation, additive concentration, pigment or filler content, printer unit, optical components, firmware exposure behaviour, wavelength, layer thickness, environmental conditions or post-processing. A risk-based change-control procedure should determine the extent of repetition.

7.3 Application verification

After process calibration, verify the properties linked to the intended article and foreseeable failure modes. Depending on the application, this may include dimensional stability, mechanical response, heat resistance, chemical resistance, optical response, extractables or other product-specific tests. The calibration framework does not define universal acceptance limits.

8. Limitations and scope boundaries

- The Jacobs model is an approximation and may not describe strongly scattering, conversion-dependent or broadband systems with a single linear fit.
- Published Dp and Ec values cannot replace measurement on the intended resin–printer system.
- Product dosage ranges are controlled by current product documentation and require local CRT validation; no universal concentration is specified in this paper.
- The workflow addresses VPP exposure calibration. It does not automatically transfer to material jetting, two-photon polymerisation, nanoimprint lithography, volumetric additive manufacturing or other processes.
- Calibration does not establish chemical safety, biological safety, clinical performance, regulatory approval or finished-product conformity.
- Commercial product names and documentation can change. Users must verify current TDS and SDS revisions before use.

9. Conclusions

- VPP cure response is a property of the complete formulation, printer and exposure system, not a transferable material constant.
- The working curve and CRT provide complementary model-based and empirical tools for selecting a local exposure window.
- Fine Tuners and Light Blockers can modify cure response and optical penetration, but their effects may be coupled and require formulation-specific testing.
- Every additive change triggers documented assessment of homogeneity, stability, cure and dimensional response.
- Medical and dental conclusions remain at finished-device level. Process-calibration data alone do not establish biological safety or regulatory conformity.

Revision note

Version 5.3 corrects the biological-evaluation and regulatory framing, removes unsupported material-grade labels, separates CLP/SDS information from biological-safety evidence, qualifies additive effects as potentially coupled, replaces universal dosage claims with TDS-controlled starting ranges and updates the ISO 10993 sensitisation/irritation references.

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Disclosure. Dr. Juan Segurolo is founder and Scientific Director of 3Dresyns by Resyner Technologies S.L., the producer of the CRT system and Fine Tuner and Light Blocker products discussed in this white paper. Material properties depend on the complete formulation, process and printer and must be verified for the intended application.

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