KeepLean

Spin Coating Process Simulator

Complete User Tutorial — DOE · PID Control · 4-Phase Animation · Defect Pareto · 50-Point Plotter

Microelectronics / Lithography
KEEPLEAN v1

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1. Introduction

What is the Spin Coating Simulator?

The **KEEPLEAN Spin Coating Simulator** is an interactive tool that reproduces the physics of spin coating — the standard thin-film deposition process used in **microelectronics, MEMS fabrication and lithography**. Users control the 4-phase speed profile, select the photoresist material, adjust environmental conditions and tune a PID climate controller, then observe the effect on film **thickness, uniformity and defect generation**.

The simulator uses physics-based models to calculate thickness across a 50-point measurement grid on a 100 mm wafer, providing realistic variability driven by process conditions and PID tuning quality — just like a real cleanroom environment.

🎯 **Learning Objectives:**

- Understand how spin speed and phase duration control film thickness
- Discover the effect of resin viscosity and quantity on film uniformity
- Learn how temperature and humidity affect the coating process
- Connect PID tuning quality to process variability (Gage R&R concepts)

- Identify the root causes of 9 real spin coating defects
- Apply DOE methodology to optimise thickness and uniformity simultaneously

Simulator Capabilities

Feature	Description
🧪 6 Photoresist Materials	AZ 1518 · S1813 · SU-8 2050 · PMMA 950K · HSQ · Ma-N 2403 — with real viscosity values
⚙ 4-Phase Speed Profile	P1 Deposit · P2 Acceleration Ramp · P3 Speed Thinning · P4 Final Drying — each with RPM and time
🎬 Real-Time Animation	Canvas-based animation showing wafer, resin spreading, arm nozzle — all 4 phases animated
🌡 Environmental Control	Temperature setpoint (°C) and Humidity setpoint (%) — individually tunable
⚙ PID Controller	Kp, Ki, Kd sliders controlling climate variability — poor tuning = higher process noise
📏 50-Point Plotter	Thickness measurement on a 10-circle × 5-point radial grid across the full wafer
📊 Uniformity Statistics	Mean, Std Dev, CV%, Min, Max, Uniformity % — all calculated per run
📉 T°/RH Scatter Plot	Correlation plot between temperature and humidity variations with Pearson ρ coefficient
📊 Defect Pareto	9 defect types tracked cumulatively — sorted Pareto chart with cumulative % line
📥 Export	CSV and Excel (.xlsx) export of all 50 measurement points with full process parameters

🔬 **The DOE Connection:**
This simulator is ideal for teaching **response surface methodology (RSM)** and **factorial DOE** with continuous responses. The main factors are: Final Speed S4 (rpm), Temperature T (°C), Humidity RH (%), and Material Viscosity — all affecting Thickness (µm) and Uniformity (%) as responses.

2. Quick Start (90 Seconds)

✨ Follow these steps to run your first spin coating experiment:

1 Unlock the Simulator

Enter the access password when prompted. The simulator interface appears after successful authentication.

2 Select a Material

In the **Material Parameters** panel, select **AZ 1518** (25 cP — easiest to coat). Set Resin Quantity to **100 µL**.

3 Set the Speed Profile

Use the defaults or try: Phase 1 = **10 rpm, 2s** · Phase 2 = **10 → 500 rpm, 5s** · Phase 3 = **2000 rpm, 15s** · Phase 4 = **3000 rpm, 15s**.

4 Set Environmental Conditions

In the **ENV Control** panel, set Temperature SP = **22°C** and Humidity SP = **45%**. Leave PID at default values (Kp=4, Ki=1, Kd=0).

5 Click ▶ RUN SIMULATION

The 4-phase animation starts. Watch the nozzle deposit the resin, the wafer accelerate, the film spread and thin, then enter final drying.

6 Read the Results

After the cycle: Thickness statistics appear · The 50-point plotter table fills · The scatter plot draws · The Pareto chart updates.

7 Run Again with Different Settings

Change S4 speed from 3000 to 5000 rpm and run again. Compare: thickness should decrease and new defects may appear.

Expected Results (AZ 1518 — optimal settings):
Mean Thickness: ~1.8–2.5 µm | CV: < 5% | Uniformity: > 93%
PID Status: ✅ STABLE | No defects triggered
Results vary due to realistic environmental noise — this reflects real cleanroom variability.

3. Interface Overview

Layout — Top to Bottom

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┌──────────────────────────────────────────────────────────────────────┐
│  🔬 TITLE — Spin Coating Simulator · 50-Point Plotter                 │
├───────────────────────────────┬──────────────────────────────────────┤
│  LEFT PANEL                   │  RIGHT PANEL                         │
│                               │                                      │
│  ┌──────────────────────────┐ │  ┌───────────────────────────────┐   │
│  │ 📋 Material Parameters   │ │  │ ⚙ ENV CONTROL (PID)            │   │
│  │  Material selector       │ │  │  🌡 Temp SP · 💧 RH SP          │   │
│  │  Resin Quantity (µL)     │ │  │  Kp · Ki · Kd sliders          │   │
│  └──────────────────────────┘ │  │ PID Status indicator           │   │
│                               │  └───────────────────────────────┘   │
│  ┌──────────────────────────┐ │                                      │
│  │ ⚙ Speed Profile          │ │  ┌───────────────────────────────┐   │
│  │  Phase 1 — Deposit       │ │  │ 🎬 ANIMATION                   │   │
│  │  Phase 2 — Ramp          │ │  │  Canvas + RPM display          │   │
│  │  Phase 3 — Thinning      │ │  │  Phase timeline bar            │   │
│  │  Phase 4 — Drying        │ │  │  ▶ RUN   ↺ RESET               │   │
│  └──────────────────────────┘ │  └───────────────────────────────┘   │
├───────────────────────────────┴──────────────────────────────────────┤
│  ⚠ PID STABILITY WARNING INDICATOR                                    │
├──────────────────────────────────────────────────────────────────────┤
│  📊 STATISTICS (after run)                                            │
│  Mean · Std Dev · CV% · Min · Max · Uniformity%                       │
├──────────────────────────────────────────────────────────────────────┤
│  📉 SCATTER PLOT T° / RH + Pearson ρ                                  │
├──────────────────────────────────────────────────────────────────────┤
│  📏 50-POINT PLOTTER TABLE + Export CSV / Export Excel                │
├──────────────────────────────────────────────────────────────────────┤
│  📊 PARETO — Defects Cumulative Run History                           │
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Key Display Elements

Element	Location	Purpose
Material Selector	Top left	Choose photoresist — changes viscosity, which drives film thickness model
Resin Quantity	Top left	Volume dispensed in µL — affects edge bead and film evenness
Speed Profile (P1–P4)	Left panel	4 phases with individual RPM and time settings
ENV Control Panel	Right panel	Set temperature and humidity setpoints for cleanroom simulation
PID Sliders (Kp/Ki/Kd)	ENV panel	Tune the environmental controller — affects process noise
LED Displays	ENV panel	Green LED = Temperature PV · Cyan LED = Humidity PV (updated after run)
Animation Canvas	Right panel	Live simulation of wafer spinning, nozzle, resin spreading

Phase Timeline	Animation area	4 coloured bars — active phase highlighted during animation
RPM Display	Animation area	Real-time RPM counter updating during animation cycle
PID Status Box	Below animation	✅ STABLE / ⚠ MODERATE / ✖ UNSTABLE based on Kp, Ki, Kd values
Statistics Panel	After run	6 uniformity metrics calculated from 50-point measurement
Scatter Plot	After run	T° vs RH correlation across 50 measurement points with ρ coefficient
50-Point Table	After run	Full measurement data: circle, angle, position (x,y,r), T°, RH, viscosity, thickness
Pareto Chart	Bottom	Defect frequency sorted descending with cumulative % — updates each run

4. Materials — 6 Photoresists & Their Properties

The material selector defines the **base viscosity** of the photoresist. Viscosity is the single most important material property in the Derjaguin-Landau spin coating model: higher viscosity = thicker film at the same spin speed.

⭐ **AZ 1518**

25 cP

Standard positive resist. Easy to coat. Good for beginners and DOE experiments.

⭐ **S1813**

40 cP

Shipley positive resist. Slightly thicker films. Good uniformity window.

⭐⭐ **SU-8 2050**

450 cP

High-aspect-ratio negative resist. Very thick films. Sensitive to speed changes.

⭐⭐ **PMMA 950K**

35 cP

E-beam resist. Thin films. Requires controlled environment for consistency.

⭐⭐⭐ **HSQ**

12 cP

Ultra-thin resist. Very sensitive to humidity. Challenging uniformity control.

⭐⭐⭐ **Ma-N 2403**

18 cP

Negative resist. Sensitive to temperature fluctuations. Advanced difficulty.

Viscosity and Thickness — The Key Relationship

Film thickness follows the **Derjaguin-Landau model**: `Thickness ∝ √(viscosity / ω)` where ω is angular velocity (rad/s). This means:

Effect	Direction	Magnitude
↑ Viscosity (higher cP material)	↑ Thicker film	Strong — square root relationship
↑ Final Speed S4 (rpm)	↓ Thinner film	Strong — inverse square root
↑ Temperature	↓ Lower viscosity → Thinner film	Moderate — exponential decay
↑ Humidity	↑ Slightly higher viscosity → Thicker film	Weak — linear term
↑ Resin Quantity	↑ Slightly thicker (edge effects)	Weak — saturation effect
↑ Radial position on wafer	↓ Thinner at edge (radial factor −15%)	Moderate — linear gradient

⚠ **Material Change Resets Thickness Scale:**
SU-8 2050 (450 cP) will produce films roughly 4× thicker than AZ 1518 (25 cP) at the same speed. Always compare results with the same material. Switching materials mid-experiment invalidates run-to-run comparisons.

5. Four-Phase Speed Profile

The spin coating process is divided into **4 distinct phases**, each serving a specific physical function. The combination of RPM and time in each phase determines the final film thickness, uniformity and defect profile.

💧 **Phase 1 Deposit**	📈 **Phase 2 Acceleration**	🌀 **Phase 3 Thinning**	🌬 **Phase 4 Final Drying**
Low RPM Short time	Ramp speed From → To rpm	Mid speed Film spreads	Final speed Thickness set

Phase	Physical Role	Key Parameter	Effect if Too Fast	Effect if Too Slow
P1 — Deposit P1	Resin dispensed at rest or low speed. Film covers wafer center.	Speed (≥5 rpm), Time	Comets, incomplete coverage	Edge Bead accumulation
P2 — Ramp P2	Rapid acceleration spreads resin centrifugally to wafer edge.	From RPM → To RPM, Time	Striations (radial lines)	Film too thick — material waste
P3 — Thinning P3	Solvent evaporation and centrifugal thinning. Viscosity increases as solvent leaves.	Speed, Time	Non-Uniformity, Voids	Residual solvent — poor adhesion
P4 — Final Drying P4	Final thickness set. Film solidifies. This speed is the primary thickness control parameter.	**S4 speed** (critical), Time	Pinholes, Dewetting	Film still fluid — Sticking

Phase 4 Speed S4 — The Critical DOE Factor:
The **final speed S4** is the dominant factor controlling film thickness. In the simulator model, thickness ∝ $1/\sqrt{(S4)}$. This means doubling S4 reduces thickness by ~30%. In a DOE, S4 will almost always appear as a **highly significant main effect** on Thickness.

The Phase Timeline in the Animation

During animation, the 4-phase timeline bar below the canvas highlights the current phase in real time. Each phase block has a width proportional to its duration. The **RPM display** updates continuously, and for Phase 2 it ramps linearly from the "From" value to the "To" value.

💡 **Phase 2 Acceleration Ramp:**
The "From" RPM of Phase 2 should equal or closely follow the Phase 1 RPM — to avoid a sudden speed jump that would create striations. Best practice: P1 RPM ≈ P2 "From" RPM. Example: P1 = 10 rpm → P2 From = 10 rpm → P2 To = 500 rpm.

6. Process Animation

When you click ▶ **RUN SIMULATION**, a 7-second canvas animation plays, showing a realistic view of the spin coating process. A loading bar also progresses simultaneously.

Element	What You See	Physical Meaning
👁 Wafer disk	Elliptical blue/silver disk rotating — speed indicated by visual RPM	Silicon or glass substrate on the spin chuck
🦾 Nozzle arm	Arm sweeps from right edge to wafer center during P1	Dispense arm dispensing photoresist onto wafer center
💧 Resin drop	Droplet appears at nozzle tip during P1 deposit phase	Photoresist dispensed in µL quantity
🌈 Resin film	Coloured ellipse spreads radially — colour changes per phase	Film spreading centrifugally. Colour = phase (gold/purple/cyan/red)
⚡ Phase bar	4 coloured blocks below canvas — active block glows	Current phase of the 4-phase cycle
📟 RPM counter	Number updating in real time below canvas	Instantaneous wafer rotation speed
⏱ Time display	Elapsed time / total time shown during animation	Process cycle progression

Film Radius per Phase

The animation shows the resin film expanding radially across the wafer as phases progress. The timeline sub-labels show the film radius in mm at the end of each phase:

- **End of P1:** Film radius = 0 → ~14 mm (center deposit only)
- **End of P2:** Film radius = 14 → 50 mm (full wafer coverage)
- **P3 & P4:** Film stays at 50 mm — thinning and drying in place

> ⚠ **During Animation:**
> The ▶ **RUN** and ↺ **RESET** buttons are temporarily inactive during the 7-second animation. Results appear automatically after the animation and loading bar complete. Do not reload the page during animation.

7. Environmental Control — Temperature & Humidity

Spin coating is performed in a **cleanroom environment** where temperature and humidity are tightly controlled. The simulator's ENV Control panel lets you set a target for each variable.

Variable	Setpoint Range	Default	Effect on Film
🌡 **Temperature (°C)**	15–35°C (typical)	22°C	Higher T → lower viscosity → thinner film. Increases temperature-driven noise in radial variation.
💧 **Humidity (%RH)**	20–70%RH (typical)	45%RH	Higher RH → slightly higher apparent viscosity → thicker film. Drives dewetting for RH > 62%.

How Environmental Variation is Modelled:
The simulator generates **50 correlated (T°, RH) pairs** — one per measurement point — using a bivariate normal distribution with correlation $\rho = -0.75$. This negative correlation (higher T → lower RH) mimics real cleanroom thermodynamics. The PID tuning controls the **amplitude of this variation**: poor tuning = wider scatter of T° and RH across the wafer surface.

LED Displays

The two LED displays in the ENV panel show the **actual average values** achieved during the run (PV — Process Value), updated after each simulation:

- 🌡 **Green LED** — Temperature PV (°C actual average)
- 💧 **Cyan LED** — Humidity PV (% actual average)

If PID tuning is poor, these values will deviate from the setpoints — and the scatter across 50 measurement points will be wider.

💡 **Humidity Sensitivity by Material:**
HSQ and **Ma-N 2403** (difficult materials) are particularly sensitive to humidity fluctuations. Setting RH setpoint above 55% with poor PID tuning while using these materials will trigger multiple defects rapidly — useful for teaching the importance of cleanroom environmental control.

8. PID Controller — Cleanroom Climate Regulation

The PID parameters (Kp, Ki, Kd) control the quality of the environmental controller. They directly affect the **amplitude of temperature and humidity variations** across the 50 measurement points — and therefore the uniformity of the coating.

Kp — Proportional

Range: 0 – 5.0
Default: 4.0
Reacts to current error. Too low = slow settling. Too high = oscillation.

Ki — Integral

Range: 0 – 2.0
Default: 1.0
Eliminates steady-state error. Too high = instability and overshoot.

Kd — Derivative

Range: 0 – 1.0
Default: 0.0
Anticipates future error. Reduces overshoot. Too high = noise amplification.

PID Stability Indicator

After each run, the status box shows one of three states based on a composite oscillation score derived from Kp, Ki and Kd:

Status	Osc. Score	Effect on Results
✅ **STABLE**	< 1.0	Low variability · tight T°/RH scatter · high Uniformity%
⚠ **MODERATE**	1.0 – 2.5	Moderate variability · visible scatter · Uniformity may drop
✕ **UNSTABLE**	> 2.5	High variability · wide T°/RH scatter · poor Uniformity · defects likely

⚠ **Effect of Poor PID Tuning:**
Setting Kp = 5.0 and Ki = 2.0 will produce an UNSTABLE status. The temperature and humidity will vary significantly across the 50 measurement points, increasing CV% and decreasing Uniformity%. This directly increases the risk of triggering Non-Uniformity, Striations and Pinholes defects — exactly as in a real out-of-control cleanroom HVAC system.

9. Understanding Results — Thickness & Uniformity

The 6 Statistics Panel

After each run, six uniformity metrics are displayed in the statistics panel:

Metric	Unit	Description	Target
Mean	µm	Average thickness across all 50 measurement points	Depends on process window
Std Dev	µm	Standard deviation of 50 thickness values — process variability indicator	As low as possible
CV%	%	Coefficient of Variation = (Std Dev / Mean) × 100. Relative variability measure.	< 5% (good), < 10% (acceptable)
Min	µm	Thinnest point across 50 measurements — usually at wafer edge (circle 10)	—
Max	µm	Thickest point — usually at wafer center (circle 1)	—
Uniformity%	%	= (1 − (Max−Min)/(2×Mean)) × 100. Standard semiconductor uniformity metric.	> 95% (good), > 88% (acceptable)

Uniformity Colour Coding

Uniformity %	Status	Typical Cause
≥ 95%	🟢 Excellent	Well-tuned PID, good material, appropriate speed
88 – 94%	🟡 Acceptable	Moderate PID noise, or speed too high/low for material
< 88%	🔴 Poor	Poor PID tuning, or CV > 18%, triggers Non-Uniformity defect

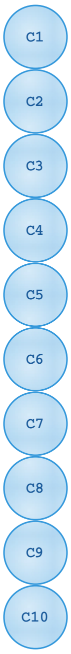
> **Radial Thickness Gradient:**
> The simulator models a realistic **radial thinning effect**: film thickness decreases from center to edge due to the centrifugal acceleration gradient. This is built into the model as a −15% reduction factor at the wafer edge (r = 50 mm) versus center (r = 5 mm). This is why **Min is always near the edge** and **Max near the center**.

10. The 50-Point Wafer Plotter

The plotter provides a complete **radial measurement grid** on the 100 mm wafer, organized in 10 concentric circles of 5 measurement points each — 50 points total.

Measurement Grid Structure

Grid Layout:



Circle	Radius
C1 (innermost)	5 mm
C2	10 mm
C3	15 mm
C4	20 mm
C5	25 mm (center)
C6	30 mm
C7	35 mm
C8	40 mm
C9	45 mm
C10 (edge)	50 mm

Each row = 1 circle (C1=5mm, C10=50mm)
5 points per circle at 0°/72°/144°/216°/288°

Plotter Table Columns

Column	Content	Notes
Point	1 to 50	Sequential measurement point number
Circle	1 to 10	Concentric circle number from center
Angle (°)	0, 72, 144, 216, 288	Angular position of measurement point
X (mm)	Cartesian coordinate	Horizontal position on wafer
Y (mm)	Cartesian coordinate	Vertical position on wafer
R (mm)	Radial distance from center	5 to 50 mm in 5 mm steps
Temp (°C)	Local temperature at measurement point	Varies due to PID noise
RH (%)	Local relative humidity	Negatively correlated with Temp
Visc (cP)	Local effective viscosity	Derived from T°, RH and base material viscosity
Thickness		**Bold — the key measurement**

(μm)	Film thickness at this point	**output**

💡 **Using the Plotter for DOE:**
Export the full 50-point dataset to Excel. In Minitab or R, plot Thickness vs. Radius (R column) for different factor combinations. You will see the radial gradient clearly — and how changing S4 speed shifts the entire thickness curve up or down while maintaining its shape.

11. T°/RH Scatter Plot & Correlation

The **Temperature vs Humidity scatter plot** shows the joint distribution of the 50 (T°, RH) pairs across the wafer surface, with a linear regression line and the **Pearson correlation coefficient ρ**.

Reading the Scatter Plot

Element	Description
Blue circles	Each of the 50 measurement points plotted as (Temperature, Humidity)
Red dashed line	Linear regression line (least squares fit)
ρ coefficient box	Pearson correlation coefficient — always negative (T↑ → RH↓)

Interpreting the Pearson ρ Coefficient

ρ Value	Colour	Interpretation
$\rho < -0.6$	🟢 Green	Strong negative correlation — well-controlled environment, tight scatter
$-0.6 \le \rho < -0.3$	🟡 Yellow	Moderate correlation — some environmental noise
$\rho \ge -0.3$	🔴 Red	Weak or no correlation — high environmental instability, poor PID tuning

Why is the Correlation Always Negative?
In a real cleanroom, temperature and humidity are **physically linked**: when air temperature rises, its relative capacity to hold moisture increases, so relative humidity (as a percentage) decreases. The simulator models this with a design correlation of $\rho = -0.75$ in the underlying bivariate normal distribution. Poor PID tuning increases the variance of both variables, making the observed ρ less negative (noisier scatter cloud).

💡 **PID Impact on Scatter:**
Run two simulations with the same speed settings: one with **good PID** (Kp=2, Ki=0.5, Kd=0.5) and one with **poor PID** (Kp=5, Ki=2, Kd=0). Compare the scatter plots side by side. The poor PID run will show a much wider cloud of points, weaker correlation, and worse Uniformity%.

12. Defect Pareto — 9 Defect Types

The Pareto chart at the bottom of the simulator accumulates defect occurrences across all runs. Defects are sorted from highest to lowest frequency — the classic **Pareto 80/20 analysis** — with a red cumulative % line.

Reading the Pareto Chart

- **Blue bars** — defect count per type, sorted descending
- **Left axis** — absolute count of occurrences
- **Red line + right axis** — cumulative percentage (reaches 100% at last bar)
- **Tooltip on hover** — shows exact count and % of runs affected
- **Mini summary strip** below the chart — colour-coded cards per defect (green/orange/red)

Defect Reference Guide

Phase	Defect	What it Looks Like	Trigger Condition
P1 Deposit	**Edge Bead** 💧	Thick ring of resist at wafer edge — excess material builds up	Resin quantity > 300 µL AND speed < 1500 rpm
	Comets ☄	Comet-shaped streaks from particles dragged across surface	P1 speed too high (> 50 rpm) with high resin quantity
	Contamination 🦠	Foreign particles embedded in film — visible as dots or streaks	Humidity > 55% (moisture particles) or very high resin quantity
P2 Ramp	**Striations** 〰	Radial lines visible in film — caused by unstable Marangoni flow	PID oscillation score > 1.0 (MODERATE or worse)
P3 Thinning	**Non-Uniformity** ⭕	Visible thickness variation across wafer — colour rings in optical inspection	CV > 18% OR Uniformity < 88%
	Voids / Bubble ○	Air bubbles or voids trapped in film — visible as circular defects	S4 final speed > 5000 rpm (excessive centrifugal force)
	Dewetting 🫧	Film ruptures and dewets — holes appear in coating	Humidity > 62%RH (moisture-induced surface energy change)
P4 Drying	**Pinholes** ⋯	Micro-holes through film — too thin at high speed with poor uniformity	S4 > 4500 rpm AND CV > 15%
	Sticking 📌	Film adheres to chuck or cover — incomplete drying, film too	S4 < 300 rpm AND resin quantity > 250 µL

		thick	

⚠ **Defect Interactions — Combinations Matter:**
Like injection molding defects, spin coating defects are often triggered by **combinations** of conditions. Dewetting alone requires only high humidity, but **Pinholes require both** high speed AND poor uniformity simultaneously. Understanding these interactions is the core of DOE-based defect prevention.

💡 **Worst-Case Scenario — Generate All Defects:**
Set: S4 = 5500 rpm · Resin = 350 μL · RH Setpoint = 65% · Kp = 5.0, Ki = 2.0. Run 4 cycles. You should see 5–7 defect types appearing. Use this as a teaching example of "parameter out of window" conditions.

13. Exporting Data

Two Export Formats

The simulator provides two export buttons above the 50-point plotter table:

Button	Format	Content	Best For
📥 **Export CSV**	.csv	All 50 measurement rows + process parameters header	R, Python, quick import into any software
📊 **Export Excel**	.xlsx	Formatted spreadsheet with parameters + full 50-point data	Minitab import, Excel analysis, sharing reports

File Naming

Files are automatically named with the date: `SpinCoating_YYYYMMDD.csv` or `SpinCoating_YYYYMMDD.xlsx`

Export File Structure

Section	Content
Header rows	Title, copyright, blank line
Parameters	Material, Final Speed (S4), Temperature SP, Humidity SP
Measurement Data	50 rows: Point, Circle, Angle, X, Y, R, Temp, RH, Visc, Thickness

> ⚠ **Export Before Reset:**
> Clicking ↺ **RESET** clears all run results including the plotter table and scatter plot. Always export your data before resetting if you want to keep the measurement results. The Pareto chart also resets to zero on Reset.

> 💡 **Multi-Run DOE Export Strategy:**
> Since each run overwrites the plotter table with the latest run, export after **each individual run** if you need the 50-point data for multiple conditions. Alternatively, focus on the statistics panel (Mean, CV, Uniformity) as summary outputs — these can be manually recorded into a DOE worksheet across multiple runs.

14. DOE Applications

Factors and Their Levels

Factor	Symbol	Low Level (−)	High Level (+)	Units
Final Speed (P4)	**A**	2000	5000	rpm
Temperature Setpoint	**B**	18	26	°C
Humidity Setpoint	**C**	35	55	%RH
Resin Quantity	**D**	50	200	µL

Responses

Response	Unit	Target Direction	Notes
Mean Thickness	µm	Nominal target (depends on process)	Primary response — read from stats panel
Uniformity %	%	Maximise (> 95%)	Key quality response
CV%	%	Minimise (< 5%)	Alternative variability metric

Suggested Experiment Designs

Design	Runs	What You Learn
One-Factor-at-a-Time (OFAT) on S4	5–8	Thickness vs speed curve — demonstrates the $1/\sqrt{\omega}$ relationship
Full Factorial 2^2 (A=Speed, B=Temp)	4	Main effects of speed and temperature + their interaction on thickness
Full Factorial 2^3 (A, B, C)	8	Speed + T° + RH effects — explores humidity sensitivity
Full Factorial 2^4 (A, B, C, D)	16	All factors including resin quantity — comprehensive study
Central Composite Design (CCD)	10+	Response Surface — find optimal speed and temperature for target thickness

Material as a Blocking Factor:
If you want to compare results across materials (e.g., AZ 1518 vs SU-8), treat the **material as a blocking factor** in your design. Run the full factorial within each material separately. The thickness response will scale with viscosity, but the direction and magnitude of factor effects (especially speed) will be consistent across materials.

15. Practical Tips & Exploration

Suggested Exploration Exercises

A Speed vs Thickness — Verify the Physics

Keep all parameters constant. Vary S4 only: 1000, 2000, 3000, 4000, 5000 rpm. Record Mean Thickness each run. Plot Thickness vs $1/\sqrt{(S4)}$ — it should be a straight line. This is the Derjaguin-Landau model validated in the simulator.

B PID Tuning Impact on Uniformity

Run 4 cycles with Kp=4, Ki=1, Kd=0 (good). Record Uniformity%. Reset. Run 4 cycles with Kp=5, Ki=2, Kd=0 (poor). Compare average Uniformity%. This demonstrates how HVAC controller quality directly impacts product uniformity — a key lesson in process capability.

C Material Comparison

Run S4 = 3000 rpm with AZ 1518, then with SU-8 2050, then with HSQ. Compare Mean Thickness. The ratio should approximate: SU-8/AZ ≈ $\sqrt{(450/25)}$ ≈ 4.2×. Does the simulator match the predicted ratio?

D Humidity Effect on Defects

Start with RH = 35%. Run 3 cycles. Observe Pareto. Then increase RH to 65%. Run 3 more cycles. Watch which defects appear or intensify (Dewetting, Contamination). This teaches humidity's role in cleanroom yield management.

E Mini DOE — Speed × Temperature 2^2

Run: (S4=2000, T=18°C) · (S4=5000, T=18°C) · (S4=2000, T=26°C) · (S4=5000, T=26°C). Record Mean Thickness and Uniformity. Calculate the main effect of speed, the main effect of temperature, and their interaction effect on Thickness.

Common Mistakes to Avoid

Mistake	Consequence	Solution
P1 speed below 5 rpm	Alert message — simulation blocked	Set Phase 1 speed ≥ 5 rpm (minimum for spin)
Comparing results across different materials	Thickness scales differently — wrong conclusions	Fix material for entire experiment, then change
Not exporting before Reset	50-point plotter data lost	Export CSV or Excel before clicking Reset
Changing PID between DOE runs	Uncontrolled noise variable confounds results	Fix Kp, Ki, Kd at start of experiment — keep constant
Setting S4 > 6000 rpm with low-viscosity materials	Film too thin — unrealistic results, multiple defects	Stay within realistic process window for chosen material

Ignoring the scatter plot ρ value	Missing signal about PID quality	Check ρ after each run — green = stable environment

Quick Reference Card

Objective	Key Parameters to Adjust
Increase film thickness	↓ S4 speed · Use higher viscosity material · ↓ Temperature
Improve uniformity	Improve PID tuning · Reduce RH · Keep S4 moderate (2000–3500 rpm)
Eliminate Edge Bead	↓ Resin quantity · ↑ S4 speed
Eliminate Striations	Improve PID (reduce oscillation) · check Kp/Ki balance
Eliminate Dewetting	↓ RH setpoint below 55%
Eliminate Pinholes	↓ S4 below 4500 rpm · improve uniformity
Reduce variability (σ)	Tune PID to STABLE status · reduce T° and RH variation
Target specific thickness	Use physics: $S4 = (2000 \times \sqrt{visc\_base/visc\_target})^2$ — then fine-tune

> 🎓 **The Challenge:**
> Finding the right combination of **S4 speed, temperature, humidity and resin quantity** that simultaneously achieves the **target thickness, Uniformity > 95%, CV < 5% and zero defects** — for a specific photoresist material — is a classic multi-response optimisation problem. This is exactly the challenge that **DOE and Response Surface Methodology** are designed to solve efficiently, with the minimum number of experimental runs.