RSM Saves the Circuit Board

Design of Experiments as a Root Cause Analysis Tool

Richard s. Williams

"Quality isn't something that can be argued into an article or promised into it. It must be put there."
- C. G. Campbell

About me

- Chemical Engineer with a Business Degree
- 38 Years in the chemical industry
  - Most recently as a Six Sigma Master Black Belt
    - ASQ Certified Six Sigma Black Belt
    - Certified Master Black Belt
  - Specific expertise in SPC and DOE
- Private consultant since 2016
  - Teach DOE courses and webinars with Stat-Ease

Richard Scott Williams, LLC

The Situation

- A computer company experienced a third round of Thermal Management Interface (TMI) bubbles in a 3-year period – leading to scrapped chips.
- Prior root cause efforts failed to resolve this sporadic bubbling issue
- TMI manufacturer (my client) faced with a need for immediate resolution – or lose the business
- A team was assembled and charged with identifying and correcting root cause – quickly
  - I was brought in to provide leadership and a sense of neutrality and independence
- The computer company did not want to be heavily burdened with time-consuming participation in correcting the issue.

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DOE for RCA?

- Problem of consequence + Incomplete Knowledge = Need for new knowledge (aka – experimentation)
  - Data Mining, Fishbone Analysis, SPC, etc. are all helpful. But for these tools to truly build knowledge, validation (trials) are needed
  - RCA relies on establishing causation, not merely correlation
- Need for new knowledge + budget constraints is the domain of DOE.
  - Maximum Benefit, minimal work (cost)
  - Statistically valid conclusions
  - Creation of sustainable solutions

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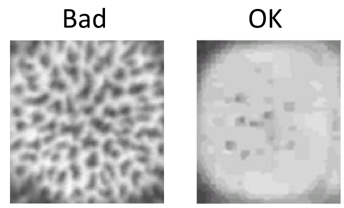
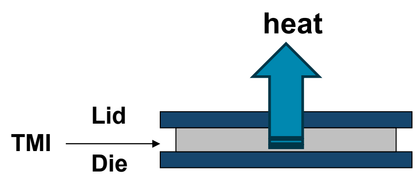
TMI Bubbles: RCA

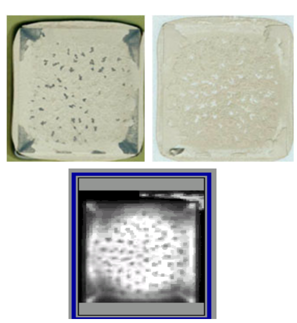




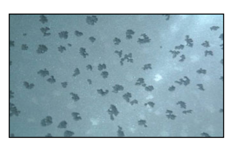
The TMI is a curable matrix containing 80-90% thermally-conductive filler

In-Spec TMI Batches can be “good” or “bad”

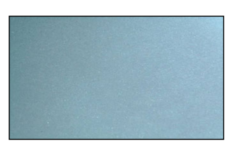
Customer Die Evaluation



Microscope Slide Visual Test



Known Bad Batch



Known Good Batch

TMI manufacturer able to replicate the problem: Customer is “off the hook”

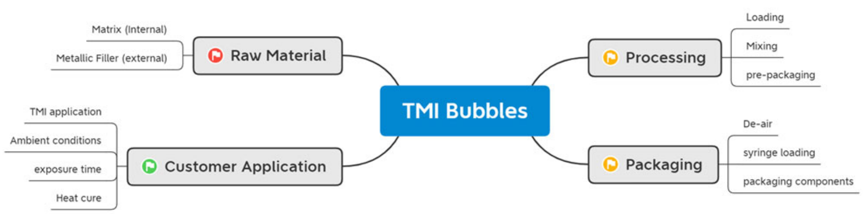
Process Map & Fishbone

Raw Material
- Internal (Matrix)
- External (Filler)

Processing
- Mixing
- Pre-packaging

Packaging
- Processing
  - De-air
  - Load
- Materials

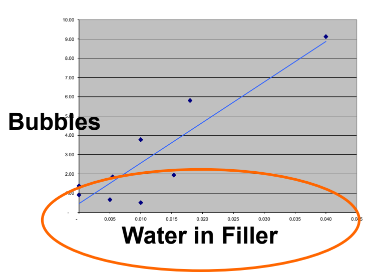
Customer Processing
- Application
- Exposure time
- Heat Cure

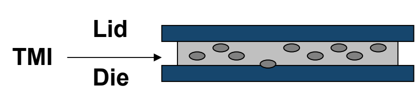


3-Factor DOE: Validate Root Cause Theory

H2O + Matrix → H2 (g)
base

Formulation 80-90% Filler





- **Filler found to be basic**

3-Variable DOE envisioned to Validate Root Cause Theory and to Identify target "good zone"

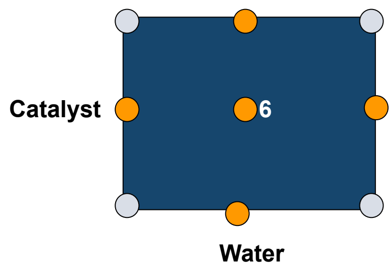
- **A customer process factor was also linked to the bubble phenomenon and was included in the study**

3-Factor DOE: Validate Root Cause

Intent was to run a 3-factor Face Centered CCD

Filler Supplier Prepared 4 different Fillers:

- High Water / High Base Catalyst
- High Water / Low Base Catalyst
- Low Water / High Base Catalyst
- Low Water / Low Base Catalyst



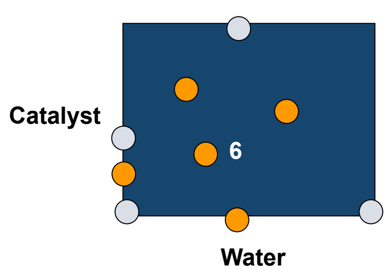
Evaluated at 3 "Process Factor" Levels

3-Factor DOE: Validate Root Cause

Intent was to run a 3-factor Face Centered CCD

Filler Supplier Prepared 4 different Imperfect Fillers:

- High Water / High Base Catalyst
- High Water / Low Base Catalyst
- Low Water / High Base Catalyst
- Low Water / Low Base Catalyst



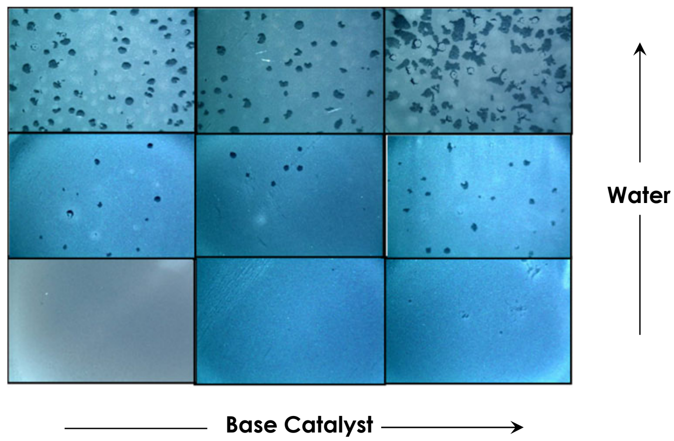
Evaluated at 3 "Process Factor" Levels

2-Factor DOE: Validate Root Cause – LAB Pre-DOE

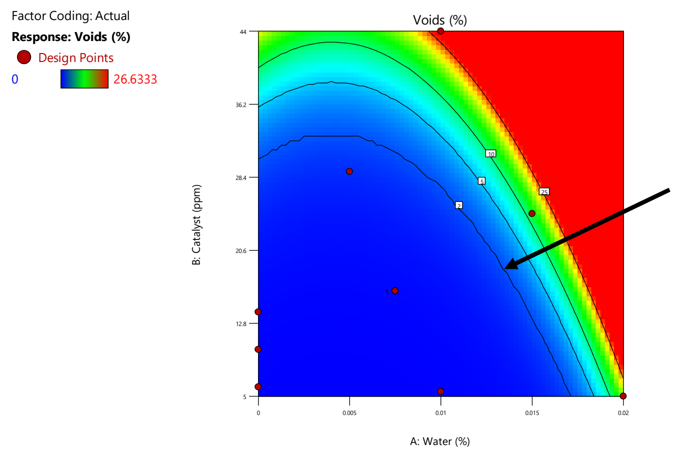
- The Lab DOE was a preliminary effort to prove concept – did not involve customer time and effort
- A 2-factor Central Composite Design was selected and executed, inputting the actual "imperfect" factor values
- Design contained 4 factorial points, 4 axial points, and 5 center points, for a total of 13 runs.
- The customer's process factor was excluded from this pre-DOE
- Lab blends of the 4 fillers were made to create the axial and center point fillers
- Note: an optimal design would have been a better choice, taking into consideration the skewed design space required (the subsequent DOE made this adjustment)

Lab DOE Results

A picture is worth a thousand words

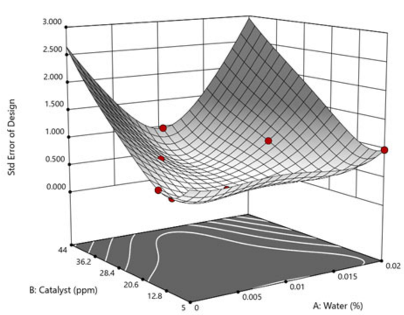


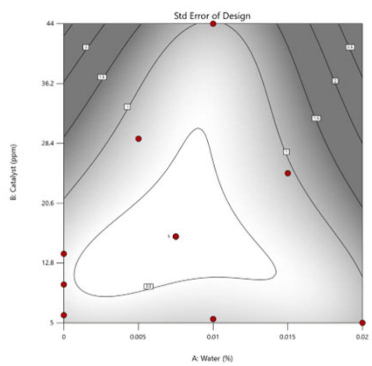
Lab DOE Results



Customer requires Voids (bubbles) below 2%

Lab DOE Results





- Note that there are regions in the design space that have poor predictability (high standard errors)
- The customer wanted these regions excluded in the next round of studies; i.e., no extrapolation allowed!

Full-Scale RSM with Customer Participation

- Armed with a validated RCA theory, the customer was invited to participate in a second RSM DOE
- This 2nd DOE would be a full-scale replicate of the Lab DOE
- The customer would add their Process Factor to the study, performed on their shop floor
- Actual customer voids (bubble) data would be collected
- The goal of the DOE would be to gather sufficient information to validate filler specifications that would give acceptable TMI performance directly at the customer's production process.
- With a validated root cause in hand, and substantial benefits within reach, the customer was eager to participate.

Full-Scale RSM: Design Approach

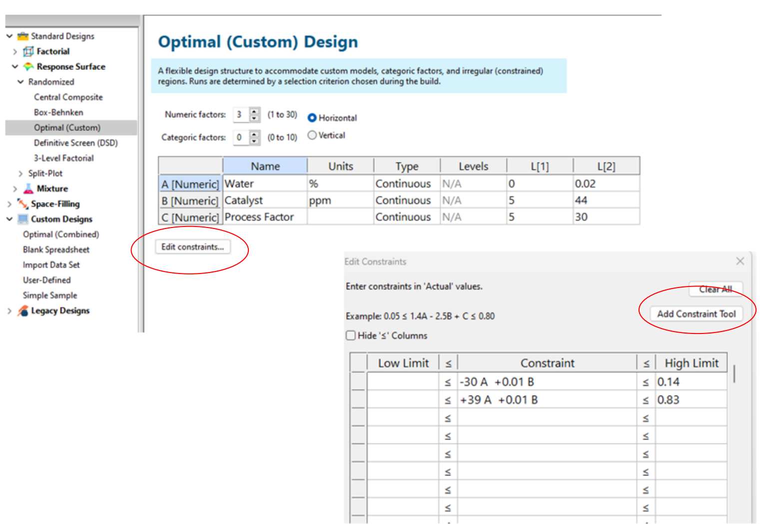
- An Optimal RSM design was selected, allowing for the constraint tool to crop the design space to where data cold be collected (no extrapolation)
- While the DOE was essentially a 3-factor study, in actuality it was a 2-factor study, with each resulting run evaluated under 3 "process factor" settings at the customer
- 6 center points were run
- The actual runs conducted in the 2-factor design were limited by the available filler properties. So a manual layout was created on a spreadsheet rather than allowing the optimal design to dictate the runs
- The resulting design had 42 runs: 4 factorial points, 4 axial points, and 6 center points, each evaluated at 3 process factor settings
- The samples were not identified at the customer; i.e., it was a blind study

Manual Layout (based loosely on a CCD approach)

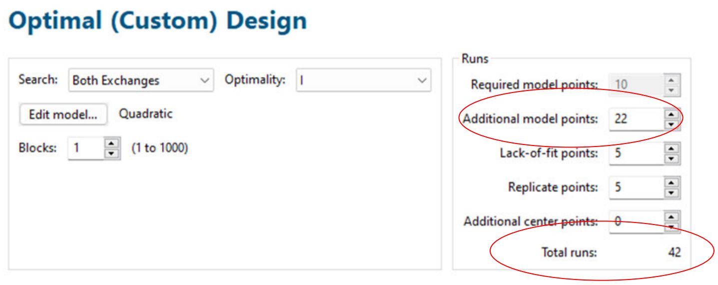
Run	A:Water	B:Catalyst	C:Process Factor
1	0.0075	16.25	5
2	0.0075	16.25	17.5
3	0.0075	16.25	30
4	0	6	5
5	0	6	17.5
6	0	6	30
7	0.01	44	5
8	0.01	44	17.5
9	0.01	44	30
10	0.0075	16.25	5
11	0.0075	16.25	17.5
12	0.0075	16	
13	0	1	
14	0	1	
15	0	1	

31	0	10	5
32	0	10	17.5
33	0	10	30
34	0.0075	16.25	5
35	0.0075	16.25	17.5
36	0.0075	16.25	30
37	0.005	29	5
38	0.005	29	17.5
39	0.005	29	30
40	0.01	5.5	5
41	0.01	5.5	17.5
42	0.01	5.5	30

Cropping the Design Space



Creating the design template



- The 42 points will be replaced by the manual template
- But the optimal design approach allowed the design space to be cropped as intended

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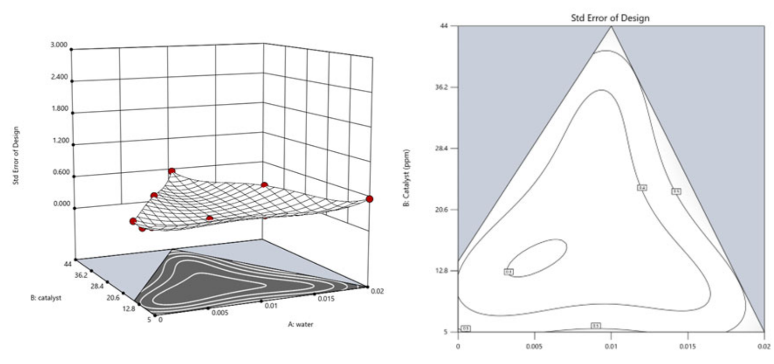
Standard Error within Cropped Design Space



- Despite the manual point selection, the standard error plots look solid
- Reminder: the customer wanted these regions excluded; i.e., no extrapolation allowed!

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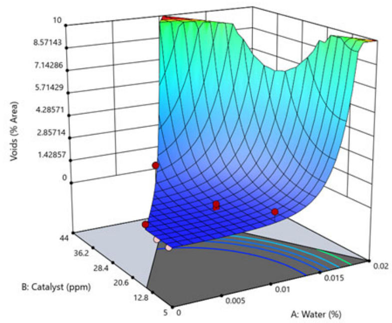
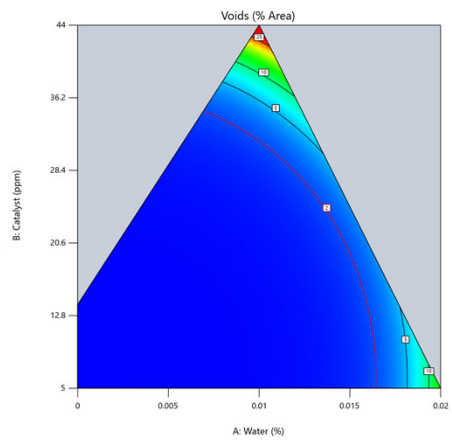
Voids at middle of Process Factor Setting Range





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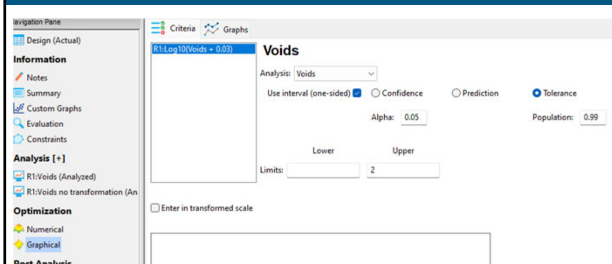
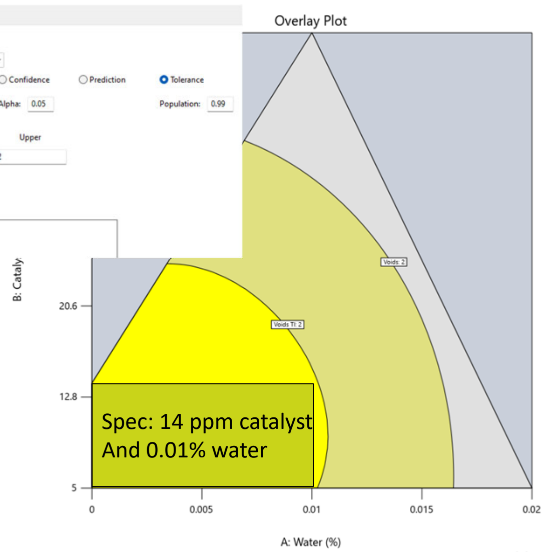
Filler Specifications Resolved – No more Voids!





Specifications set within zone of success – essentially every batch would be expected to produce less than 2% voids!

Key Takeaway Message

- Quality is what the customer says it is
  - We either build quality into the product, or we don't
- Incomplete specifications at product inception can lead to significant problems down the road
- DOE's are fantastic tools to
  - Understand factors (or mixture components) of importance
  - Efficiently gather sufficient information to establish meaningful specifications (Tolerance Intervals)
  - Aid Root Cause Analyses – when it appears our product understanding at inception was lacking and new learnings are needed
- StatEase Design Expert has the tools needed to handle get the job done – with confidence!