

# Efficient Robust Design Experimentation

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# Acknowledgments

Highlights of:

ASA Continuing Education Workshop  
 1994 Joint Statistical Meetings

Planning and Analyzing Robust Design Experiments:  
 Combining Engineering and Statistics to  
 Reduce Sensitivity to Variation

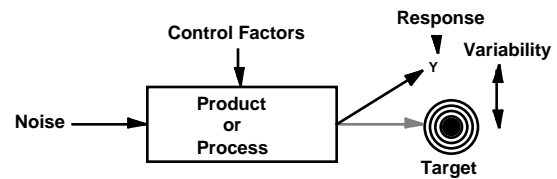
by

Ramón V. León and Robert W. Mee

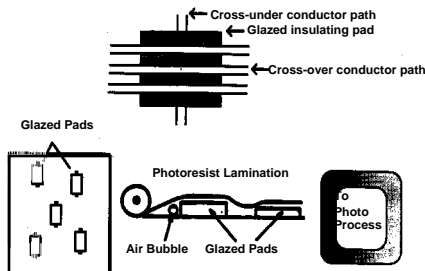
# Presentation Outline

- ➡ ■ What is robust design?
  - A strategy for planning robust design experiments
  - Elements of the strategy
    - Choosing the response
    - Noise representation plan
  - Two more ideas
  - Conclusion

# What is Robust Design?



## Robust Design Example: Photoresist Lamination Process



## Robust Design Example: Photoresist Lamination Process

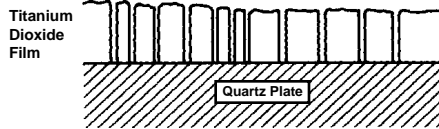
**Problem:** Electrical shorts in cross-over paths

- Noises:**
- Tall glazed pads
  - Air bubbles

- Possible solutions:** Eliminate Noise
- Reduce glazed pad variation
  - Remove air

**Robust design solution:**  
 -Change process speed (Reduced shorts by 50%)

**Robust Design Example:**  
Optical Filter Used in Wavelength-Division Multiplexers



**Problem:** Variable index of refraction  
**Noise:** Humidity in factory and in the field  
**Possible solution:** Eliminate process noise  
 Use expensive hermetic seals  
**Robust design solution:**  
 Change process so that the film is dense with few crevices to trap water molecules

\*Robust Design: A Cost-Effective Method for Improving Manufacturing Processes, R. N. Kacker and A. C. Shoemaker AT&T Technical Journal (1986)

**Robust Design Definition**

**Robust Design:**

A method for identifying those settings for the process controls that:

- Make the process less sensitive to hard-to-control sources of variation (noises)
- Minimize deviation of process performance from ideal

**Presentation Outline**

- What is robust design?
- ⇒ ■ A strategy for planning robust design experiments
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**A Strategy for Planning and Analyzing a Robust Design Experiment**

- ① Choose responses
- ② Identify components of variation and their likely physical causes (noises)
- ③ Choose noise representation plan
- ④ Identify process controls to manipulate
- ⑤ Choose the experimental plan
- ⑥ Conduct the experiment
- ⑦ Analyze the experiment to predict robust settings
- ⑧ Confirm and generalize predictions

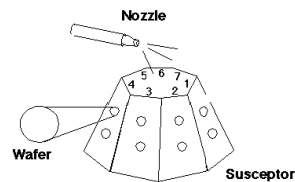
**The Planning Strategy in Contrast to a Common Practice**

Common approach:

- Brainstorm on all the factors that affect responses
- Sort them into two categories
  - Control factors: factors that can be economically controlled
  - Noise factors: factors that cannot be economically controlled
- Frequently leads to:
  - Unwieldy large numbers of noise and control factors
  - Uninformative experiments
  - Curvature and interactions that are an artifact of how the problem is posed

**Strategy for Planning Robust Design Experiments: An Example**

Epitaxial Layer Growth



Objective:

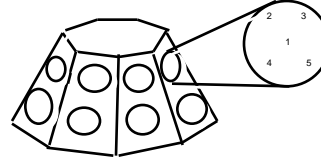
- Grow a uniform 14.5 μm thick epitaxial layer**
- low within wafer variability
  - low across wafer variability

## Following the Planning Strategy: The Epitaxial Layer Example

- ① Choose responses
  - The epitaxial layer thickness
- ② Identify components of variation and their likely physical causes (noises)
  - Important components of variation: within wafer, facet-to-facet, top-to-bottom, batch-to-batch
  - Noises: Uneven temperature, vapor composition, and vapor concentration (mixing problems)

## Following the Strategy: The Epitaxial Layer Example

- ③ Choose noise representation plan
  - Wafers on all facets
  - Wafers on top and bottom of each facet
  - Five measurements per wafer



**Remark**

Representation plan "sees" the effect of the following components of variation:

- facet-to-facet
- top-to-bottom
- within wafer

## Following the Strategy: The Epitaxial Layer Example

- ④ Identify process controls to manipulate
  - Components of variation captured in the noise representation plan: top-to-bottom, facet-to-facet, within wafer
  - Physical systems: Chemical and mixing
  - Control factors that might affect mixing: Rotation method, nozzle position, arsenic flow rate, and hydrochloric acid flow rate
  - Control factors that might affect chemistry: Deposition temperature and hydrochloric acid etch temperature
  - Control factors that might affect components of variation
    - » Facet-to-facet: rotation method
    - » Top-to-bottom: nozzle position
  - Adjustment factor: Deposition time

## Following the Strategy: The Epitaxial Layer Example

- ⑤ Choose the experimental plan
  - Seven control factors each studied at two settings

Control factors	Initial Setting	Test Setting A	Test Setting B
A. Rotation direction	Oscillating	Continuous	Oscillating
B. Deposition temperature	1215°C	1210°C	1220°C
C. Deposition time	Low	High	Low
D. Arsenic flow rate	57%	55%	59%
E. Hydrochloric acid etch temp.	1200°C	1180°C	1215°C
F. Hydrochloric acid flow rate	12%	10%	14%
G. Nozzle position	4	2	6

## Following the Strategy: The Epitaxial Layer Example

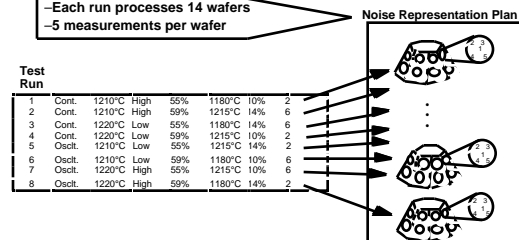
- ⑤ Choose the experimental plan (Cont.)
  - Seven control factors each studied at two settings
  - 8 run fractional factorial in the seven control factors

Test Run	Control Factors						
	Rotation Method	Dep. temp.	Dep. Time	Arsenic Flow Rate	HCl Acid Etch Temp.	HCl Acid flow Rate	Nozzle Position
1	Cont.	1210°C	High	55%	1180°C	10%	2
2	Cont.	1210°C	High	59%	1215°C	14%	6
3	Cont.	1220°C	Low	55%	1180°C	14%	6
4	Cont.	1220°C	Low	59%	1215°C	10%	2
5	Oscil.	1210°C	Low	55%	1215°C	14%	2
6	Oscil.	1210°C	Low	59%	1180°C	10%	6
7	Oscil.	1220°C	High	55%	1215°C	10%	6
8	Oscil.	1220°C	High	59%	1180°C	14%	2

## Following the Strategy: The Epitaxial Layer Example

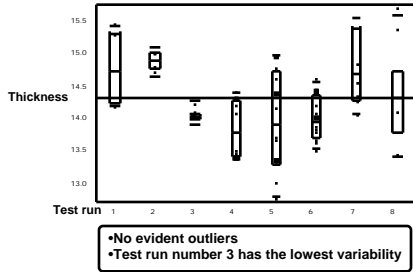
- ⑤ Choose the experimental plan (Cont.)
  - Seven control factors each studied at two settings
  - 8 run fractional factorial in the seven control factors

- Each run processes 14 wafers
- 5 measurements per wafer



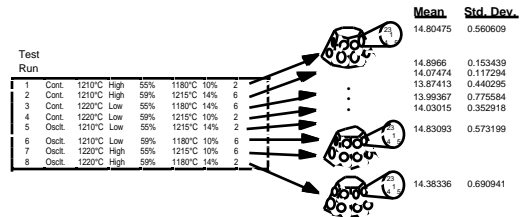
## Following the Strategy: The Epitaxial Layer Example

- Analyze the experiment to predict robust settings
- Experiment data inspection



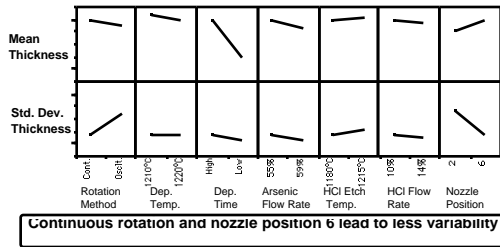
## Following the Strategy: The Epitaxial Layer Example

- Analyze the experiment to predict robust settings
- Performance measure analysis



## Following the Strategy: The Epitaxial Layer Example

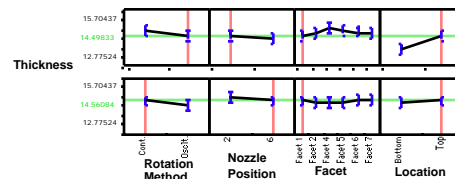
- Analyze the experiment to predict robust settings
- Performance measure analysis



Remark: Note that deposition time is an adjustment

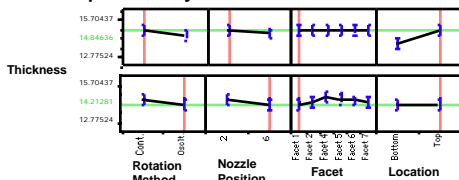
## Following the Strategy: The Epitaxial Layer Example

- Analyze the experiment to predict robust settings
- Response analysis



## Following the Strategy: The Epitaxial Layer Example

- Analyze the experiment to predict robust settings
- Response analysis



Added insight:  
•Rotation Method affects facet-to-facet variability  
•Nozzle Position affects top-to-bottom variability

## Robust Design Experimentation Approach: Multistage Experimentation

### 1 Predict robust settings

- Experiment at exaggerated, well-controlled noise conditions

Exploratory Experiment

### 2 Confirm and generalize predictions

- At experimental noise conditions
- Under production noise conditions

Confirmatory Experiment

Exploratory experimentation emphasizes different DOE ideas than confirmatory experimentation, e.g., noise factors versus blocking factors.

## Following the Strategy: The Epitaxial Layer Example

- ⑧ **Confirm** and generalize predictions
  - At experimental noise conditions

Rotation Method	Initial	Oscit.	1215°C	Low	57%	1200°C	12%	4	Std. Dev.
Initial	Oscit.	1215°C	Low	57%	1200°C	12%	4	.378	
Predicted	Cont.	1215°C	Low	57%	1200°C	12%	6	.239	

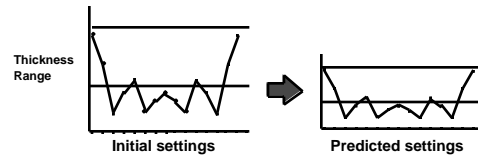
### Remarks:

- A new test run is done at the initial settings
- The predicted and initial settings differ by only two controls settings
- The predicted settings was not one of the experimental test runs
- One may also want to rerun the best test run

38% reduction in standard deviation

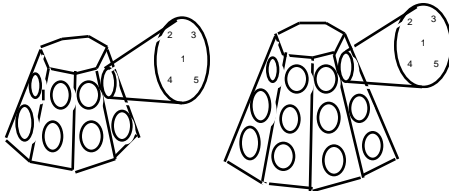
## Following the Strategy: The Epitaxial Layer Example

- ⑧ **Confirm** and generalize predictions
  - At production noise conditions
    - At one instance of time
    - Over time



## Following the Strategy: The Epitaxial Layer Example

- ⑧ Confirm and **generalize** predictions



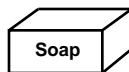
Can we recommend that all susceptors be rotated in one direction?

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## Guiding Principle 1: Choose Appropriate Response

**Problem:** Many bars of soap are underweight



**Question:**

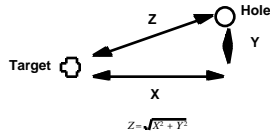
What is the right response to solve this problem?

## Appropriate Responses Are:

- Connected to engineering and economic goals
- Causally related to the factors
- One per physical system
- Independent of imposed values
  - e.g., specifications, targets

**Poorly chosen responses can unnecessarily complicate a model**

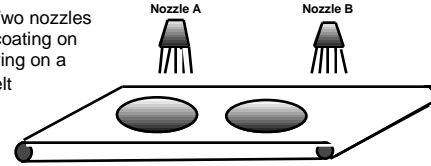
## A Poorly Chosen Response Can Unnecessarily Complicate a Model



- **Assume:**
  - Linear relationship between X-control and response Z
  - Linear relationship between Y-control and response Z
- **Result:**
  - X-control and Y-control show curvature and interaction when the response is Z

## A Poorly Chosen Response Can Unnecessarily Complicate a Model

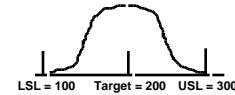
**Example:** Two nozzles spraying a coating on objects moving on a conveyor belt



Y = total thickness of coating on surface of object

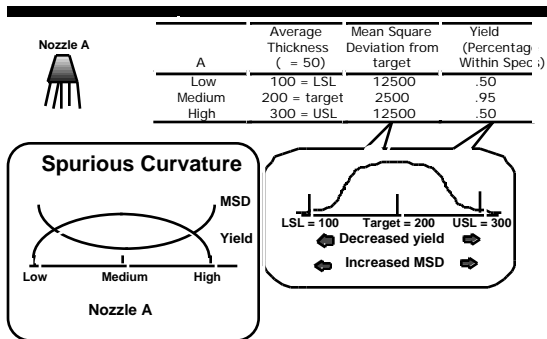
A = Flow rate of Nozzle A

B = Flow rate of Nozzle B

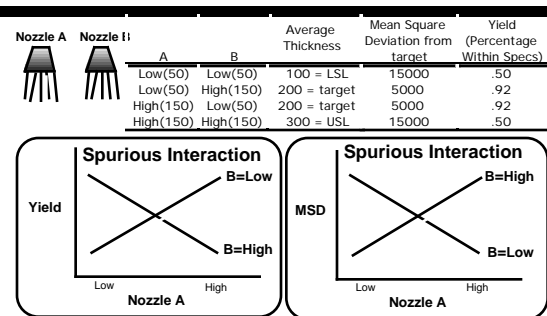


**Remark:**  $Y = \mu + \sigma_A A + \sigma_B B$ , i.e. no curvature or interaction

### 1. Choose Responses: Problems with Responses that Depend on a Target or Specifications



### 1. Choose Responses: Problems with Responses that Depend on a Target or Specifications



## Implications of Response Objectives

### On target

- Example: Epitaxial thickness
- Minimize variability around a fixed target
- Goal is to attenuate effect of noise on variability
- Control-by-noise interactions are very important
- Adjustments that control the mean without substantial effect on variability are usually available
- Mean response only of secondary interest

## Implications of Response Objectives

### Larger-the-better

- Example: Shelf life of candy bars
- Usually want large values reproducibly (high average response with low variability so analysis should be in terms of mean and variance of response)
- Maximizing response under worst case noise conditions is sometimes sufficient (e.g. shelf life at high ambient temperature)

## Implications of Response Objectives

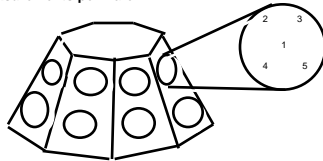
### Smaller-the-better

- Example: Rolling friction of ball bearings
- Poor example:** Defect rate
- Usually want small values reproducibly
- Variance often produces little additional information over the mean when response has a lower bound
- Transformations are frequently necessary for statistical analysis because of order of magnitude ranges in the response
- Minimizing response at worst noise conditions is sometimes sufficient (e.g. rolling friction at high load)

## Epitaxial Layer Example

### Noise representation plan:

- Wafers on all facets
- Wafers on top and bottom of each facet
- Five measurements per wafer



Representation plan "sees" the effect of the following components of variation:

- facet-to-facet
- top-to-bottom
- within wafer

## Noise Representation: Statistical Implications

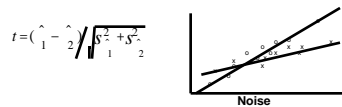
### ■ Sampling noise conditions

- Comparison of response under naturally occurring noise conditions

$$F = \frac{s_1^2}{s_2^2}$$

### ■ Sampling noise conditions plus noise covariate

- Comparison of response under naturally occurring noise conditions with recording of noise levels



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- What is robust design?
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## Noise Representation: Alternative Strategies

### ■ Sampling noise conditions

- Example: Sampling voltage over time in aluminum smelting pot

### ■ Sampling plus noise covariate

- Example: Pepper count on semiconductor devices plus measurement of particulates in the air

### ■ Manipulating noise conditions

- Example: Height of leaf springs quenched at different oil temperatures

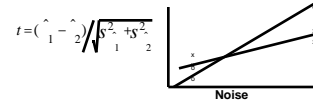
### ■ Scanning extreme noise conditions

- Example: Sampling epitaxial layer thickness of wafers at top and bottom of susceptor

## Noise Representation: Alternative Strategies

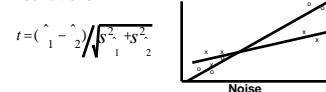
### ■ Direct manipulation of noise conditions

- Comparison of response at **controlled** extreme noise conditions

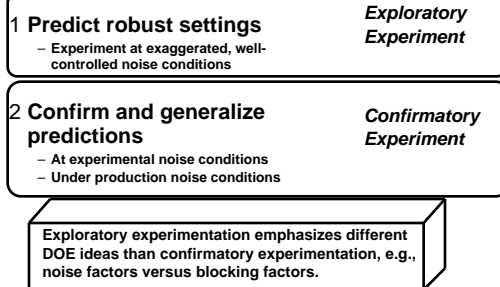


### ■ Scanning of extreme noise conditions

- Comparison of response at **sampled** extreme noise conditions



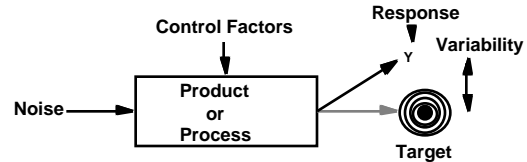
## Robust Design Experimentation Approach: Multistage Experimentation



## Noise Representation Plan: Rationale

### ■ To efficiently compare sensitivity to noise at different control settings

- Strive for identical noise conditions
- Exaggerate noise conditions



## Representation Plan: Principle of Exaggerated Comparison

Use extreme noise conditions when comparing sensitivity to noise at different control settings

## Noise Representation Plan: Principle of Fair Comparison

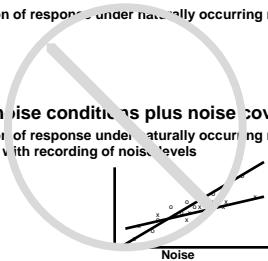
Strive for identical noise conditions when comparing sensitivity to noise at different control settings

- Control noises during the experiment
- Eliminate (or correct for) extraneous sources of variation

*Fairness is not guaranteed by random sampling of noise*

## Using Product Array Experimental Plans: Not for First Two Noise Representation Strategies

- Sampling noise conditions
  - Comparison of response under naturally occurring noise conditions
- Sampling noise conditions plus noise covariate
  - Comparison of response under naturally occurring noise conditions with recording of noise levels



## Conducting Noise-Efficient Experiments: Cake Recipe Example 2

Consider a robust design experiment for cake recipes:

Noise array consists of four baking (noise) conditions  
 -  $2^2$  factorial in baking time and temperature

Time	Temperature

Control array consists of eight different recipes (runs)

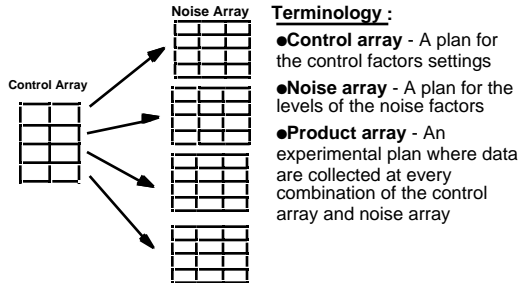
Eight combinations of flour, shortening, egg, and sugar

RECIPE	Flour	Shortening	Egg	Sugar
1				
2				
3				
4				
5				
6				
7				
8				

Product array experiment needs a total of **32 cakes**

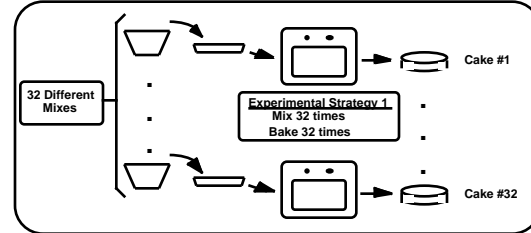
Consider **four** experimental plans for conducting the experiment

## Using Product Array Experimental Plans: What is a Product Array?



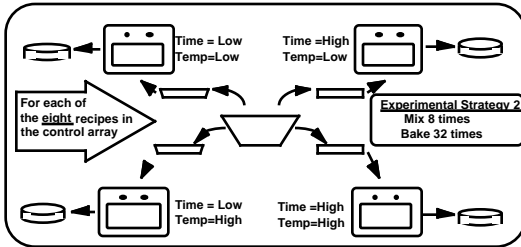
## Conducting Noise-Efficient Experiments: Cake Recipe Example 2

**Experimental Strategy 1:** 32 cakes individually mixed and baked in random order. The total experiment involves 32 oven runs.



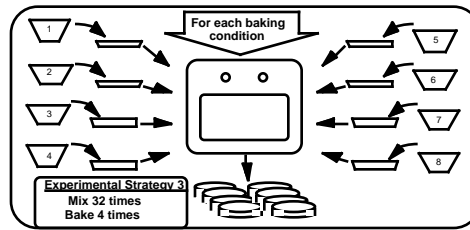
## Conducting Noise-Efficient Experiments: Cake Recipe Example 2

**Experimental Strategy 2:** Mix each of the eight recipes just once (not four times as in Plan 1). Prepare four cakes from each of these eight mixes and bake these four cakes at the four baking (noise) conditions. The total experiment involves 32 oven runs.



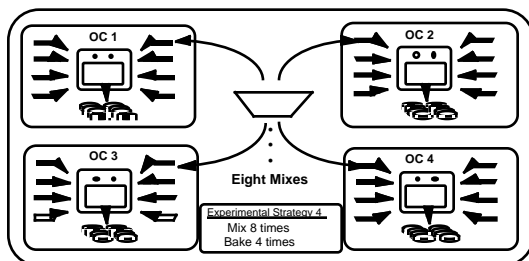
## Conducting Noise-Efficient Experiments: Cake Recipe Example 2

**Experimental Strategy 3:** Mix the eight recipes and bake at the first oven condition. Repeat this process for the other three baking conditions. The total experiment involves just four oven runs.



## Conducting Noise-Efficient Experiments: Cake Recipe Example 2

**Experimental Strategy 4:** Same as Experimental Strategy 3 but each of the eight recipes is mixed just once



## Conducting Noise-Efficient Experiments: Cake Recipe Example 2

<b>Experimental Strategy 1</b> Mix 32 times Bake 32 times	<b>Experimental Strategy 2</b> Mix 8 times Bake 32 times
<b>Experimental Strategy 3</b> Mix 32 times Bake 4 times	<b>Experimental Strategy 4</b> Mix 8 times Bake 4 times

### Questions:

- Which experimental strategies give
  - the greatest within-noise-level consistency?
  - the greatest within-control-setting consistency?
- Which experimental strategy is best for identifying the recipe robust to baking time and temperature variation?

## Conducting Noise-Efficient Experiments: Concept

### A noise-efficient design is :

- A design that is efficient for comparing process sensitivity to specified noises at several control factor settings
- A design which ensures:
  - Across-noise-level disparity
  - Within-noise-level consistency
  - Within-control-setting consistency
  - Control of all other known sources of variation

Focus experiment on sensitivity to the noises being studied

## Conducting Noise-Efficient Experiments: Test Run Order for a Product Array

### Motivating Example:

- One control factor: Material (A, B, & C)
- One noise factor: Temperature (1500, 1600)
- Six run product array replicated twice

Control Array	Noise Array
A	1500
B	1600
C	

Experiment Plan 1			Experiment Plan 2		
Run Order	Temperature	Material	Run Order	Temperature	Material
1	1500	A	1	1500	B
2	1500	C	2	1500	A
3	1500	B	3	1600	A
4	1600	C	4	1500	A
5	1600	A	5	1600	C
6	1600	B	6	1500	B
7	1500	A	7	1500	C
8	1500	C	8	1500	B
9	1500	B	9	1600	B
10	1600	B	10	1600	A
11	1600	A	11	1500	A
12	1600	C	12	1600	C

Which test run order would you choose? Why?

## Conducting Noise-Efficient Experiments: Test Run Order for a Product Array

### Answer:

Experimental Plan 1

Run Order	Temperature	Material
1	1500	A
2	1500	C
3	1500	B
4	1600	C
5	1600	A
6	1600	B
7	1500	A
8	1500	C
9	1500	B
10	1600	B
11	1600	A
12	1600	C

### Why :

- Experimental Plan 1 is more efficient for comparing process sensitivity to noise at the three material levels
- Experimental Plan 1 ensures more within-noise-level consistency

## Conducting Noise-Efficient Experiments: Statistician's Jargon

### Split-plot designs

- Change certain factors less frequently
  - These factors are called "whole-plot factors"
- Product array designs naturally lend themselves to split-plot (and related) run orders
- Use noise factors as whole-plot factors to achieve greater efficiency in comparing control factors

\* Box and Jones (1992) examine alternative split-plot plans

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## Economizing in Robust Design Experiments: Two Ideas

- Sliding Levels to Avoid Interactions
  - By eliminating noise-by-noise or control-by-control interactions, we can use smaller control and noise arrays
- Noise Compounding
  - When two noises are strongly correlated in practice, we may combine them as a single compound factor in our experiment

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## Robust Design Experimentation Approach: Multistage Experimentation

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