In 1946, R.L. Plackett and J.P. Burman published their now famous paper “The Design of Optimal Multifactorial Experiments” in *Biometrika* (vol. 33). The paper described the construction of economical designs with the run number a multiple of 4, rather than a power of 2, like full factorial and fractional factorial designed experiments.

Plackett-Burman designs are very efficient screening designs when only main effects are of interest. These designs are used for screening experiments because main effects are, in general, confounded with two-factor interactions.

Designed experiments that are confounded are described by their resolution. A designed experiment that has a main factor confounded with a two-factor interaction is a Resolution III. An easy way to remember this is to hold three of your fingers up in front of you, grab two of your fingers with your opposite hand and you have one finger that is confounded with the two held in your other hand. This simple example can be used with Resolution IV and V designs to visualize the confounding, using four and five fingers respectively.

Another way to look at this is by correlation analysis. With a Resolution III fractional factorial design, the correlation between a main effect and a two factor interaction is either -1 or +1 (remember that correlations range between -1 and +1, and in correlation analysis we usually examine correlations that are ≥ 0.70). An example of this is shown with a $2^3$ half fractional design in Figure 1. The (-) and (+) signs represent the low and high factor levels and are coded as such. Summing this up, what we have with fractional factorials ($2^{k-p}$) Resolution III designs, is a main effect column $X_i$ is either orthogonal to $X_iX_j$ (sums to 0) or is identical to minus one (-1) or plus one (+1) $X_iX_j$.

Even though the Plackett-Burman designs are Resolution III, they possess one unique attribute. The two-factor interaction column $X_iX_j$ is correlated with every $X_k$ (for $k$ not equal to $i$ or $j$) at a correlation value of -0.33 or +0.33; with this weak correlation the effects of confounding are minimized. Furthermore, the interactions are uniformly dispersed over all the experimental runs. These two attributes make the Plackett-Burman designs good choices for screening experiments when the number of factors being studied is ≥ 5.

Plackett-Burman design runs are a multiple of 4, beginning with 12 runs (there is no 16 run experiment). Each design can have up to $k = (n-1)$ factors; for example, the simplest Plackett-Burman, the 12 run, can have up to 11 factors ($11 = [12 – 1]$). One can easily see the advantages to a 12 run experiment being able to model up to $2^{11} = 2,048$ different

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**Figure 1.** Confounding effects of a Resolution III design with correlation of -1 or +1.

**Figure 2.** Power curve for the Plackett-Burman 12 run DoE with 10 factors and an alpha level of 0.05.
process combinations!

These designs are also known as saturated main effect designs, because all the degrees of freedom are utilized to estimate main effects. If no p-values (probability) are calculated, due to design saturation, then the analysis can be done graphically or by calculating percentages based upon the main effects Sum of Squares divided by the total Sum of Squares. If we apply the principles of Pareto, then we’ll most likely be removing multiple main effects, which will, in turn, give us the needed degrees of freedom to calculate the p-values.

If we use a maximum of \(k = (n-2)\) factors, this allows one degree of freedom for the error term, which allows the calculation of p-values for each of the main effects in the model simultaneously. Even with this we can still have up to \(2^{10} = 1,024\) different process combinations.

**Saturated** Plackett-Burman designs typically have low power. Power is defined as the conditional probability that you will *avoid* a Type II error, and a Type II error is failing to reject (accepting) the null hypothesis when, in fact, it is true. And we do that by increasing the alpha (\(\alpha\)) value in the significance testing. Figure 2 shows a power curve for a Plackett-Burman 12 run experiment with 10 factors and an alpha value of 0.05. We can see on the horizontal axis that with 50% power we’ll need to see an effect size of \(\pm 5\) standard deviations! And the effect size is the difference between the low and high factor level means. (Discussions on power calculations can get lengthy, so we’ll save that for another day.)

Historically, alpha values of 0.05 or 0.10 were used due to computations being done by hand. With the advent of the modern computer we can easily alter the alpha value and determine its effects. For screening experiments I recommend using alpha values up to \(\sim 0.15\) be used to increase power in the experiment. After all, it’s a screening experiment and we don’t want to make the acceptance criteria too harsh.

There are six basic steps to follow when designing and running experiments:

1) State the problem, define the objectives
2) Design the Experiment
   a. Choose factors &
   b. Determine appropriate responses & how to measure
   c. Select a design, know your pros & cons, and review runs
   d. Approximate power of the experiment
3) Randomize & run the experiment
4) Analyze the experiment
5) Confirmation runs & Ppk estimations
6) Report & recommendations

It does make sense to use the Plackett-Burman family of designed experiments to separate the “vital few” factors from the “trivial many” when troubleshooting a process.

Let’s look at a real example using the Plackett-Burman 12 run screening experiment:

**Problem statement:** During electroless nickel/immersion gold (ENIG) plating of printed circuit boards a random defect is seen that is known as stray plating (plating of nickel and subsequent gold on top of the soldermask). See Figure 3 for an example of stray plating. This defect leads to rework and potential shorts during or after assembly.

After a brainstorming session, the factors and levels were chosen and are shown in Table 1. Concurrently the defect sample in Figure 3 was removed with Scotch® tape and sent to an outside lab for analysis using SARiSTM Material Analysis, which is a combination of high-power laser beam technology used to ablate the sample and subsequent analysis with the high mass resolution capability of the ICP-MS; elemental survey and quantitative analysis of the material

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**Table 1. DoE factors and levels.**

<table>
<thead>
<tr>
<th>Factors</th>
<th>-1</th>
<th>+1</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step Exposure</td>
<td>10</td>
<td>15</td>
<td>Stouffer step wedge exposure level for the soldermask</td>
</tr>
<tr>
<td>Developer Passes</td>
<td>1</td>
<td>2</td>
<td>Number of passes through the soldermask developer</td>
</tr>
<tr>
<td>Pre Cure</td>
<td>No</td>
<td>Yes</td>
<td>Soldermask pre cure time @180°F</td>
</tr>
<tr>
<td>Final Cure (min)</td>
<td>15</td>
<td>65</td>
<td>Soldermask cure time @ 300°F</td>
</tr>
<tr>
<td>UV Bump</td>
<td>No</td>
<td>Yes</td>
<td>Ultra violet bump of the soldermask prior to ENIG processing</td>
</tr>
<tr>
<td>Pre Scrub</td>
<td>Yes</td>
<td>No</td>
<td>Light brush scrub prior to processing the ENIG line</td>
</tr>
<tr>
<td>Cleaner</td>
<td>Yes</td>
<td>No</td>
<td>Use of acid cleaner in the ENIG line</td>
</tr>
<tr>
<td>Micro Etch (μ-in)</td>
<td>10</td>
<td>90</td>
<td>Micro-inch removal in the etch step in the ENIG line</td>
</tr>
<tr>
<td>Pre Dip (min)</td>
<td>1</td>
<td>5</td>
<td>Sulfuric pre dip time prior to the palladium activator in the ENIG line</td>
</tr>
<tr>
<td>Activator (min)</td>
<td>1</td>
<td>4</td>
<td>Palladium activator time in the ENIG line</td>
</tr>
</tbody>
</table>

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Figure 3. Stray plating defect seen on blue soldermask.
Lurking variables can be tolerated when they’re managed correctly but disastrous when they’re not. To help in reducing noise it’s important that the test vehicles mimic the real production pieces, so for this experiment the test vehicles were actual multilayer printed circuit boards, in panel form, with a dimension of 16 x 18 inches. Another critical step in negating noise is to randomize the experimental runs; if noise is present we generally see an inflation of the error variance without adding bias to the real differences between the factor levels.

The responses to each of the 12 individual experimental runs are shown in Table 3. The counts of stray plate are actual individual pieces found on each test vehicle.

Analysis of variance (ANOVA) was used to analyze the full model; Table 4 shows the ANOVA, while Figure 4 shows a Pareto chart of the standardized effects. The final model (reduced) ANOVA and Pareto chart of the standardized effects are shown in Table 5 and Figure 5.

We can see in final model ANOVA...
The general protocol would be to abandon the tentative regression model in attempts to find a more appropriate equation. Due to the lack-of-fit we will abandon the secondary objective and ignore this condition.

We have detected two statistically significant variables, that of Micro Etch and Final Cure, which deserve further investigation.

Table 4. ANOVA of the full model.

Table 5. ANOVA of the final model.

The screening DoE was able to eliminate a significant number of the study variables, and study variables that are eliminated contain a wealth of information about the process itself and are key in developing enhanced process knowledge. Therefore, it is recommended that time be allotted to debrief team members and those responsible for the processes under study.

Armed with the identification of the two significant factors and the results of the SARIS analysis, further investigations were made into the entire upstream processing. It was found that soldermask operators were slip sheeting and stacking final cured panels as they were coming out of the oven. The slip sheets were investigated as a potential source of contamination.

Contaminated slip sheets were transferring copper particles to the hot soldermask surface when the panels were stacked after final cure.
The more advanced the cross-linking of the soldermask (longer final cure time) the less likely the soldermask was to pick up copper particles, which makes sense. These types of stray defects are usually amorphous in appearance, and once the root cause of the problem was identified and eliminated the stray plating ceased.

Knowledge of the potential for soldermask to pickup particulate should be disseminated throughout the manufacturing organization, and lessons learned should be archived in a FMEA (Failure Mode Effects Analysis). These activities are known as process management.

**SUMMARY**

When trouble arises in today’s complex manufacturing processes, the process engineer needs to react quickly. Many times the engineer is faced with dozens if not hundreds of process control options to change. Using designed experiments as a tool for troubleshooting can be very effective, saving both time and money.

The Plackett-Burman family of designed experiments can be an effective tool to aid the process engineer in troubleshooting a process as it allows one to separate the “vital
Experiments with Minitab, ASQ Quality Press, Milwaukee, WI.


REFERENCES
2. SARIS™ Laser Ablation ICP-MS analytical technique developed by Balazs NanoAnalysis

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few” factors from the “trivial many.” The process engineer must keep in mind that statistics are only tools to help us; they don’t replace the engineers’ skill and intelligence.

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