

Using JMP® for designing and analyzing experiments: A manufacturing example

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Abstract: JMP® is a Statistical Discovery tool from SAS Institute Inc. This paper will illustrate some of the discovery and visualization features one can use for the design of experiments (DOE) using JMP. Based on a real life situation, consider an engineer at a device manufacturer who has the need to make up to 60 lead attachments to an integrated circuit. If connection breakage forces are recorded we want to design so that we maximize the break forces while simultaneously minimize the variability. With two different connection substrates (nominal) and three continuous factors we can run the concatenation of two Box-Behnken response surface designs, one for each substrate, in 26 runs and understand the optimal settings instead of passively running a Plackett-Burman screening design. If the supplier supplies additional substrates we can run an augmented design for verification.

Introduction: The XYZ Corporation produces a medical device, which is dependent on an internal integrated circuit (IC). Sixty leads are attached to this IC and lead to other circuits within the device. There are two possible substrates (A and B) for the ICs and three additional factors to consider: Power (the amount of power to attach each lead), Time (the attachment time), and Force (the crimping force for each attachment). What substrate and what settings for Power, Time, and Force will maximize the mean of the breakage force over 60 attachments (mean Y) and minimize variation (std Y)?

Design Considerations: With 60 lead attachments we definitely want to minimize the number of experimental runs. If we use the "one factor at a time" approach as most engineers are taught, we search only along the 3 axes (Power, Time, and Force) and if we use a two level screening design our search is only at center and all corner points (see Czitrom (1999)). But if we really want to examine the entire space and allow for curvature (maxima and minima at internal values) then we should consider a response surface design. The minimum run response surface for 3 factors is a 13-run Box-Behnken design with only one centerpoint.

Generating the Design: The steps that will generate the design table are:

1>From within JMP select **Tables:Design Experiment**
2>From within **Choose Design Type** select **Define Factors and Levels** and enter names and high and low values. Then return to **Choose Design Type** select **Response Surface** and for 3 factors choose 15 runs (Box-Behnken), Figure 1. By clicking **Generate Selected Design** you get a 15 run Box-Behnken as a JMP data table. Delete the last two rows and you have the "kernel" of the experiment. See the BBDesign 1 table in Figure 2.
3>Next concatenate BBDesign 1 with itself and rename the 26 run data set as "Substrate(all)". Next add 60 columns, Y1, Y2, ..Y60 that hold all the lead breakage strength data, and three calculated columns, meanY, stdY and Experiment where these are generated in the JMP Calculator as mean of(Y1,Y2,...Y60) and std of(Y1,Y2...Y60) and the row number respectively. We are now ready to take measurements and analyze results. Figure 3 shows a small part of the entire table and Figure 4 visualizes the double (substrate A and B) Box-Behnken design.

Analysis: We want to maximize the lead separation force while at the same time minimize the variability of the force. If the breakage force is highly variable then we have no good idea of quality assurance of the device. We use **Fit Model** with meanY and stdY as responses, substrate and a response surface in Power, Time, and Force as the effects, and Screening as the model type (see Figure 5). The resulting Prediction Profiles with desirabilities set to "bigger is better" for meanY and "smaller is better" for stdY are shown in Figures 6a and 6b. It's clear from the desirabilities in the last row that substrate is the most compelling factor and that as we move the selection line from A to B the mean substantially decreases and the standard deviation almost doubles. Next we run separate Box-Behnken analyses for substrate A (Figures 7a and 7b) and substrate B (Figure 8). We first notice that the error of prediction is larger, especially for substrate B. Secondly, the settings have changed. In the first model substrate was the dominant effect, but once we analyze within a substrate Power and Time (and especially the Power*Time interaction (Figure 7b)) become the dominant factors and it is very possible that the substrates will differ in their optimal settings. This is the case here with lower Power yielding higher means and lower standard deviations when Time=20 for substrate A. In contrast for substrate B higher values of Power give higher mean lead separations.

Since substrate A is superior we decide to verify it on another IC with substrate A. Create another Box-Behnken design and concatenate it with the first 13 rows of the Substrate(all) data set to augment the design with readings from a second IC with substrate, A. Enter the lead breakage values and the meanY and stdY will automatically be calculated. A summarized table showing the mean and std (but not any of the raw values) is shown in Figure 9. Using this table we confirm the same settings as we had in the first 16 runs only (Figures 10a and 10b). Interestingly comparing Figures 7a and 10a the prediction error bars are tighter for the mean but wider for the standard deviation. To examine this, we do a comparison on stdY vs. Batch# using **Fit Y by X**. The graph in Figure 11 shows that stdY is quite a bit higher for the second IC (last 13 runs) vs. the first IC with substrate A (first 13 runs) and Figure 12 indicates that the p-value of that comparison is .0577, only slightly insignificant.

Conclusions: We have shown that an IC with substrate A has the potential of larger lead breakage forces and less variability, that due to a substantial interaction we can optimize when Power and Time are at their low values, and that the lead attachment force, Force, is not an important factor. We also have an indication that there is still quite a bit of variability in breakage force within the 60 leads and that this can vary between integrated circuits having substrate A.

Reference

Czitrom V. (1999) "One-Factor-at-a-Time Versus Design Experiments", The American Statistician, 53 No. 2, 126-131

Note: JMP® software is a registered trademark of SAS Institute Inc. in the USA and other countries. ® indicates USA registration.

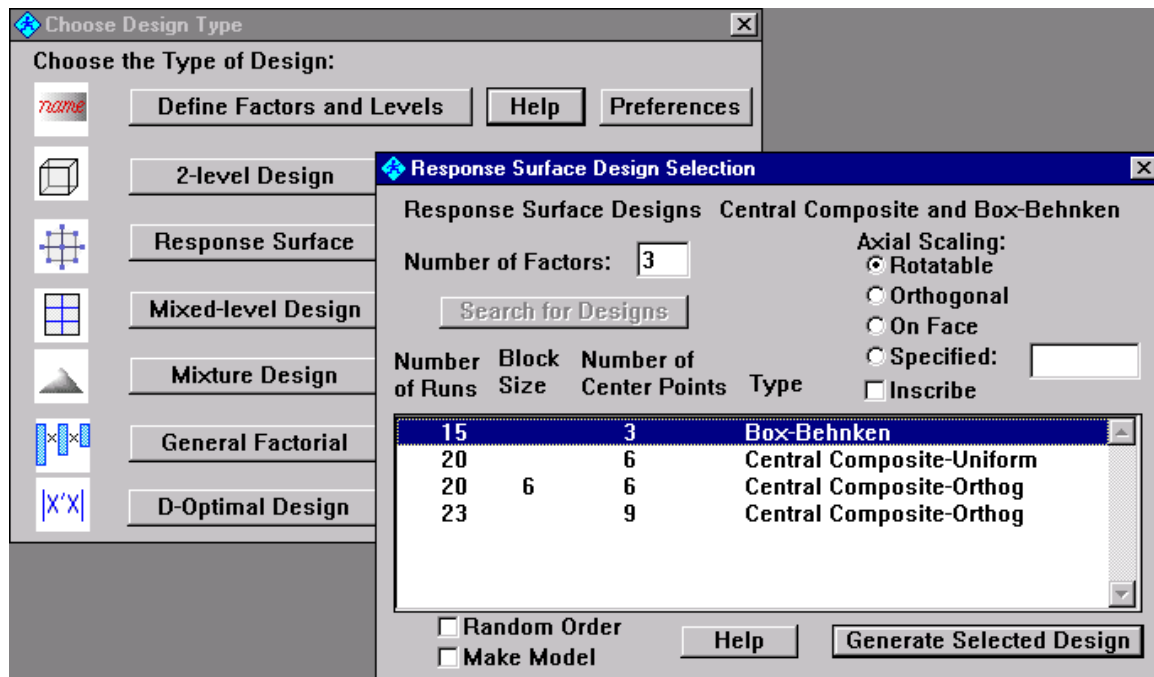


Figure 1: Tables:Design Experiment yields a dialog to choose from design types and by choosing **Response Surface** we can create a minimum-run 3 factor Box-Behnken design.

BBDDesign1

6 Cols ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐

13 Rows

	Pattern	Block	Power	Time	Force	Y
1	--0	1	80	20	90	?
2	+-0	1	80	30	90	?
3	+0-	1	130	20	90	?
4	++0	1	130	30	90	?
5	0--	1	105	20	80	?
6	0+-	1	105	20	100	?
7	0+-	1	105	30	80	?
8	0++	1	105	30	100	?
9	-0-	1	80	25	80	?
10	+0-	1	130	25	80	?
11	-0+	1	80	25	100	?
12	+0+	1	130	25	100	?
13	000	1	105	25	90	?

0 \ 0 Selected

Figure 2: The "kernel" of our design. The last 2 rows of repeated centerpoints have been deleted.

Substrate(all)													
69 Cols													
26 Rows	Experiment	Pattern	Block	Power	Time	Force	Substrate	meanY	stdY	Y1	Y2	Y3	
1	1	--0	1	80	20	90	A	17.922	1.965	15.7	18.05	15.2	
2	2	++0	1	80	30	90	A	17.119	1.801	17.75	16.05	16.9	
3	3	+00	1	130	20	90	A	17.386	2.103	18.9	16.5	14.55	
4	4	++0	1	130	30	90	A	17.284	2.314	15.3	16.25	15.3	
5	5	0--	1	105	20	80	A	17.570	1.983	16.5	16.35	15.25	
6	6	0+-	1	105	20	100	A	17.570	1.983	16.5	16.35	15.25	
7	7	0+-	1	105	30	80	A	17.287	2.104	17.2	15.6	17.9	
8	8	0++	1	105	30	100	A	17.237	2.103	15.55	17.5	16.2	
9	9	-0-	1	80	25	80	A	17.811	2.117	15.1	16.95	17.9	
10	10	+0-	1	130	25	80	A	17.248	2.367	18.7	18.25	18.1	
11	11	-0+	1	80	25	100	A	17.754	2.185	16.8	16.6	15.2	
12	12	+0+	1	130	25	100	A	17.346	2.438	17.1	14.25	16.8	
13	13	000	1	105	25	90	A	17.425	2.317	16.25	14.5	14.5	
14	14	--0	1	80	20	90	B	16.414	3.599	19.05	19.65	19	
15	15	++0	1	80	30	90	B	14.209	4.080	6.3	12.5	14.2	
16	16	+00	1	130	20	90	B	16.509	3.026	18.5	18.05	18.3	
17	17	++0	1	130	30	90	B	14.568	3.215	9.85	9.15	11.75	
18	18	0--	1	105	20	80	B	16.412	2.391	9.25	10.7	14.25	
19	19	0+-	1	105	20	100	B	16.209	3.147	17.3	18.4	19.05	
20	20	0+-	1	105	30	80	B	15.488	3.249	13	15.65	13	

Figure 3: The first 20 rows of our designed experiment with data recorded from both substrates. (Y4 through Y60 not shown).

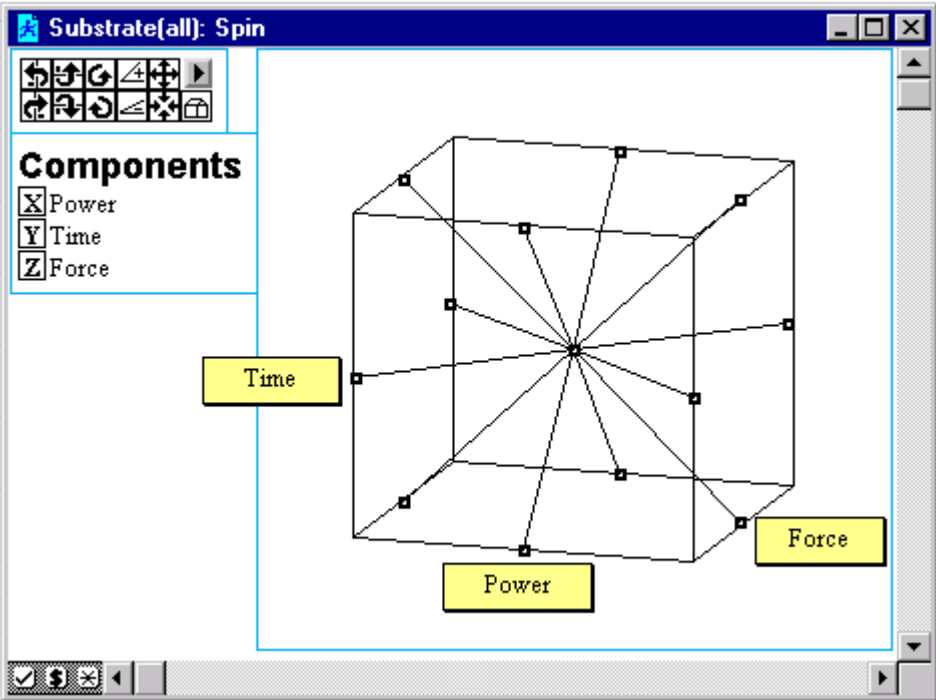


Figure 4: Picturing a Box-Behnken Design. A Box-Behnken design "covers" the space by taking measurements at the centerpoint and the midpoints of each factor.

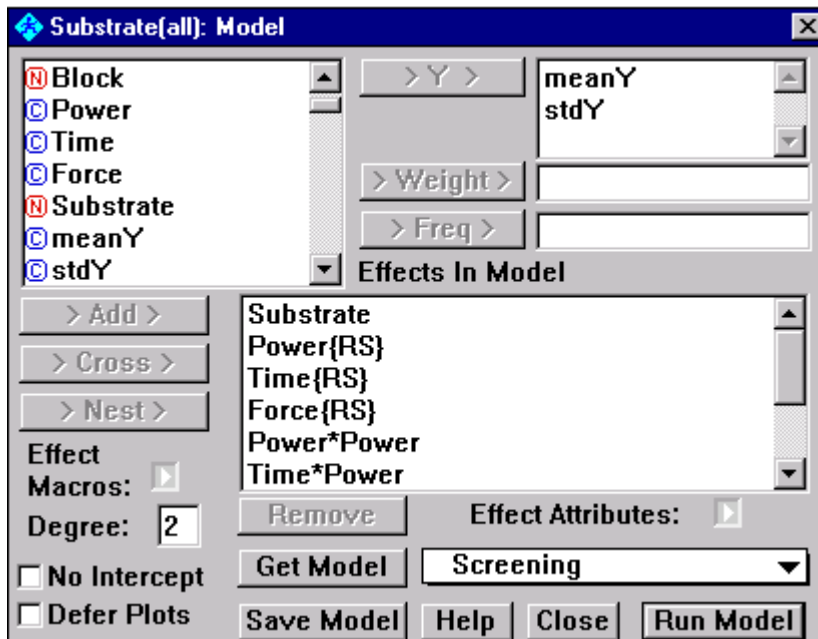


Figure 5: Specify the analysis with the Fit Model dialog. Choose meanY and stdY as responses, Screening as the model type, Substrate as an effect with the >Add> button, and the remaining effects as a Response Surface in Power, Time, and Force using the Effect Macros selection.

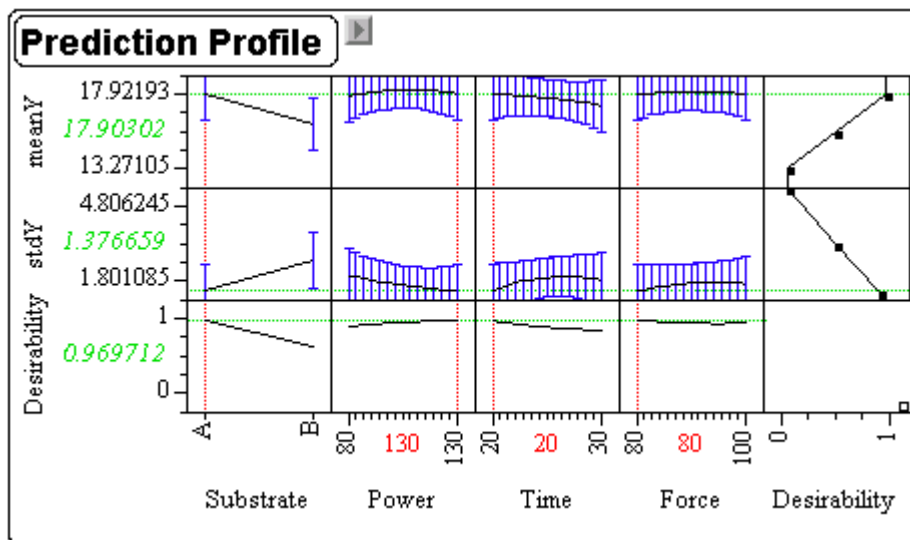


Figure 6a: Prediction Profiler showing that substrate is the dominant effect with substrate A giving smaller variance and greater means (Compare with Figure 6b) .

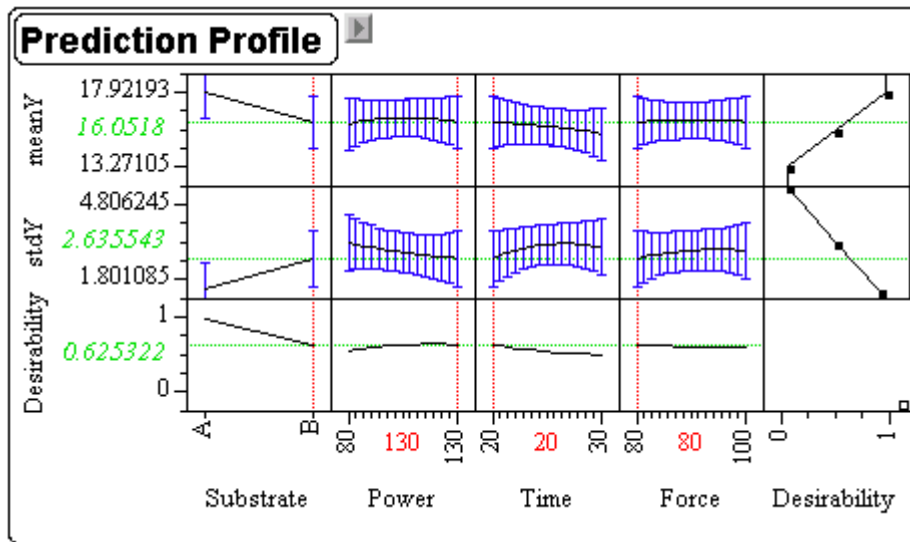


Figure 6b: Prediction Profiler showing that substrate is the dominant effect with substrate B giving larger variance and smaller means (Compare with Figure 6a) .

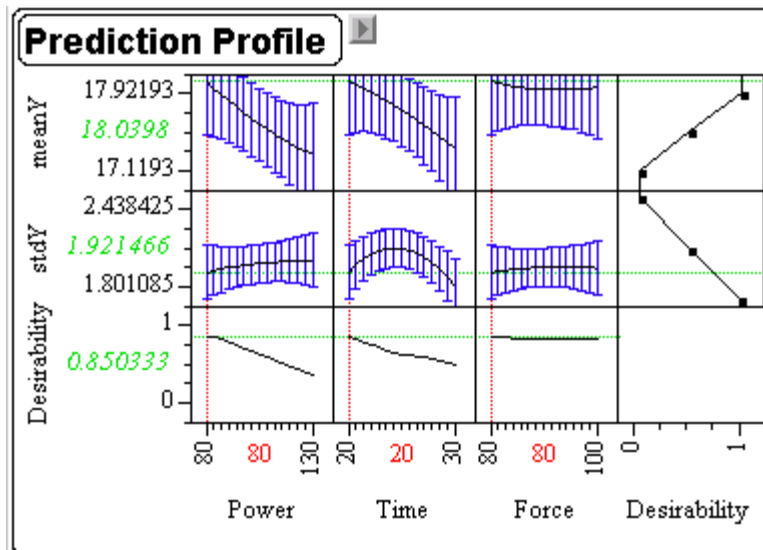


Figure 7a: Prediction profiler for substrate A only for a 13 run Box-Behnken. Note that the profile shapes have changed now that there are no substrate B data, and that Power and Time are the important effects.

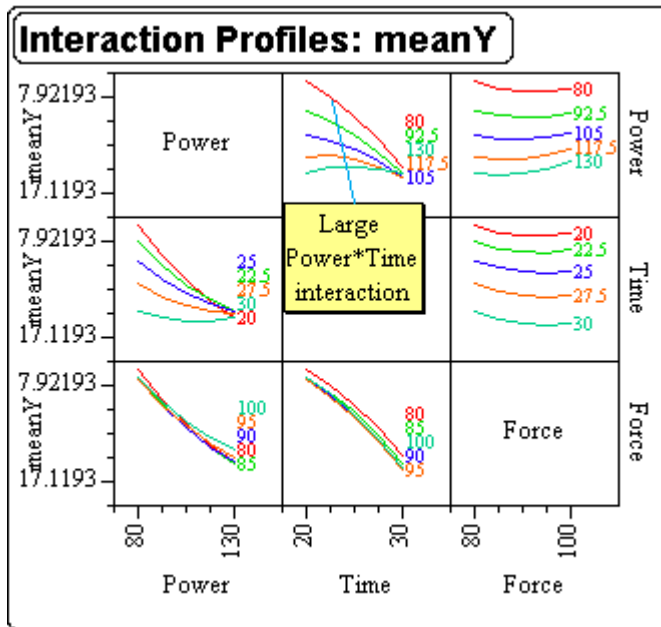


Figure 7b: Also important is the Power*Time interaction.

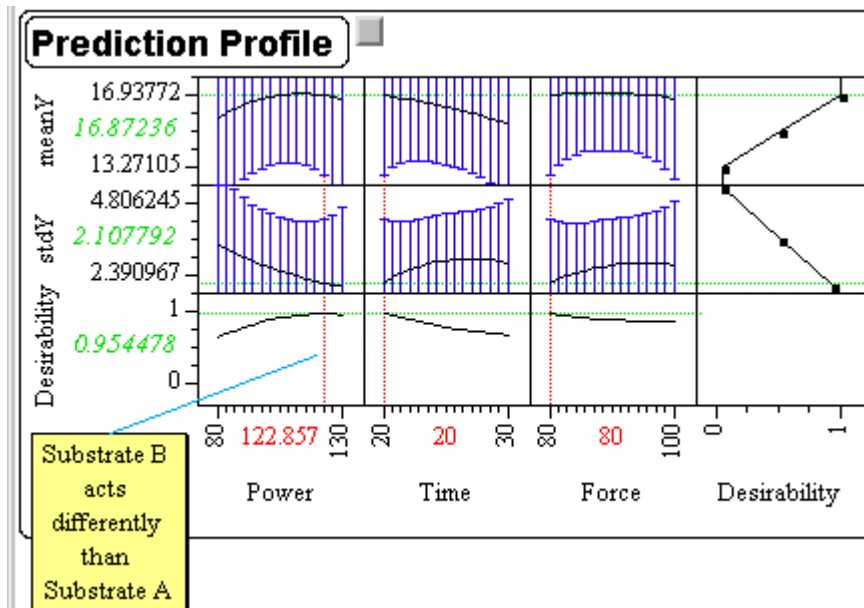


Figure 8: Prediction profiler for substrate B only for a 13 run Box-Behnken. Note that the profile shapes have changed now that there are no substrate A data, and that the prediction error is large.

Substrate1(Augmented)											
10 Cols											
26 Rows	Pattern	Experiment	Batch#	Block	Power	Time	Force	Substrate	meanY	stdY	
1	--0	1	1	1	80	20	90	A	17.92193	1.965279	
2	-+0	2	1	1	80	30	90	A	17.1193	1.801085	
3	+0	3	1	1	130	20	90	A	17.38596	2.10282	
4	++0	4	1	1	130	30	90	A	17.28421	2.314283	
5	0--	5	1	1	105	20	80	A	17.57018	1.98287	
6	0+-	6	1	1	105	20	100	A	17.57018	1.98287	
7	0+-	7	1	1	105	30	80	A	17.28684	2.10411	
8	0++	8	1	1	105	30	100	A	17.23684	2.102943	
9	-0-	9	1	1	80	25	80	A	17.8114	2.117276	
10	+0-	10	1	1	130	25	80	A	17.24825	2.366903	
11	-0+	11	1	1	80	25	100	A	17.75351	2.18495	
12	+0+	12	1	1	130	25	100	A	17.34561	2.438425	
13	000	13	1	1	105	25	90	A	17.42544	2.317078	
14	--0	14	2	1	80	20	90	A	17.79509	2.068174	
15	-+0	15	2	1	80	30	90	A	17.01676	2.058357	
16	+0	16	2	1	130	20	90	A	17.47089	2.141696	
17	++0	17	2	1	130	30	90	A	17.43769	2.73103	
18	0--	18	2	1	105	20	80	A	17.64424	1.997666	
19	0+-	19	2	1	105	20	100	A	17.30015	2.274227	
20	0+-	20	2	1	105	30	80	A	17.54447	2.074733	

Figure 9: Augmented design. Original 13 run design augmented by results from a 2nd Integrated Circuit with both being based on substrate A (first 20 observations).

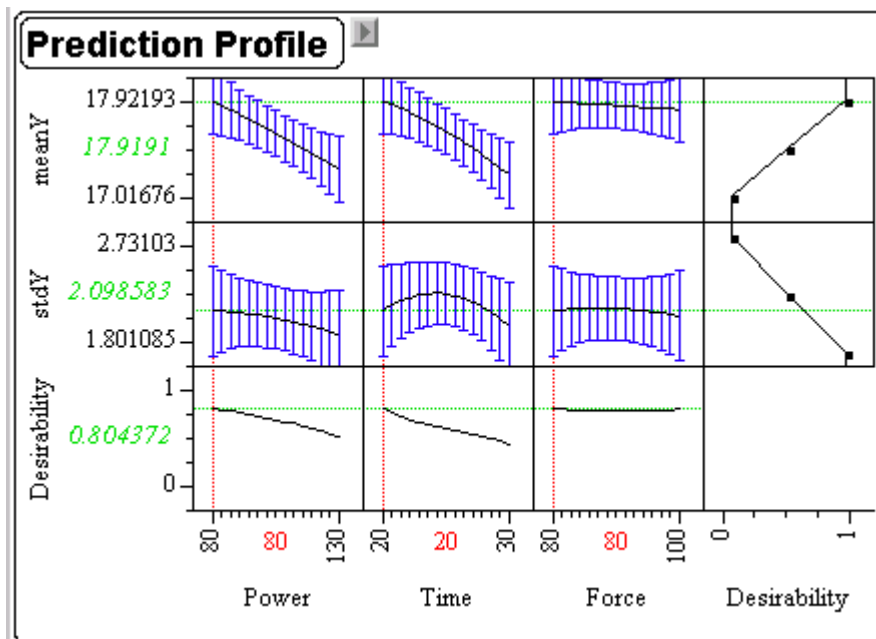


Figure 10a: Settings for augmented design confirmed but much larger prediction errors for stdY exist.

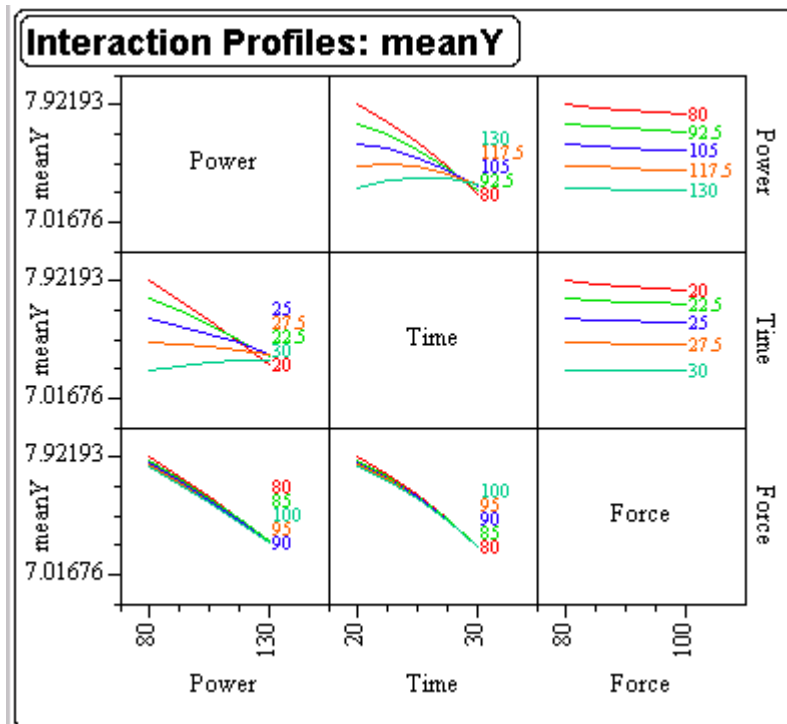


Figure 10b: Large Power*Time interaction confirmed with augmented data.

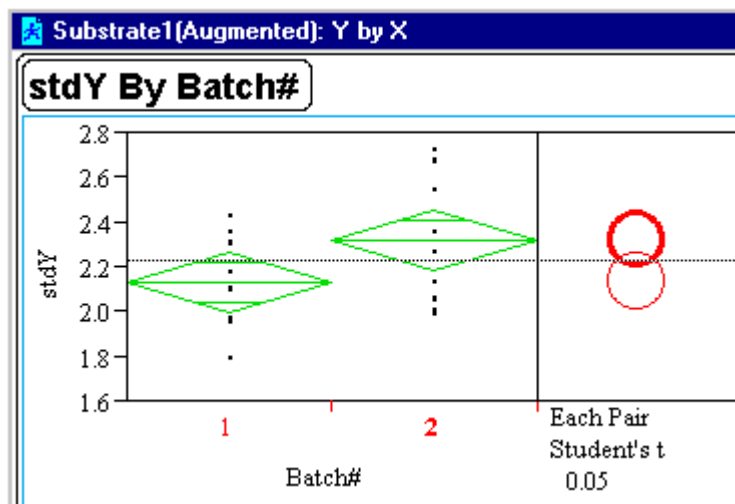


Figure 11: The second integrated circuit in the augmented design had much more variability in breakage force within the 60 leads.

t-Test				
	Difference	t-Test	DF	Prob> t
Estimate	-0.18683	-1.993	24	0.0577
Std Error	0.093741			
Lower 95%	-0.3803			
Upper 95%	0.006639			
Assuming equal variances				

Figure 12: t-test showing that the difference has a p-value of .0577, "marginally insignificant".