Experiments to Control the Specific Gravity of a Resin

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Abstract

This report summarizes two experiments conducted to control the specific gravity of a resin. The first one was a volumetric cylinder system and the second on a chemical pump system. Information from the first was utilized in the second. In each experiment it was found that interactions were important in controlling the variability.

1. Background and the Problem

This study was concerned with a Reaction Injection Moulding (RIM) process which used a plastic resin to mould front and rear bumper fascias for many car lines. The plant had two types of recirculation systems- a volumetric cylinder system and a chemical pump system. This study deals with the chemical feed system which supplies the moulding machine (or clamp) with the resin. The density of the resin is critical to the quality of a part formed by the reaction.

The prime reasons for implementing this study were to:

1. Reduce the amount of scrap resin
2. Reduce the RIM process variability
3. Increase the understanding of the recirculation system

Manufacturing Process

The resin is supplied to fourteen different machines (clamps) by eight different recirculation systems (see Appendix Figure A1) which control the density of the resin. These systems, used as day tanks, are then fed from the tank farm where the resin is stored in bulk. These systems pump the resin around a loop that can be hooked up to a number of different moulding machines. Each loop serves two or three moulding machines at a time.

Volumetric cylinder recirculation systems are labelled as A1-A5 and the chemical pump systems are referred to as B1, B2 and B3. Since we had to deal with two types of systems the project was divided into two parts. A1 was chosen to be studied first and then B1.

The actual process studied in these experiments was called the 'nucleation process', which occurred in each recirculation system and was used to decrease the density of the resin that flowed through the system. It consisted of nitrogen gas being injected into the resin through a porous stone, which was placed in the clamp loop return line (See Figure 1). It was activated by the control system that consisted of a density gauge and a controller, which interpreted the signal from the gauge and responded by turning the nitrogen supply either on or off, depending on the set point of the controller. Adjusting the set point could be used to shift the process mean.

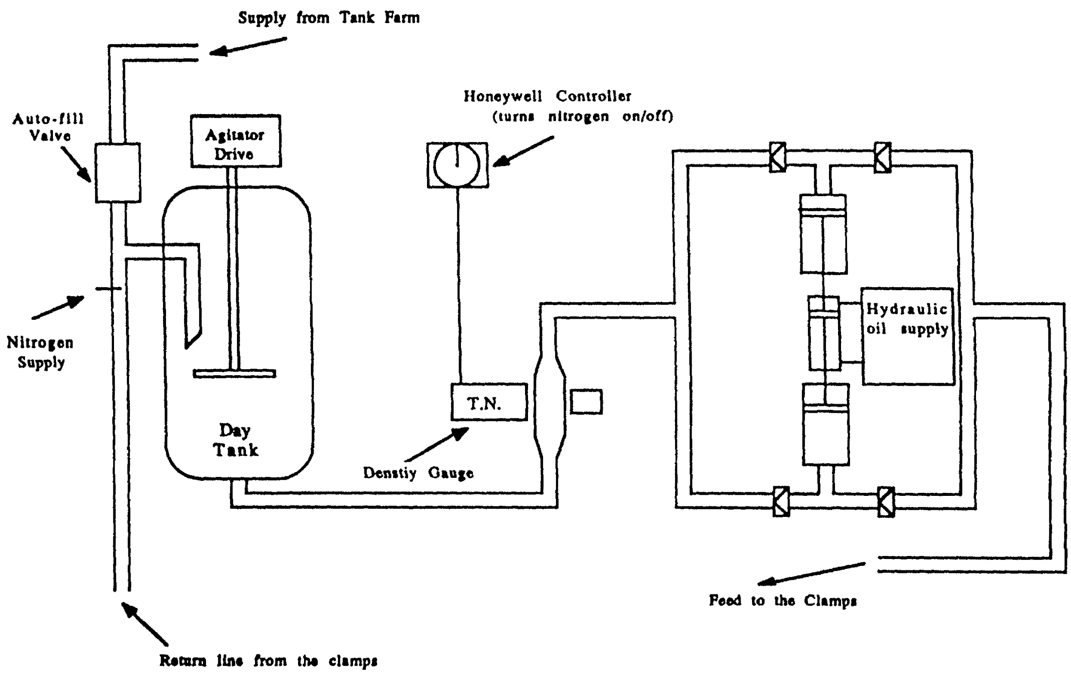

Figure 1: Volumetric Cylinder System

2. Planning

With the knowledge of the process, an experiment must be planned to pinpoint the elements of the nucleation process that caused the increased incidence of resin scrap. The team members including engineers, line personnel and a consultant participated in a brainstorming session to identify the possible causes and then developed a cause-and-effect diagram (Figure A2), which was instrumental in focusing the experiment on the possible causes (factors).

After two subsequent meetings the team decided on six factors. It was felt that some factors could be set at 3 levels, however this was discouraged for the first experiment to keep it less complicated. Thus the initial study involved 6 factors each at two levels (see Table 1) which were very carefully chosen by the team after consultation with the operating personnel.

Table 1: Factors and their Levels

		Levels	
Factor	**Description**	**Low**	**High**
Resin Temperature (T)	This factor was chosen since temperature affects the viscosity of the resin. Some problems were noted in the past in controlling the temperature due to sudden climatic changes.	115 °F	130 °F
Air Pressure (N)	This is the pressure at which air is injected in the resin.	45 psi	65 psi
Agitator Speed (A)	This is the number of revolutions the agitator makes and it can be set with a great deal of accuracy. Experience has shown some relationship to over oxygenating the process through a process similar to cavitation on a propeller.	100 rpm	150 rpm
Tank Pressure (D)	The day tank has a blanket of nitrogen gas on top of the resin in the tank. This was a decidedly difficult factor to change during the experiment. Adjusting this pressure required a re-calibration process which resulted in shutting the process down for 20 minutes. Plant management did not wish to shut the process down during regular production not only due to the downtime but also the increased scrap that was produced in starting up the process.	10 psi	20 psi
Resin Flow (F)	This is the rate at which the resin is re-circulated around the clamp loop. This was chosen because the resin might pass the porous stone more often with a higher flow resulting in increased oxygenation.	5 GPM	8 GPM
Resin Pressure (P)	The pressure at which the resin circulates in the clamp loop. This factor was chosen because of the high degree of pressure dependency of the process.	100 psi	125 psi

Specific gravity of the resin at ambient pressure was the only response variable considered in the experiments. This was chosen for the ease in measurement, its adjustability through the control system and its known relationship to scrap production.

3. Experiment One

The first experiment was to be performed on the volumetric cylinder system A1. Since six factors were to be considered each at two levels and some two-factor interactions might be important the team decided to use a sixteen run experiment, which was to be blocked over four weeks with four runs per week. This allowed for one spare day a week in case of production problems. The design is shown in Table 2 and it has resolution IV (see Box, et.al (1978)). There was confounding of two-factor interactions with other two-factor interactions. This was not a big concern since it was an initial experiment. There was commitment to conduct confirmation runs or another experiment if necessary. The confounding pattern (Given in Appendix Table A1) was discussed by the consulting team to ensure that likely interactions were not confounded. In addition two columns in Table 2 (B1= 123 and B2= 134) were used to define the four blocks. Thus, this design allowed the examination of the main effects of the six factors (unconfounded with two-factor interactions) as well as seven two-factor interactions (which are confounded with other two-factor interactions). This experiment was one of the first for the engineers involved. Consequently, it was important to ensure some degree of success. Trial runs were recommended by the consultant and the engineers took few challenging combinations and performed trial runs to ensure the whole process of running the experiment would work well. (See Abraham et.al (1990-91) and Young and MacKay (1988)).

To perform the experiment the runs were rearranged into four blocks (weeks) as shown in the Appendix (Table A2). The 'blocks' were randomly assigned to the weeks and the runs within a week were randomly assigned to the days. Thus for instance the run labeled as '1' in Table A2 was taken on day one in week three.

The experimental runs were preformed with little difficulty. Three samples were taken four times a day for each experimental run. Data were reviewed on a daily basis to see if there were any problems with the data. For any data that appeared to be suspicious a search for the cause was made and it was often an obvious condition such as tank fills during the collection of the sample. Table 2 gives the contrast table for this experiment which shows all sixteen runs and 15 effects. It also gives the average and the standard deviation for each run (These values were coded to avoid confidentiality concerns). As indicated before, the confounding patterns of the design are given in Table A1.

Table 2: Design Table and Data for Experiment 1

	1	**2**	**12**	**3**	**13**	**23**	**123**	**4**	**14**	**24**	**124**	**34**	**134**	**234**	**1234**		
Run	**F**	**P**	**FP**	**N**	**FN**	**PN**	**B1**	**D**	**FD**	**PD**	**A**	**ND**	**B2**	**T**	**NT**	Avg.	Std.
1	-1	-1	1	-1	1	1	-1	-1	1	1	-1	1	-1	-1	1	**14.99**	**0.26**
2	1	-1	-1	-1	-1	1	1	-1	-1	1	1	1	1	-1	-1	**15.02**	**0.11**
3	-1	1	-1	-1	1	-1	1	-1	1	-1	1	1	-1	1	-1	**15.01**	**0.05**
4	1	1	1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	**14.69**	**0.64**
5	-1	-1	1	1	-1	-1	1	-1	1	1	-1	-1	1	1	-1	**14.84**	**0.31**
6	1	-1	-1	1	1	-1	-1	-1	-1	1	1	-1	-1	1	1	**15.02**	**0.08**
7	-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1	**14.97**	**0.05**
8	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	-1	**15.21**	**0.65**
9	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1	1	-1	**14.93**	**0.32**
10	1	-1	-1	-1	-1	1	1	1	1	-1	-1	-1	-1	1	1	**15.03**	**0.09**
11	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1	**14.99**	**0.17**
12	1	1	1	-1	-1	-1	-1	1	1	1	1	-1	-1	-1	-1	**14.96**	**0.12**
13	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	**14.97**	**0.24**
14	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	**14.99**	**0.10**
15	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	**15.02**	**0.18**
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	**14.95**	**0.17**

T: Resin Temperature, N: Air Pressure, A: Agitator Speed
D: Tank Pressure, F: Resin Flow, P: Resin Pressure

Analysis

The probability plot of the effects for the averages (See Appendix Figure A4) is almost linear indicating that none of the factors chosen has an effect on the process mean. This confirmed the engineers' knowledge that the set point of the controller did in fact control the process mean.

The probability plot for the effects of log s (see Figure A4) shows that there were two large two factor interactions, Resin Flow vs. Resin Pressure (FP) and Resin Flow vs. Tank Pressure (FD). Main effect of Agitator speed (A) was also large. To obtain an estimate of the variability the sum of squares for the smaller effects were pooled. Sum of squares corresponding to the larger effects are shown in Table 3 together with the sum of Squares of Error. Since the apparent significant interactions FP and FD involve P, D and F, their main effects were not included in the sum of squares of Error. The Anova table indicates that FP, FD and A are significant (see Table 3).

The FP interaction explained about 57% of the variability, FD about 19% and Agitator speed (A) about 21% (see Table 3). 97% of the variablility captured in the experiment was explained by these factors F, P and A. It is important to note that the variability explained by the experiment applied only to the time frame of the experiment. In a long term production situation, other sources of variability would inevitably enter into the process.

Plots of the significant interactions and the main effect were then examined to determine the best choice for the level of each factor. Since the process average was not affected, log s was examined for the choices which would minimize process variability. Using the plots in Figure 2 the 'Optimum' settings of the factors were chosen and are shown in Table 4. Note that levels of the insignificant factors N, and T were chosen based on convenience and cost.

Table 3: ANOVA Table for Log-s, Experiment 1

Source	Df	S-Squares	M-Square	F-Stat	%-Var
F	1	0.0082	0.0082	0.3594	
P	1	0.0104	0.0104	0.4613	
D	1	0.0220	0.0220	0.9693	
DF	1	1.6836	1.6836	74.2428	19.157
PF	1	5.0027	5.0027	220.6118	56.924
A	1	1.8574	1.8574	81.9067	21.134
Error	**9**	**0.2041**	**0.02267**		
Total	**15**	**8.7884**			

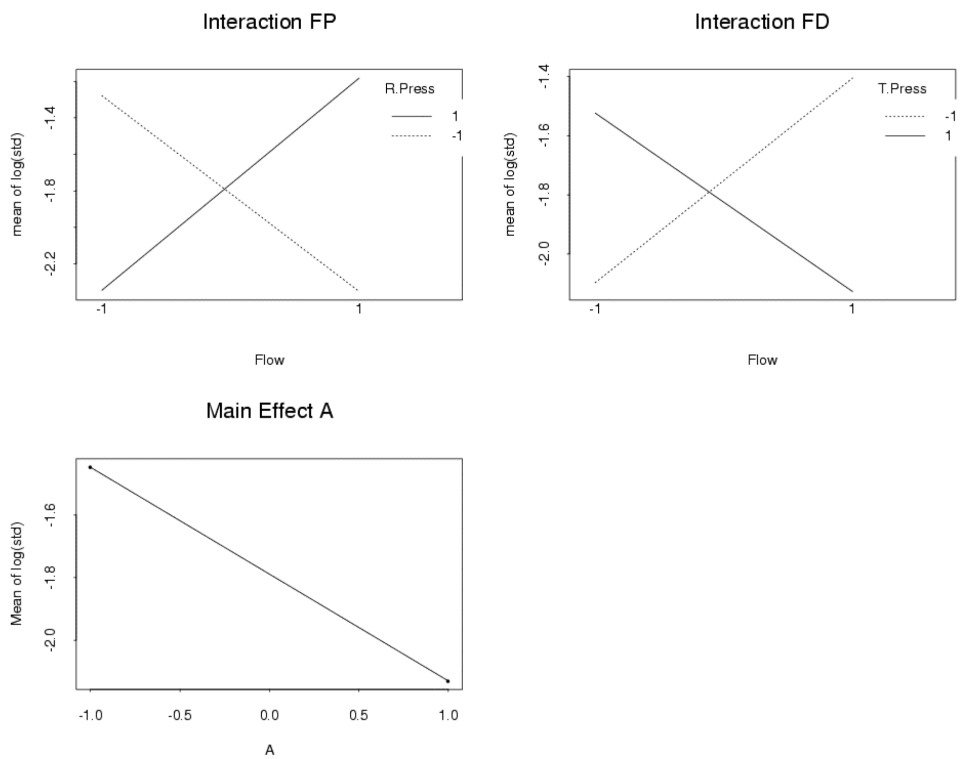

Figure 2: Log-s Factor Plots for Experiment 1

Table 4: Optimum Settings of the Six Factors

Factor Name	Level	Setting
Resin Flow (F)	High	17 GPM
Resin Pressure (P)	Low	100 psi
Tank Pressure (D)	High	20 psi
Air Pressure (N)	High	65 psi
Agitator Speed (A)	High	150 rpm
Resin Temperature (T)	Low	115 °F

4. Experiment Two

A second experiment was considered for the chemical pump systems (See Figure A3). The factors Resin flow and Resin pressure were interdependent and, for this experiment, they were combined into one single factor. In experiment one, it was discovered that Air pressure and Resin temperature had little effect on resin specific gravity and they also were not in any interactions with other variables, thus they were not included in experiment two. Therefore only three factors were studied in this experiment: Resin pump flow (F), Agitator speed (A) and Tank pressure (D). The Agitator speed was included because of a different agitator blade and daytank design. Tank pressure was included because of the significant interactions found in the previous experiment. The chosen levels of the three factors for this experiment are shown in Table 5.

Table 5: Factors and their Levels for Experiment 2

	Level	
Factor	**Low**	**High**
Resin Pump Flow (F)	5 GPM	8 GPM
Agitator Speed (A)	100 rpm	150 rpm
Tank Pressure (D)	10 psi	20 psi

This was a full factorial experiment with eight runs which were performed in two one week blocks with four runs per week. Table 6 gives the contrast table for this experiment. The blocks were defined by the FAD contrast. This means that runs, 1, 4, 6,7 were done in the first week and the others were done in the second week. The average and the standard deviation for each run are also shown in Table 6 (as before these numbers are coded to avoid confidentiality concerns).

Table 6: Contrast Table and Summary Statistics for Experiment 2

	1	**2**	**3**	**4**	**5**	**6**	**7**		
Run	**F**	**A**	**FA**	**D**	**FD**	**AD**	**FAD**	**Average**	**S.D.**
1	-1	-1	1	-1	1	1	-1	14.67	0.058
2	1	-1	-1	-1	-1	1	1	14.71	0.024
3	-1	1	-1	-1	1	-1	1	14.71	0.114
4	1	1	1	-1	-1	-1	-1	14.70	0.066
5	-1	-1	1	1	-1	-1	1	14.70	0.078
6	1	-1	-1	1	1	-1	-1	14.71	0.118
7	-1	1	-1	1	-1	1	-1	14.69	0.029
8	1	1	1	1	1	1	1	14.68	0.062

Analysis

The data from this experiment were analyzed in a manner similar to those from the first experiment. Once again, the probability plot of the effects of the average was almost linear. However, the probability plot for the effects of log s showed (See Figure A5) that there were two large two-factor interactions, FD (Resin Flow vs Tank Pressure) and AD (Agitator Speed vs. Tank Pressure). Table 7 shows the ANOVA table. The sum of squares for the smaller effects which are not shown individually were pooled to obtain an estimate of the error variability. The ANOVA table shows that FD and AD are significant. The FD interaction explained 36% of the variability and AD accounted for

59% of the variability (see Table 7). Thus about 95% of the variability captured in the experiment was explain by these two interactions.

Table 7: ANOVA Table for Log-s Experiment 2

Source	Df	S-Squares	M-Square	F-Stat	%-Var
FD	1	0.83942	0.83942	42.49799	36.35
AD	1	1.37115	1.37115	69.41829	59.37
Error	5	**0.09876**	**0.01975**		
Total	7	**2.30933**			

Plots of the two significant interactions (see Figure 3) were used to choose the optimum settings for each of the three factors which would minimize variability.

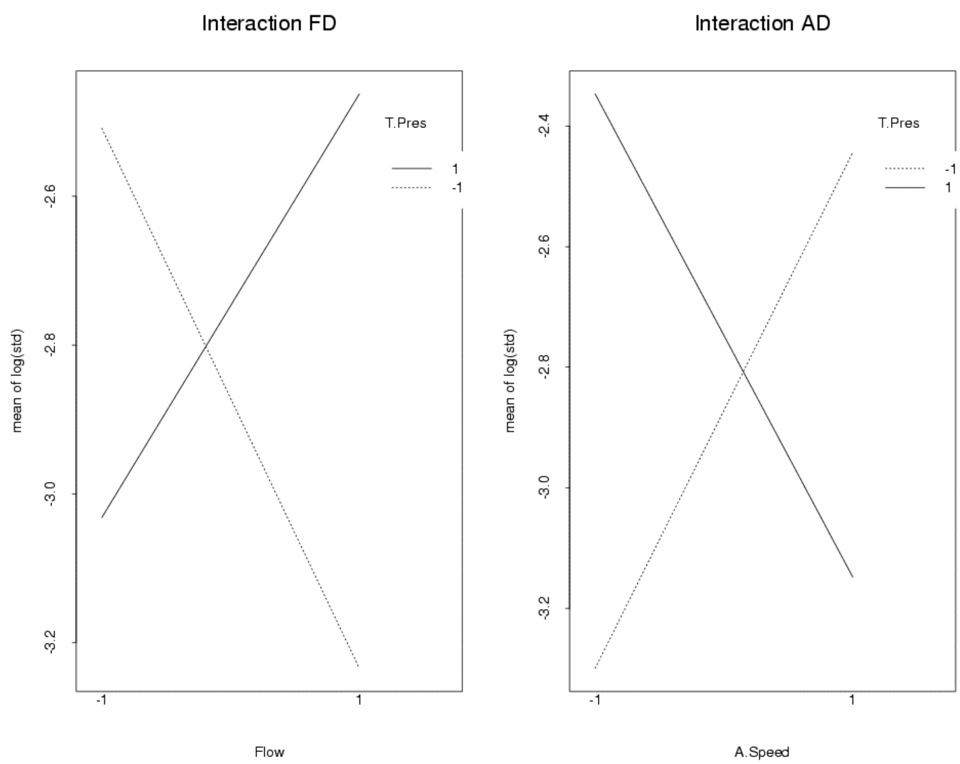

Figure 3: Log-s Factor Plots for Experiment 2

Table 8: Optimum Settings of the Three Factors

Factor	Level	Setting
Resin Flow (F)	High	8 GPM
Tank Pressure (D)	Low	10 psi
Agitator Speed (A)	Low	100 rpm

5. Confirmation and Discussion

Some confirmation runs were taken at the new settings. On the volumetric cylinder recirculation system A1 involved in the first experiment, the process variability was reduced by 300%. On the chemical pump recirculation system B1, the process variability was reduced by 20%. This difference was explained by the fact that B1 was already running with the specified limits and only modest improvements were possible. A1 was running so poorly that it was possible to make a large improvement.

Discussion

It was very interesting that in both experiments two factor interactions were discovered to be significant while main effects were of little or no importance. Traditional one-factor-at-a-time experiments would have not yielded this information. It is also interesting that one of the two factor interactions was comprised of factors that would appear to be related – Resin Flow and Resin Pressure.

Also of note is the two ways in which the experiments were concluded. An experimenter without process knowledge may have attempted one experiment utilizing the type of recirculation system as a factor with two levels, A1 and B1. However, the two types of recirculation systems were really two different processes. This was evident by examining the process schematic. Combining the experiments, although might have been more efficient, would have led to confusing results. Moreover, information that was learned in the first experiment was applied to the second. The value of sequential experimentation is often overlooked. Many times teams try to "do it all" in one experiment only to end up with disappointing results.

Another interesting item in this experiment was the fact that it led to the confirmation that the process was stable if the controller was left alone. The controller is a good example of what Taguchi would call an "adjustment factor". Factors which would lead to minimizing variability were discovered. This clearly demonstrated the advantage of analyzing mean and standard deviation separately.

References:

Abraham, B., Young, J.C., and Whitney, J.B. (1990-91). Design Implementation in a Foundary: A case study. *Quality Engineering* 3(2), 167-180.

Box, G.E.P, Hunter, W.Q., and Hunter, J.S. (1978). *Statistics for Experimenters. An introduction to design, data analysis and model building*. Wiley, New York.

Young, J.C. and Mackay, R.J. (1988). The Design of Experiments Principles and Applications. *IIQP Notes, University of Waterloo*.

Appendix:

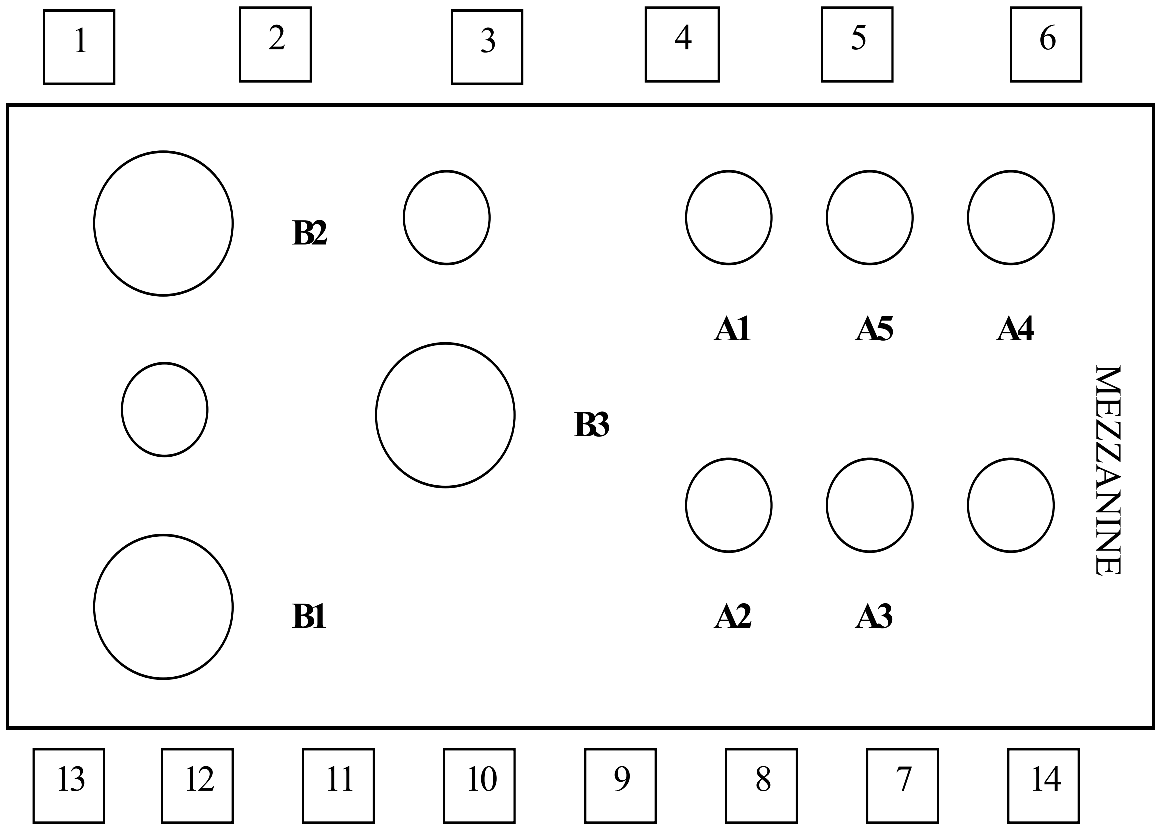

Figure A1: Layout of the Recirculation Systems and Clamps

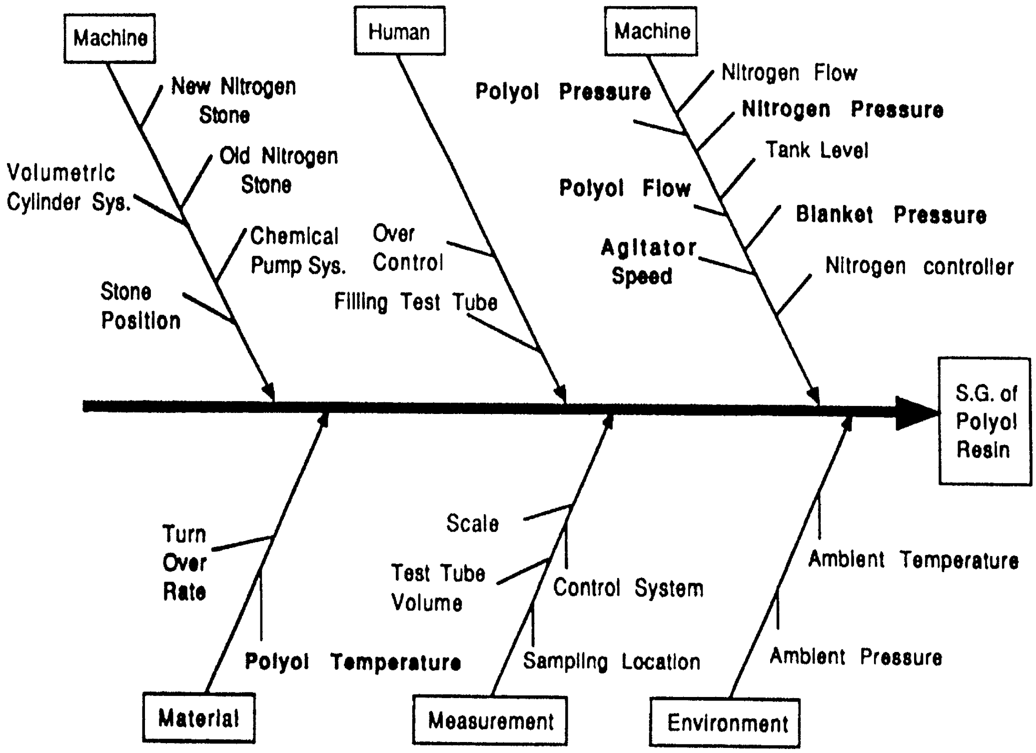

Figure A2: Cause-and Effect Diagram

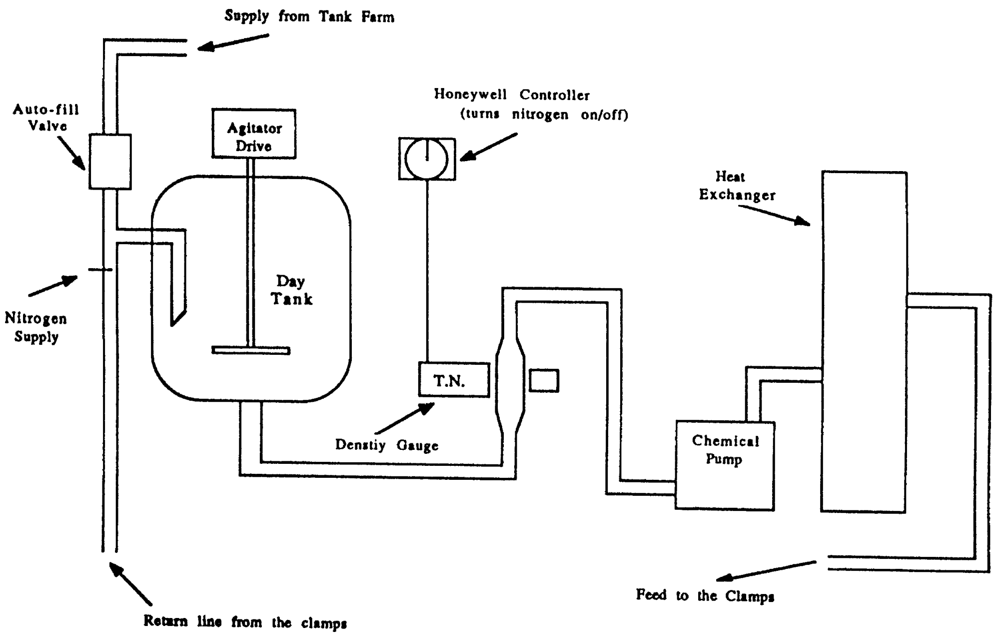

Figure A3: Chemical Pump System

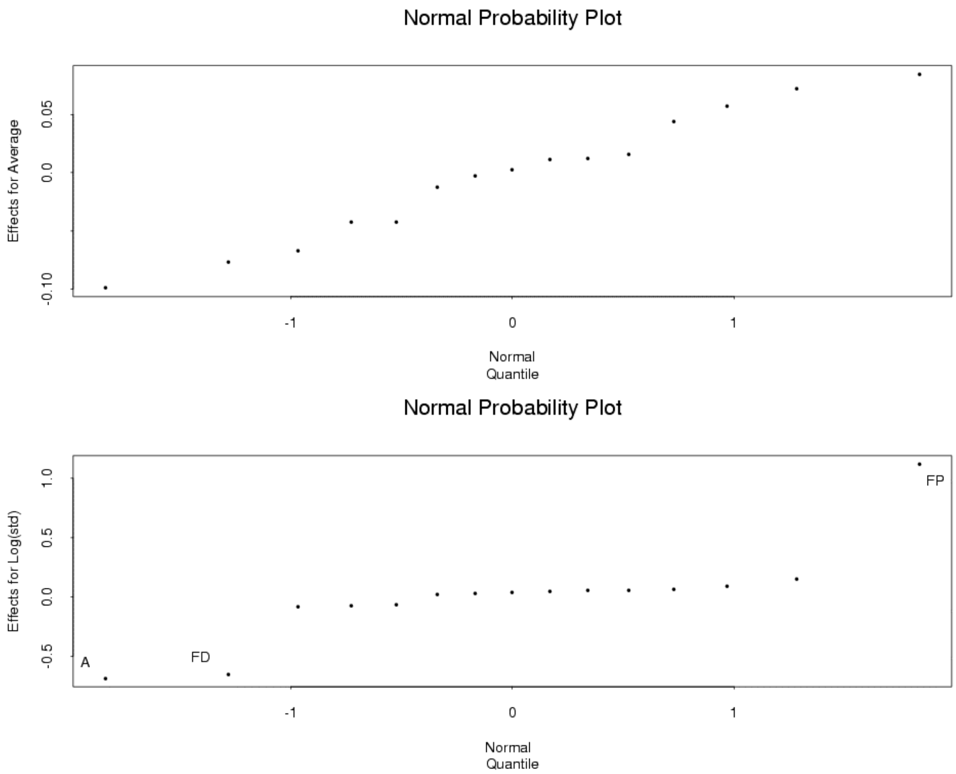

Figure A4: Probability Plots for Experiment 1

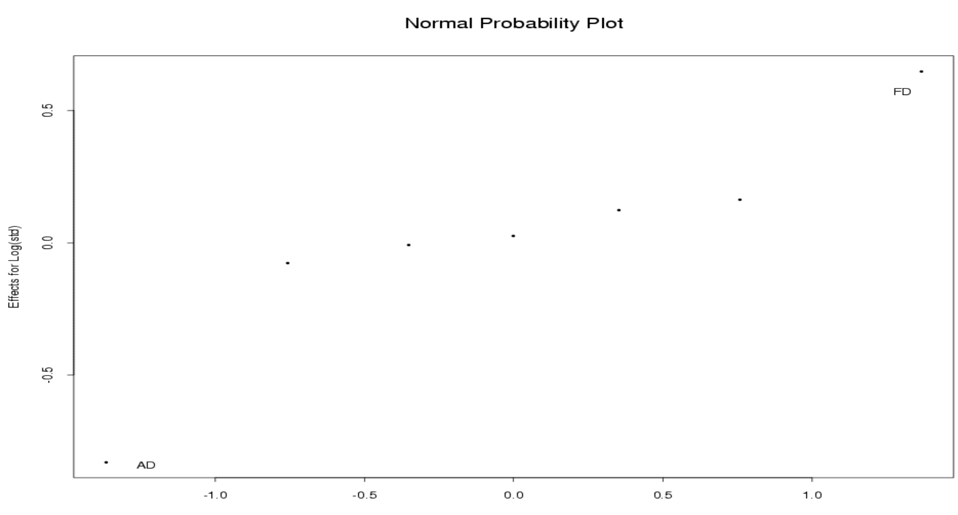

Figure A5: Probability Plot for Experiment 2

Table A1: Confounding Pattern for Design 1

1 (F)		
2 (P)		
12 (FP)		
3 (N)		
13 (FN)	25 (PA)	
23 (PN)	15 (FA)	
8=123 (B1)		
4 (D)		
14 (FD)		26 (PT)
24 (PD)		16 (FT)
5=124 (A)		
34 (ND)		56 (AT)
7=134(B2)		
6=234 (T)		
1234	45 (DA)	36 (NT)

(Note: Two factor interactions involving block variables B1 and B2 are not shown.)

Table A2: Experimental Plan: Running Order

Serial No.	Week	Day	Block B1 B2	Runs	Factors Level					
					F	P	N	D	A	T
1		1	+1 +1	5	-1	-1	+1	-1	-1	+1
2		2	+1 +1	2	+1	-1	-1	-1	+1	-1
3	1	3	+1 +1	16	+1	+1	+1	+1	+1	+1
4		4	+1 +1	11	-1	+1	-1	+1	-1	-1
5		1	-1 +1	9	-1	+1	+1	-1	+1	-1
6		2	-1 +1	14	+1	-1	-1	-1	-1	+1
7	2	3	-1 +1	7	-1	+1	-1	+1	+1	+1
8		4	-1 +1	4	+1	-1	+1	+1	-1	-1
9		1	-1 -1	1	-1	-1	-1	-1	-1	-1
10		2	-1 -1	6	+1	-1	+1	-1	+1	+1
11	3	3	-1 -1	12	+1	+1	-1	+1	+1	-1
12		4	-1 -1	15	-1	+1	+1	+1	-1	+1
13		1	+1 -1	13	-1	+1	-1	-1	+1	+1
14		2	+1 -1	10	+1	+1	+1	-1	-1	-1
15	4	3	+1 -1	3	-1	-1	+1	+1	+1	-1
16		4	+1 -1	8	+1	-1	-1	+1	-1	+1