Design of an experiment for injection blow molding

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Abstract

This research was requested by the quality control engineer of a company manufacturing plastics products such as bottles and caps. These products are manufactured with polyethylene and polipropylene resin, using two molding processes: injection blow molding and extrusion blow molding.

We designed an experiment to find out the inconsistency in the diameter of the threads of bottle # 20914, which the customers claim does not meet the required specifications. This product is manufactured by injection blow molding.

Sinopsis

Diseño de un experimento de moldeo de inyección por soplado

Esta investigación surge como petición del ingeniero de control de calidad de una compañía que se dedica a fabricar productos de plástico, tales como botellas, tapas y reductores de orificios. Estos productos se fabrican con resina de polietileno y prolipropileno usando dos tipos de moldeo: de inyección por soplado y de extrusión por soplado.

El producto específico en el cual se basa nuestro proyecto es la botella #20914, la que presenta inconsistencia en el diámetro de su rosca y ha causado reclamaciones de los clientes de la compañía. Para fabricar este producto se usa el método de moldeo de inyección por soplado.

Introduction

The problem is to analyze the variability in the diameter of the threads of bottle # 20914. To manufacture this product the company uses the injection blow molding process and high density polyethylene resin. An experimental design allows us to study the factors and variables that affect the thread and to understand how to control the factors that affect the response. With the response of the surface method we intend to find a better manufacturing condition. By convention, whenever we refer to the response we mean the dimension of the threads. Refer to Appendix 1 for all the figures.

In injection blow molding, the hopper is used to supply the resin pellets to the volumetric feeder, which, in turn, feeds a controlled intermittent volume of pellets (fig. 1). Those pellets then advance to the rotating screw area, which is actuated by a hydraulic motor and moved to the front of the barrel (preplasticator cylinder) to get plasticity. The rotating screw is forced backward by the resin and stops when the correct amount of resin has been fed. Then the nozzle moves forward, acting as a ram and the resin, which is already turned into a hot liquid, is injected to the preformed mold through the nozzle.

Once the melted plastic is on the preformed mold, a parison is created around a core pin in the exact quantity of the required resin. The preform mold is kept at a controlled temperature. After injection, the mold opens and the core pin and the still warm preform rotate 90 degrees, depending on the machine stations. Then the blow mold is closed over the preform and air is injected through the core pin. After the piece is blown, a cold fluid is run over the walls of the blow mold to cool it down. Finally the mold is opened and the core pin returns to the preform mold to repeat the cycle.

Objective

Experimental design provides information about the nature of a process and its variations. Once the reasons for these variations are identified, the process can be improved. We will build a mathematical model to relate the response of the process with its input parameters.

Figure 2 shows the input and output parameters of an injection blow mold process. Experimental design will help us find out how the input parameters affect the response of the process. By identifying the levels of these input parameters we will be able to optimize the mean response and to minimize the variability of the response. If the scrap and reworks are reduced, then the overall cost will be reduced.

Justification

Experimental design will help us reduce the variability and the defects of threads. We will also reduce the manufacturing time and will end up with a product that fulfills the specifications required by the customers. This design will also allow us to ascertain the parameters required for the best response of the process.

Once the determinant factors of the process are identified, we will better understand how to adjust these parameters and the optimum area by using the response of surface method. The factorial experiment is the most efficient for this type of research because it allows us to work on all level combinations of the variables to be analyzed. The outcome gives us information about which factors have to be controlled with more caution to prevent high level defects and errors while manufacturing the bottle.

Methodology

The success of this kind of study requires team work of all the key people associated with the process. A list of the input parameters must be obtained and it must be decided how to measure the input and how many levels per input to use. Table 1 shows the information that we obtained with the help of the quality control and process technicians.

Table 1. Table of factor adjustments

Factors	Low level	High level
Neck temperature	60° F	100° F
Screw speed	150 rpm	200rpm
Barrel temperature	450° F	490° F
Injection pressure	5000 psi	5400 psi
Cycle time	12 sec.	14 sec.

Considering the limitations of available material, available machine time, personnel involved and the factors to be analyzed in this study, we decided to make a fractional experiment. Fractional factorial design allows us to work only a portion or fraction of the total number of runs to identify the factors that have an important effect in the process.

With the information available we designed a fractional factorial 2^{5-1} with resolution V. The number 2 means the number of levels on which the experiment was developed (low and high) and the number five represents the factors considered (A,B,C,D and E). The (-1) represents the effects not chosen but generalized in other effects.

Our experiment consists of 16 random runs. This first experiment is a screening design so that we can identify the factors that influence the process. The thread measurements were taken at the Quality Laboratory with a multigage (table 2).

Once the factors of major influence in the response were identified, a second experiment was conducted to find the optimum region. The method of steepest ascent is used to localize the optimum region. Then the optimum region is analyzed with the surface response method, to look for a treatment combination that causes a maximum or a minimum in the response. Table

3 shows the adjustments that resulted from the second experiment.

Table 2. Results from the second experiment

	Factor						Response
Treatment	Correlation	Neck temperature (°F)	Screw speed (rpm)	Barrel temperature (°F)	Injection pressure (psi)	Cycle time (sec)	Thread diameter (in)
ABCDE	1	100	200	490	5400	14	1.2494
D	2	60	150	450	5400	12	1.2503
ABE	3	100	200	450	5000	14	1.2475
BDE	4	60	200	450	5400	14	1.2495
ABC	5	100	200	190	5000	12	1.2443
BCD	6	60	200	490	5400	12	1.2483
ADE	7	100	150	450	5400	14	1.2511
ACD	8	100	150	490	5400	12	1.2478
ACE	9	100	150	490	5000	14	1.2512
ABD	10	100	200	450	5400	12	1.2495
A	11	100	150	450	5000	12	1.2439
BCE	12	60	200	490	5000	14	1.2515
C	13	60	150	490	5000	12	1.2464
E	14	60	150	450	5000	14	1.2467
CDE	15	60	150	490	5400	14	1.2509
B	16	60	200	450	5000	12	1.2465

Table 3. Factors' adjustments.

Factors	Low level	High level
Barrel temperature	440° F	450° F
Injection pressure	5300 psi	5450 psi
Cycle time	13 sec.	14 sec.

With the information in table 3, a 2^3 factorial experiment with eight runs was conducted. Repetitions were made by using the center point technique to obtain an estimate of the experimental pure error, verify the interactions, the quadratic effect and adequacy of the model.

Among other limitations in this experiment, the injection blow molding machine could not bear more than 5,450 psi. Also, it was not feasible for the company to increase the cycle time to more than 14 seconds. These limitations made it impossible for us to study the level factors found with the rapid ascent method, so they were adjusted to be close to the optimum area. For these reasons we have to verify the accuracy of the model and to determine whether it behaves lineally.

To analyze the data we chose a bottle at random by treatment. The measurements of the threads were taken at the Quality Laboratory with a multigage. Table 4 shows these measurements.

Table 4. Design matrix with respective adjustments.

Treatment	Run	Factors			Response
		Barrel temperature (°F)	Injection pressure (psi)	Cycle time (sec)	thread diameter (in)
1	1	440	5300	13	1.2523
A	2	450	5300	13	1.2512
B	3	440	5450	13	1.2522
AB	4	450	5450	13	1.2515
C	5	440	5300	14	1.2530
AC	6	450	5300	14	1.2523
BC	7	440	5450	14	1.2531
ABC	8	450	5450	14	1.2525
-	9	445	5375	13.5	1.2523
-	10	445	5375	13.5	1.2525
-	11	445	5375	13.5	1.2522
-	12	445	5375	13.5	1.2523

Procedure

All the data obtained for the study were analyzed with statistical tools. These statistical tools helped us to evaluate processes, study data and reach conclusions according to the purpose and objectives of the study.

Design matrix

The design matrix (table 5) is a matrix that represents the experimental settings. It usually contains values ranging from low (-1) to high (+1). The rows represent the runs and the columns represent the factors. This matrix allows us to estimate the response effect of the factor and interactions.

Table 5. Design matrix for our experiment

Run	A	B	C	D	E	Response
1	+	+	+	+	+	1.2494
2	-	-	-	+	-	1.2503
3	+	+	-	-	+	1.2475
4	-	+	-	+	+	1.2495
5	+	+	+	-	-	1.2443
6	-	+	+	+	-	1.2483
7	+	-	-	+	+	1.2511
8	+	-	+	+	-	1.2478
9	+	-	+	-	+	1.2512
10	+	+	-	+	-	1.2495
11	+	-	-	-	-	1.2439
12	-	+	+	-	+	1.2515
13	-	-	+	-	-	1.2464
14	-	-	-	-	+	1.2467
15	-	-	+	+	+	1.2509
16	-	+	-	-	-	1.2465

Analysis of variance (ANOVA)

The ANOVA describes a statistical tool based on F ratios that measures wether a factor contributes significantly to the variance of the response. The response is analyzed into components, which are observed in a systematic way.

A regression model that involves more than one regressor variable is called a multiple regression model (equation 1).

$$\hat{y} = b_0 + b_1 x_1 + \ldots b_i x_i \tag{1}$$

where $\hat{y}$ is the estimated response, x_i is an independent variable, b_0 defines the intercept of the plane and b_i is a regression coefficient.

When the dependent variable or response $\hat{y}$ may be related to k independent variables, the model is called a multiple lineal regression with k independent variables. The parameters b_i (i = 0, 1, ... n) represent the expected change in response $\hat{y}$ per unit change in x_i when the remaining independent variables x_i are held constant.

To check the model adequacy, hypothesis tests are necessary. A statistical hypothesis is a statement or claim about some unrealized state of nature.

H_0 the mean response at low temperature is equal to the mean response at high temperatures.

H_i the mean response at low temperature differs from the mean response at high temperature.

The F statistic is used to determine the significance of a factor at specified levels, where:

$$F_{ratio} > F_{table}\text{, accept } H_i \tag{2}$$

The P-Value can be interpreted as the probability that the predictor is significant. A predictor is significant when its P-Value is less than 5 %.

The adjusted multiple determination coefficient R^2 represents approximately the proportion of the total variability in the data explained or accounted for by the regression model. It measures how well the regression equation fits the data.

$$R^2 \text{ adjusted} = 1 - \left(\frac{n-1}{n-p}\right)(1 - R^2) \tag{3}$$

Estimated effect

The estimated effect is the influence of a factor in the response when the factor is changed from one level to another. It estimates which factors and interactions affect the process. These effects could be positive or negative.

Paretto analysis

By using the shape of a Paretto chart, the size of effects and prior knowledge, we can make a fairly good decision concerning which effects should be considered in the model.

Normal probability plots

The normal probability plots represent as an ascendent line any point that can be considered a significant effect in the response. This effect is usually a point that is far from the others.

Residuals

Discrepancies between a tentative model and the data can de detected by studying the residuals. The residuals can be plotted against the expected value of the response, the time sequence or variables of interest. The residuals should be constant, independent, random and must not show any tendencies.

Main factor plots

The main factor plots show the influence a single factor has on the response when it changes from one level to another. It is represented by a line. The steepness of the line reflects the importance of each factor.

Interaction plots

The interaction plots show the influence of two or more interacting factors in the response when they are changed from one level to another. The factors are represented by lines and, if the lines cross, then an interaction is present.

Method of steepest ascent

This method of steepest ascent is a procedure for moving sequentially along the path of steepest ascent in the direction of the maximum increase in the response.

Surface response methodology

The surface response methodology is a collection of techniques used to build an efficient design to find out wether the region contains the optimum values. It is used when replications are required to estimate the pure error.

Lack of fit test

The lack of fit test is used when we want to know whether the order of the experimental model is correct. This test suggests the adequacy of the model and explains the behavior of the process.

Contours and surface response

The contours and surface response shows wether there is any relationship between the response and two quantitave variables (x_1. x_2). It also shows the best conditions and allows us to determine the new conditions if the specifications were changed.

Results

We used statistical analysis to identify and reach conclusions on the most important factors in the injection process. Table 6 shows the results obtained based on the ANOVA. The factors of influence in the process are (D) the injection process, (E) the cycle time, (CD) the barrel temperature (C) / injection pressure (D), (CE) the barrel temperature / cycle time and (DE) the injection pressure / cycle time.

Table 6. ANOVA

Effects	$SS_{treatment}$	gl	$MS_{treatment}$	F_{ratio}	P-value
C	0.00000144	1	0.0000014	1.27	0.28970
D	0.00002209	1	0.0000221	19.42	0.00170
E	0.00002704	1	0.0000270	23.77	0.00009
CD	0.00001024	1	0.0000102	9.00	0.01500
CE	0.00000841	1	0.0000084	7.39	0.02370
DE	0.00000729	1	0.0000073	6.41	0.03220
Total error	0.00001024	9	0.0000011		
Total (corr.)	0.00008675	15			

R^2-adjusted = .803266

Using the F statistic with a significance level of $\alpha = 0.05$, one degree of freedom .for each factor and interaction and nine degrees for the regression error, we can define the following hypothesis:

H_0 Treatments do not vary the response

H_1 Treatments vary the response

$F_{ratio} > F_{(.95,\,1,\,9)}$, reject H_0

According to the results in table 7, we can confirm with at least 95% confidence that treatments D, E, CD, CE and DE are significant and vary the response. Nevertheless, table 7 does not show evidence to reject H_0 for the barrel temperature (C), so we can say with at least 95 % confidence that C does not vary the response.

Table 7. F statistic and P-Value

Effects	F_{ratio}	$F_{(.95,\,1,\,9)}$	P-Value
C	1.270	5.12	0.2897
D	19.420	5.12	0.0017
E	23.770	5.12	0.0009
CD	9.000	5.12	0.0150
CE	3.390	5.12	0.0237
DE	6.410	5.12	0.0322

With the P-Value we can test the hypothesis that these factors have a degree of confidence of [(1- P-Value) x 100] of 95 %. An effect is significative when its P-Value is less than 5 %.

H_0 The main factors and interactions are not significant

H_1 The main factors and interactions are significant

From the P-Value data in table 7 we can also confirm, with a significance level of $\alpha = 0.05$, that D, E, CD, CE and DE are significant. However, we do not have enough evidence to reject H_0 for the barrel temperature (C), but we can certify, with at least 95% accuracy, that C has no significant effect in the response. Nevertheless, when C interacts with factors D and E its effect increases. This implies that C depends on the levels of the other factors and therefore is an important factor.

The adjusted R^2 lets us establish that this lineal model accounts for 80.33 % of the variability of the threads. We can assert that the regression model details very well the relationship between the threads and the factors used in the model.

The Paretto plot shows that E, D, CD, CE and DE are the most important factors and interactions (fig. 3). On the basis of the normal probability plot of the residuals, these factors seem to follow a normal distribution and to behave lineally (fig. 4). According to the residual plot versus expected value, the residuals look constant, independent, random and show no tendencies (fig. 5).

On the basis of the main effect plots, figure 6, the following tabulation shows the effect each factor has in the response within the experimental level.

Main factors	Effects on the response
Neck temperature	Decrease
Screw speed	Decrease
Barrel temperature	Increase
Injection pressure	Increase
Cycle time	Increase

The interaction plot shows a dependence between the barrel temperature (C) and the cycle time (fig. 7). This response shows a positive effect of C when the cycle time is high. The biggest increase in the response occurs when C and D are at their highest levels.

The interaction between the barrel temperature and the injection pressure has a positive effect on the response (fig. 8). It shows that the largest increase in the threads is obtained when the barrel temperature is low and the injection pressure is high.

Figure 9 shows two lines that are not parallel. This suggests a possible interaction between the cycle time and the injection pressure and that the largest increase in the threads is obtained when these factors are at their highest levels.

Once the factors of major influence on the response were identified and having established the first order model, we analyzed them within the estimated region to certify the adequacy of the model. Table 8 shows the results.

Table 8. Results based on the ANOVA

Effects	$SS_{treatment}$	gl	$MS_{treatment}$	F_{ratio}	P-Value
A	.0000012013	1	.0000012013	75.87	0.0032
B	.0000000313	1	.0000000313	1.97	0.2547
C	.0000017113	1	.0000017113	108.08	0.0019
AB	.0000000313	1	.0000000313	1.97	0.2547
AC	.0000000313	1	.0000000313	1.97	0.2547
BC	.0000000013	1	.0000000013	0.08	0.7998
Lack- of - fit	.0000000216	2	.0000000108	0.68	0.5691
Pure error	.0000000475	3	.0000000583		
TOTAL (runs.)	.0000030800	11			

R^2-adjusted = .9505

Using the F statistic, with a significance level of $\alpha = 0.05$, with two and three degrees of freedom, we can define the following hypothesis.

H_0 Treatment causes no variance in the response.
H_i Treatment causes variance in the response.
$F_{ratio} > F_{(.05,2,3)}$, reject H_0

From the data in table 8 we can reject H_0 and confirm, with at least 95 % confidence, that the barrel temperature and the cycle time have significant effects on the response. Also with the P-Value and a significance level $\alpha = 0.05$, we can state the following hypothesis:

H_0 The effects are significant.
H_i The effects are insignificant.
$F_{ratio} > F_{(.05,2,3)}$, Reject H_0

According to the following tabulation, we can reject H_0 and assert with a significance level of 0.05 that the barrel temperature and the cycle time are significant effects.

Effects	F_{ratio}	$F_{(.05,2,3)}$	P-Value
A	75.87	9.55	0.0032
C	108.08	9.55	0.0019

The lack-of-fit test proves wether the regression model fitted the data and that the model is a first order mathematical model. Then again we use the F statistic with two and three degrees of freedom and state the hypothesis.

H_0 There is no evidence of curvature.
H_i There is evidence of curvature.
$F_{Lack\text{-}of\text{-}Fit} = 0.68 < F_{(.05,2,3)} = 9.55$, accept H_0

Since the $F_{Lack\text{-}of\text{-}fit}$ is less than the $F_{(.05,2,3)}$, there is no evidence to reject H_0, so we can guarantee that there is no curvature in the response over the region of exploration. R^2 adjusted explained 95.05 % of the variability accounted for by the regression model.

The Paretto plot (fig. 10) shows that the barrel temperature and the cycle time are the most influential factors in the response. Based on the normal probability plot of residuals (fig. 11) and the plots of residuals versus expected value and time sequence (figs. 12 and 13), the residuals seem to be constant, independent, random and to follow a normal distribution.

Once the factors of major influence are selected and based in the ANOVA, we can present the equation model that best fits the region.

$$\hat{y} = 1.25228 - 0.0000775\, x_1 + 0.000925\, x_2 \quad (4)$$

where x_1 is the barrel temperature and x_2 is the cycle time. These levels are figured out with the surface response plot (fig. 14). The contour plot in figure 15 shows a lineal relationship between factors and response. Because of several restrictions, it was not possible to reach the optimum region.

Conclusions

On the basis of the results of our experiment, the factors of major influence in the injection blow molding process are the barrel temperature and the cycle time. Before controlling these factors, the variance of the process was 5.78333 E-6. Once these factors were controlled, the variance was diminished to 2.79697 E-7. Now the product can be manufactured according to the customers' specifications as figure 16 shows.

The resin is heated in the barrel cylinder to get plasticity before it is injected in the preformed mold. This process requires an increase of the temperature to a level that depends on the production cycle time.

The prediction equation (4) includes the limitations of the injection blow molding machine. The machine can not bear a load larger than 5,450 psi and it is not feasible for the company to increase the cycle time to more than 14 seconds. These limitations did not allow us to study the factors in the levels obtained with the method of steepest ascent. Our model considers the most influential factors of the injection blow molding process.

This surface design response for this process is completely satisfactory. It shows that the level for the barrel temperature is -1 and for cycle time is +1. Using these values in equation (4) we obtain the expected value, in this case 1.2531275 inches.

Recommendations

To improve the process we recommend a barrel temperature between 440°F and 450°F, an injection pressure between 5,300 psi and 5,450 psi, a cycle time in the range of 13 to 14 seconds, to keep the bottle neck temperature at 60°F and to keep the speed of the screw at 175 rpm.

A log book should be used to annotate, for every shift, the initial set up of the machine and any adjustments to this setup. This information should include the date, the time, the identification number of the product and the signature of the person responsible for the changes. The log book must be at a visible post in the machine or near it and should be available to the personnel.

We also recommend keeping a record of the mold utilization. The record must include the total utilization time of the mold to establish a maintenance schedule. Only authorized personnel should annotate this information and sign afterwards.

Modifications to the machine are recommended so that the optimum region of manufacture may be reached.

Apendix 1: Figures

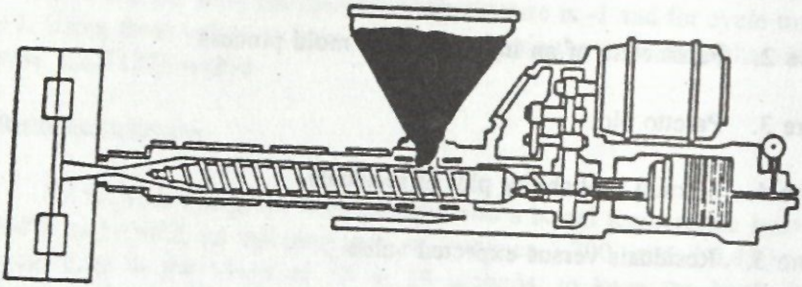

Figure 1. Volumetric feeder

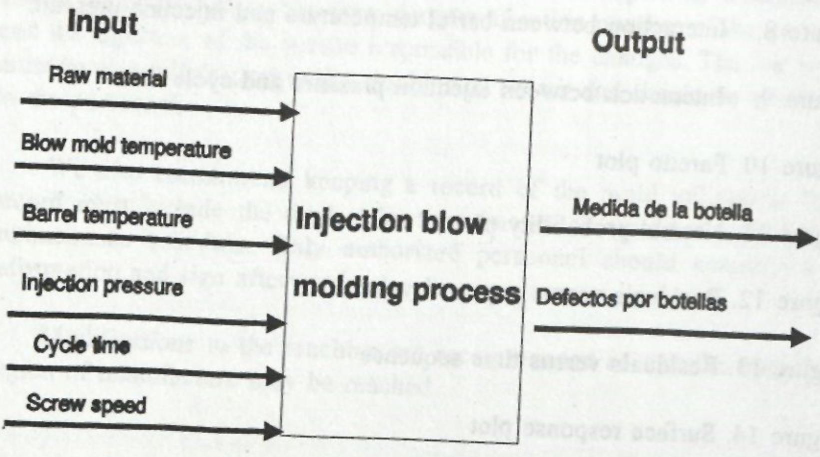

Figure 2. Parameters of an injection blow mold process

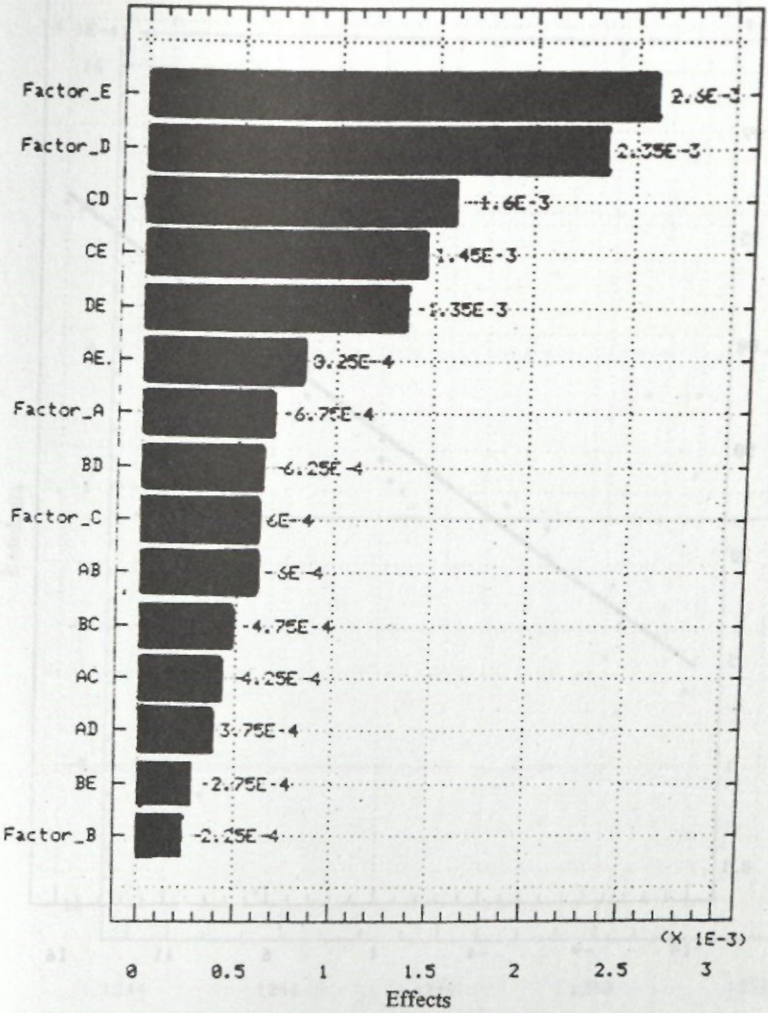

Figure 3. Paretto plot

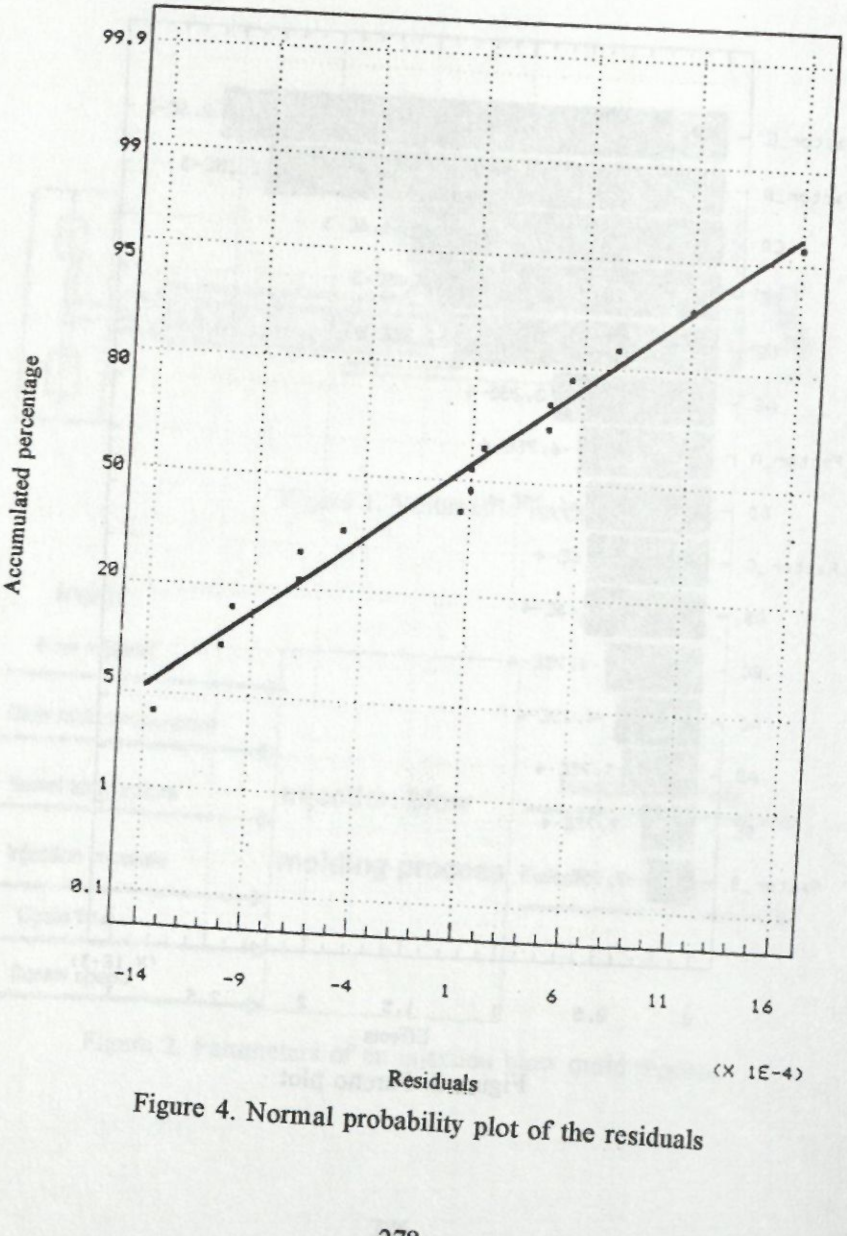

Figure 4. Normal probability plot of the residuals

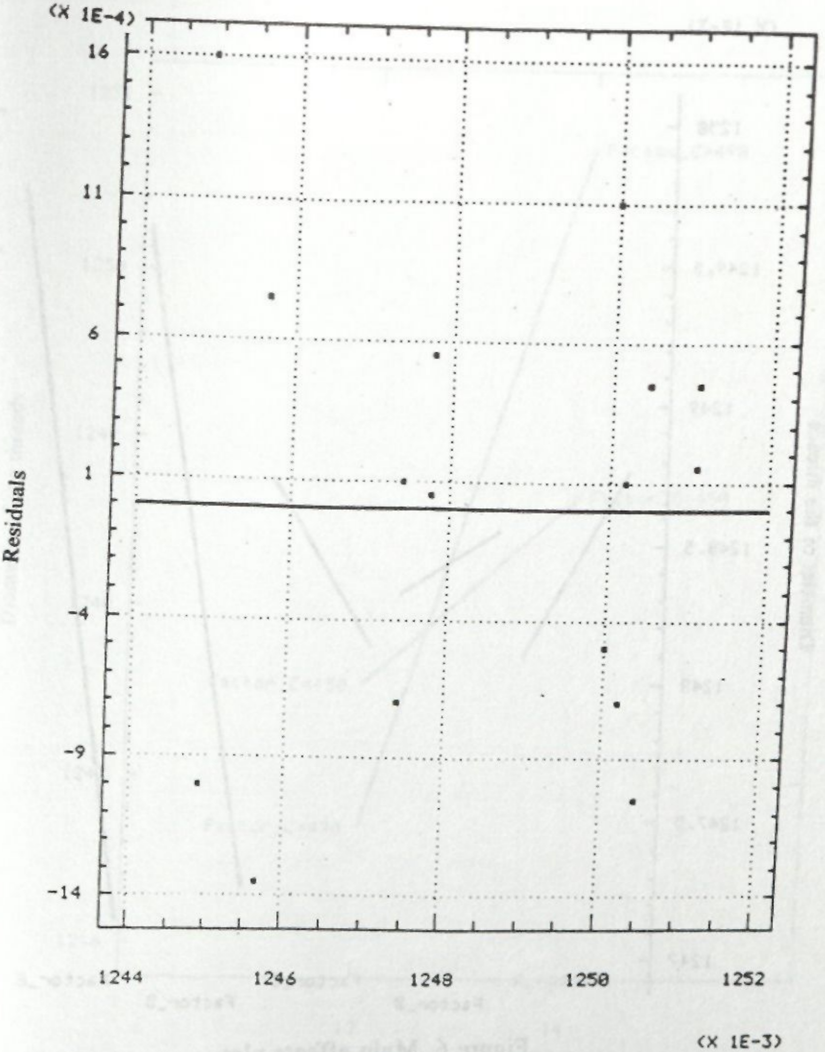

Figure 5. Residuals versus expected value

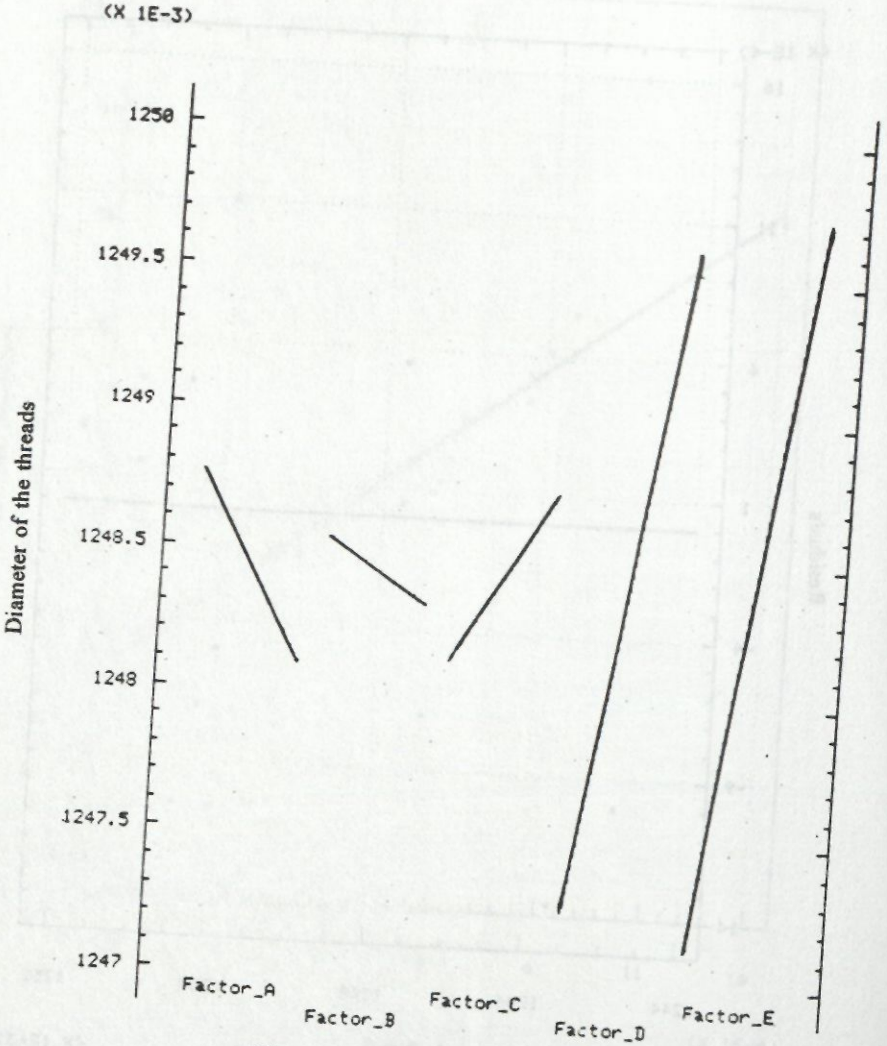

Figure 6. Main effects plot

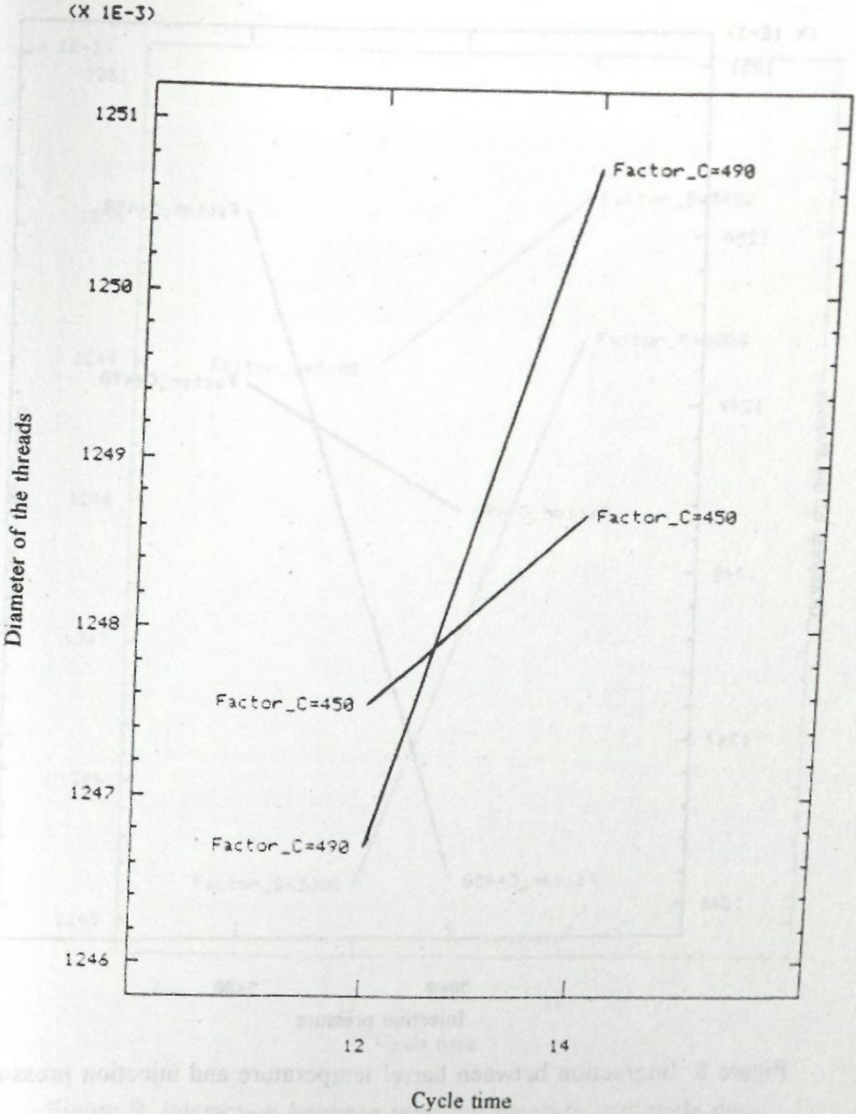

Figure 7. Interaction between barrel temperature and cycle time

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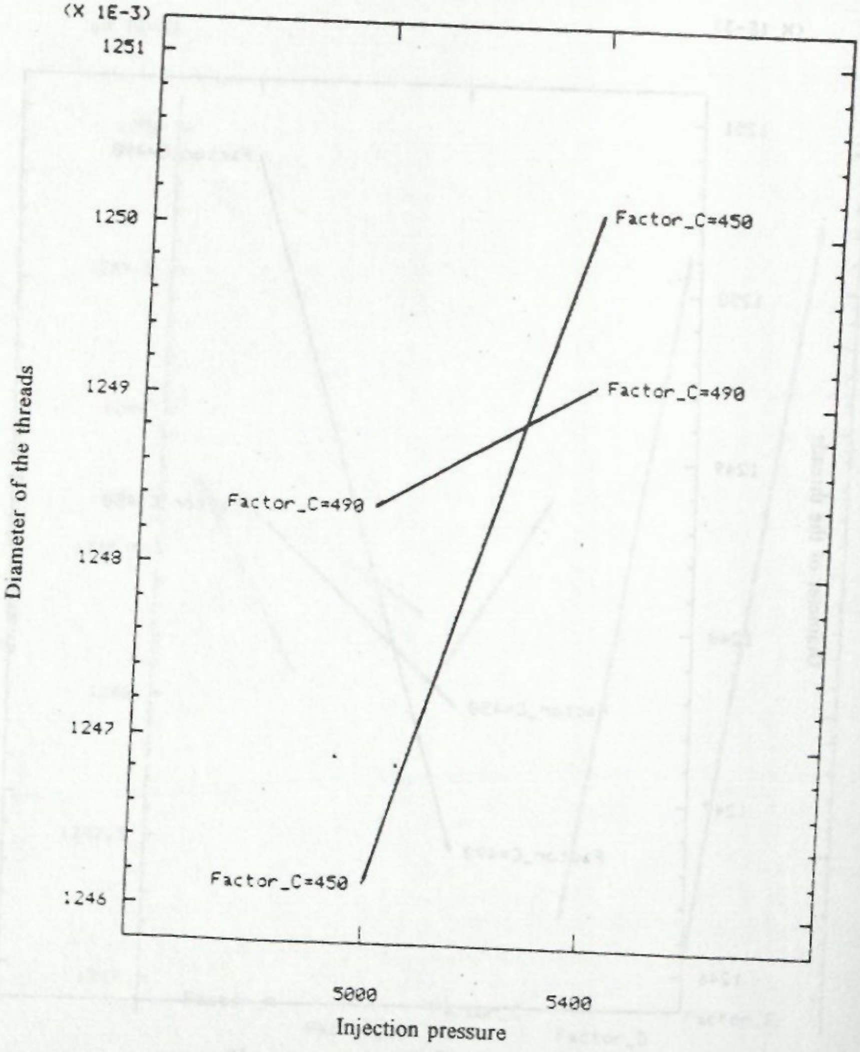

Figure 8. Interaction between barrel temperature and injection pressure

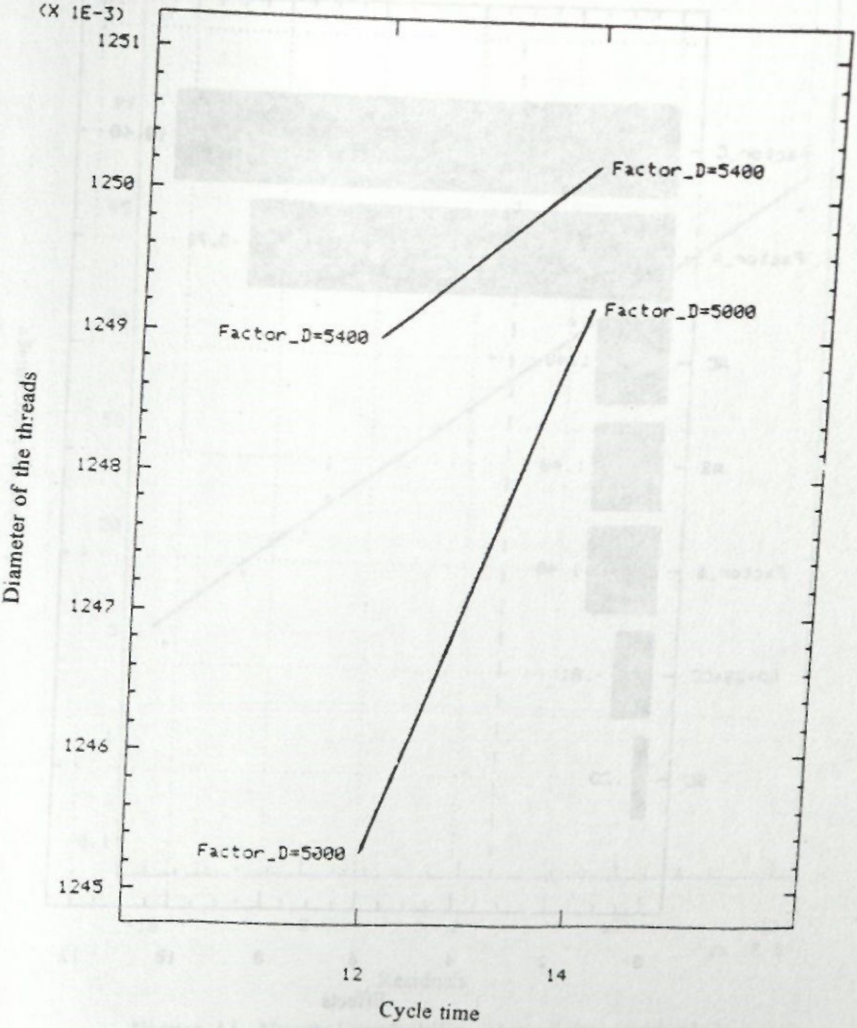

Figure 9. Interaction between injection pressure and cycle time

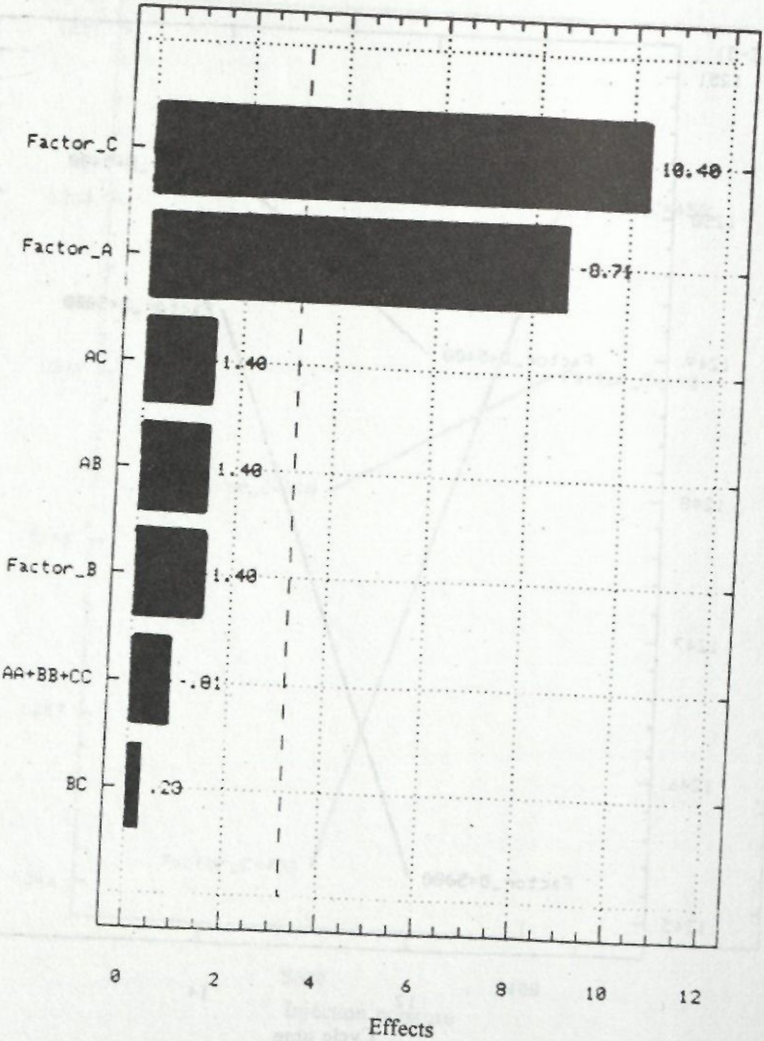

Figure 10. Paretto plot

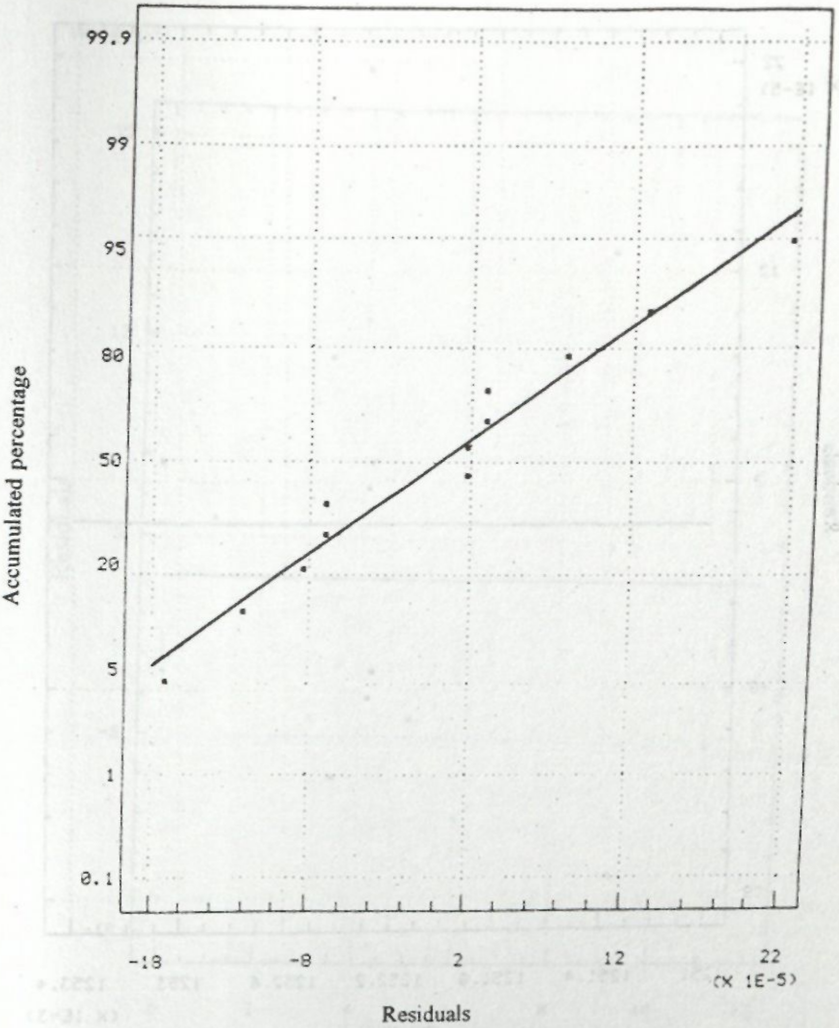

Figure 11. Normal probability plot of the residuals

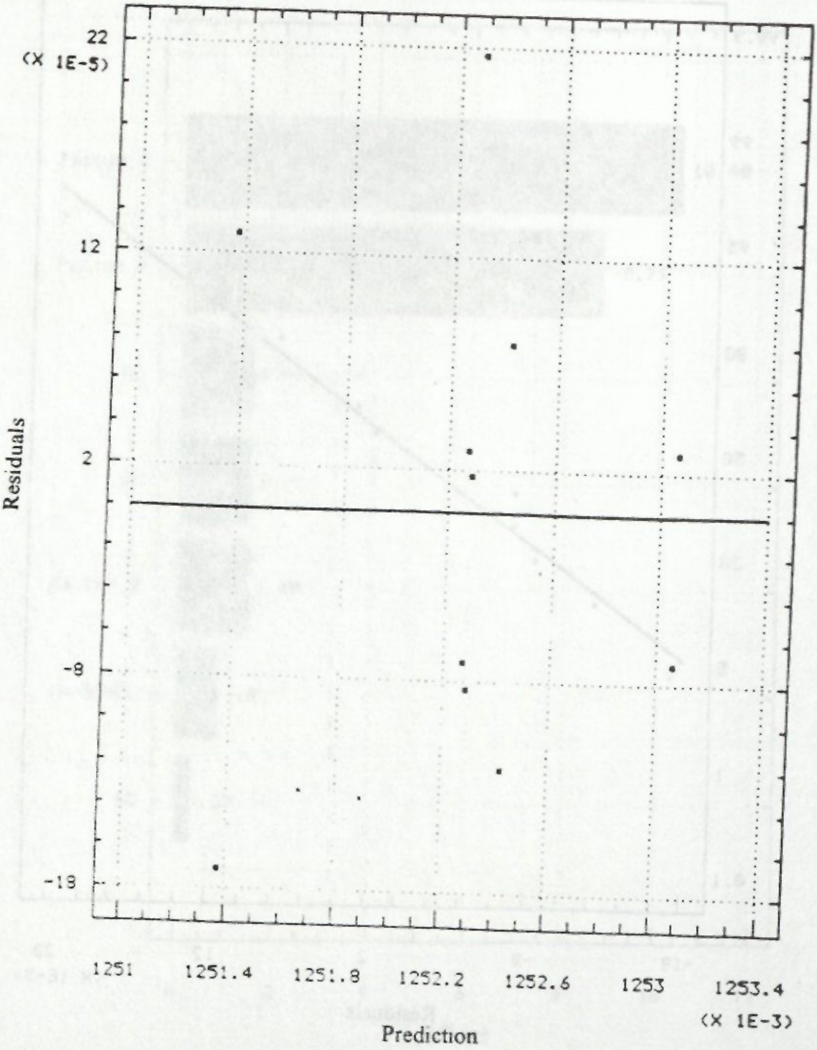

Figure 12. Residuals versus expected value

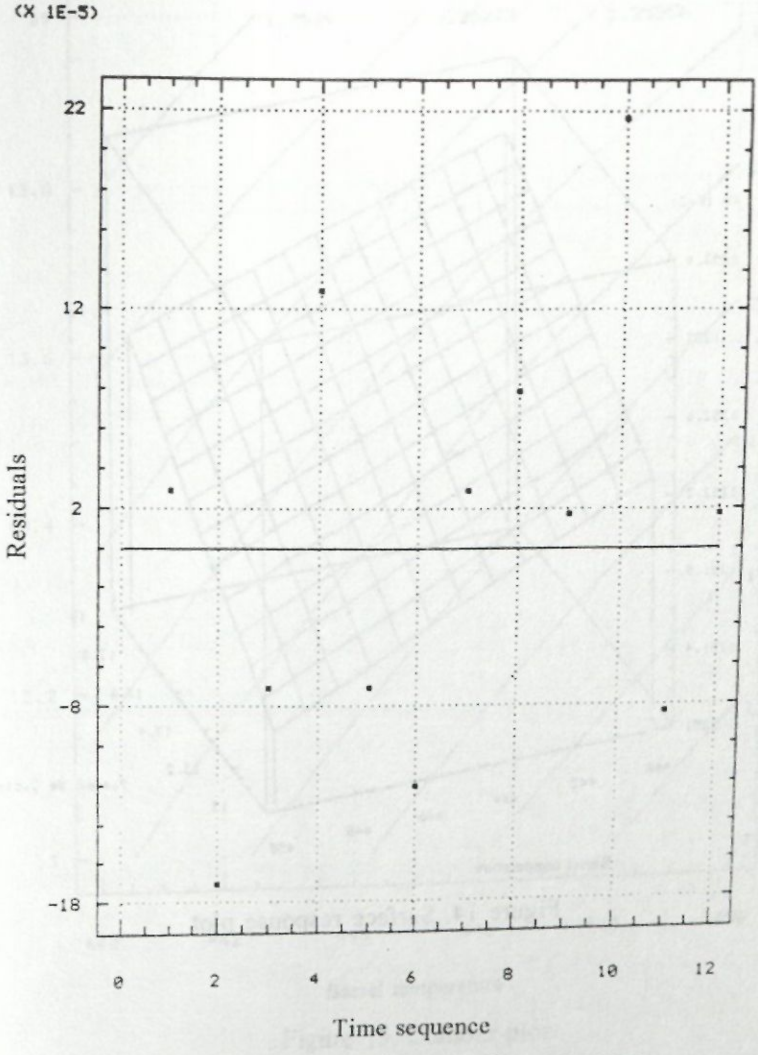

Figure 13. Residuals versus time sequence

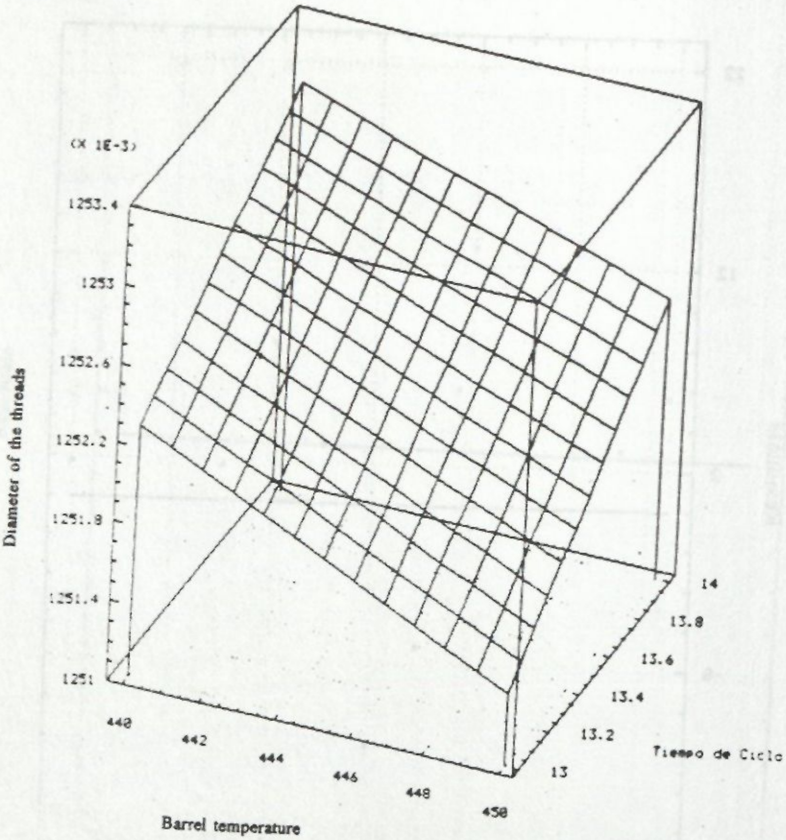

Figure 14. Surface response plot

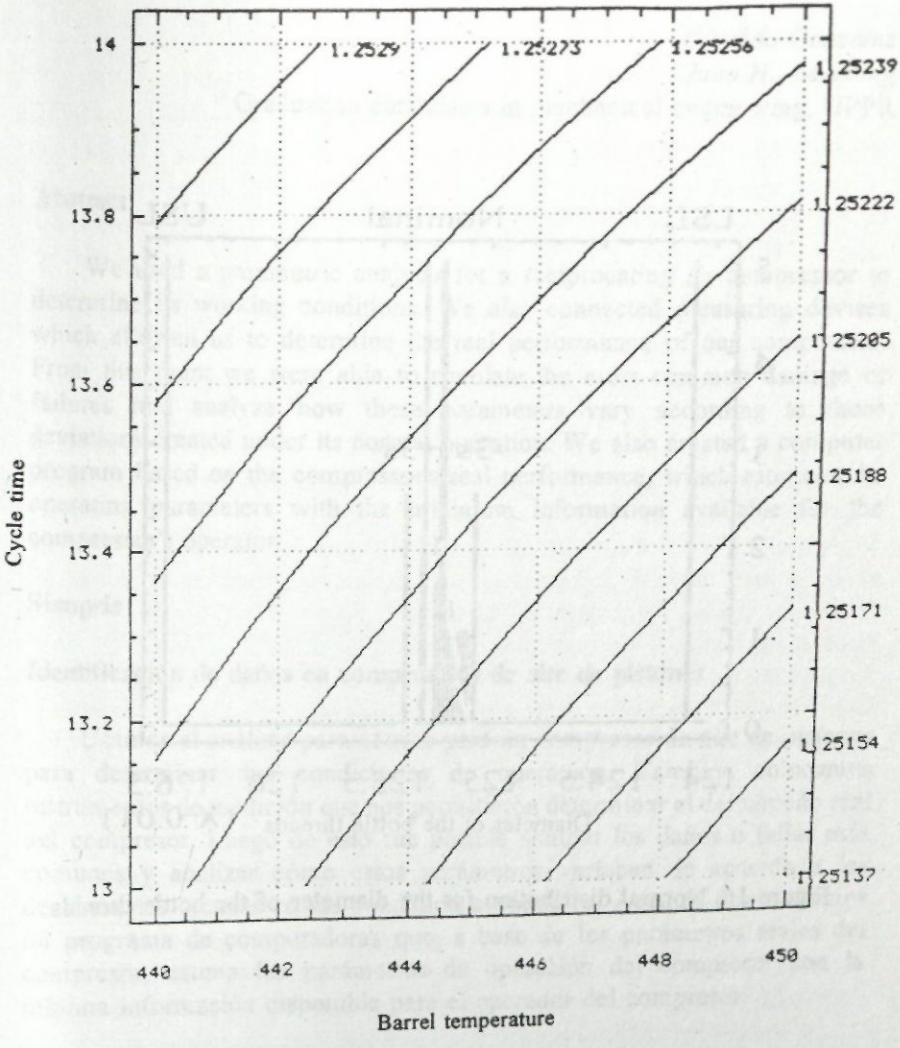

Figure 15. Contour plot

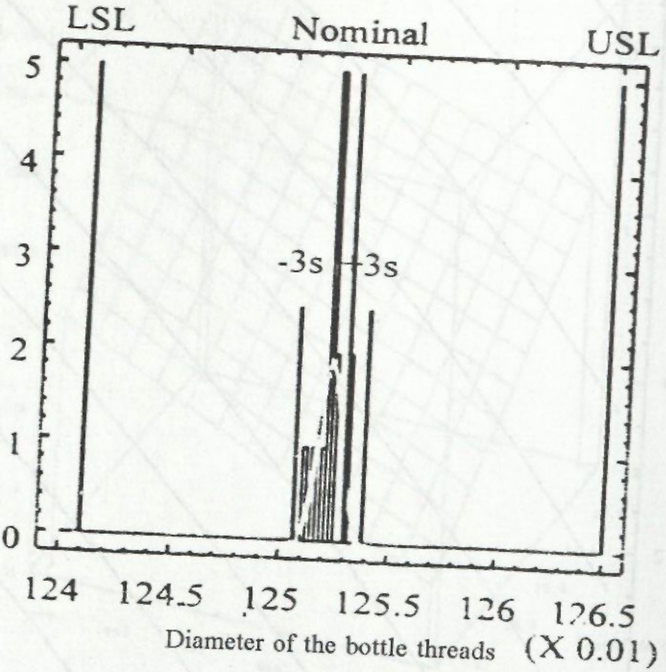

Figure 16. Normal distribution for the diameter of the bottle threads