1950

# Optimization of Parameters for Soft-Nip Calendering of Uncoated Paper

Jung-Kyu Yang
*Western Michigan University*

# OPTIMIZATION OF PARAMETERS FOR SOFT-NIP CALENDERING OF UNCOATED PAPER


by

**Jung-Kyu Yang**


**Advisor: Dr. Brian Scheller**

**A thesis submitted in partial fulfillment
of the course requirements for the
Bachelor of Paper Science Degree
Department of Paper and Printing
Science and Engineering**


**Western Michigan University
Kalamazoo, Michigan**

# TABLE OF CONTENT

## Abstract

The major reason for calendering is to impart both smoothness and gloss on paper. Smoothness, which is the degree of flatness of the surface, and gloss, which is a measurement of light reflectance, are unrelated parameters. However both smoothness and gloss are related to printing process. Strength properties affect the printing machine runability. In general, calendering reduces strength properties of the paper. The degree of finish obtained in a soft-nip calendering depends on characteristics of the paper, such as moisture content and type of filling materials. The purpose of this study is to determine the best conditions for soft-nip calender by setting different ranges of temperature, pressure, and number of nips. In this study, three major control parameters, temperature, pressure, and number of nips, are applied for soft-nip calendering. By using uncoated paper, the investigation carried out the parameters which produce optimum surface, strength and printability properties. The study is conducted using a $3^K$ factorial design. There are 27 different stages. The data was analyzed using Statistic Analyze System (SAS). By using the analysis of variance in SAS program, P-values can be determined. Most of the results from this study followed the expected results from the literature values. According to this experiment, high temperature, pressure and number of nips give the optimum conditions for gloss. However number of nips do not interact with temperature and pressure. High pressure and number of nips improves smoothness but there is not any interaction between pressure and number of nips.

## Introduction

With many grades of paper, the required degree of smoothness is achieved by calendering. Calendering is a process where a paper is run between the rolls to produce both smooth and glossy paper. Calender rolls can be made of many different materials such as metal, cotton, polymer and paper.

There are two major types of calendering applied to the paper in order to improve surface and printabilty properties; hard-nip which includes machine and supercalender and soft-nip calendering. A machine calender usually consists of 2 to 4 iron rolls. The pressure and number of nips are the major parameters for machine calendering. "The moderate loads and temperatures of conventional machine calenders produce only a moderate improvement in paper gloss and smoothness"(1). Compared with a supercalender, a machine calender gives less gloss and smoothness. Supercalenders usually consist of alternating rolls of chilled steel and pressed cotton. The steel rolls are often steam heated and the pressure between the rolls are adjustable. Passing the paper through a number of nips gives the required surface finish. "Supercalendering conditions: temperature, speed, steam, nip pressure, and filled roll conditions are varied to optimize the printing surface properties with minimum reduction in optical properties"(2). On a supercalender, the quality can be affected by means of press loading, chilled-iron roll, temperature, paper moisture, use of steam, and running speed. Soft-nip calendering is becoming popular in the paper industry as an alternative to hard-nip calendering. The soft-nip consists of a polymer or synthetic cover roll against a heated iron roll. These rolls allow use of high heat. "The most obvious, difference is that the synthetic roll nip uses a much hotter iron roll than the cotton roll"(3). In addition, when the paper goes through the nips, soft-nip gives higher residence time than hard-nips. Therefore soft-nip

calendering gives a constant density with better smoothness which produces a uniform printed image.

The three major control parameters for a soft-nip calendering machine are loading pressure, temperature of the nip, and number of nips. The purpose of this study is to determine the best condition of the three control parameters, which would result in optimum surface, strength and printability properties of the paper.

In order to achieve the best results, the following limitations have to be considered: moisture and temperature control. Moisture has a significant effect on smoothness, porosity, and oil absorbency. It can be affected by the soft-nip calender operation. Therefore, in order to achieve the proper test results, applying a constant moisture content is important. In this study, all samples were conditioned for at least 48 hours in a humidity controlled room in order to achieve constant testing results. In addition all 27 different stages ran on the same day.

Another limitation is temperature control. On a soft-nip calender machine, increasing the press loading raises the nip heat. During the operation, increased nip pressure raises temperature on the nip. This heat will leave the roll through radiation or conduction or with the paper web to be calendered. Three different temperature ranges, 120F°, 160F°, and 200F° were used. However it was hard to remaining at target temperature when the pressure is increased. In addition, overheating the nip may cause burning into the filled roll. The highest recommendable surface temperature is 225F° for a polymer roll on the pilot plant soft-nip calender machine. In this experiment, the temperature can not exceeded more than 225F°. Therefore it is hard to simulate the millcondition which usually exceeds more than 400F°.

## Objective

The objective of this study is to determine optimum conditions of the soft-nip calendering machine by applying different ranges of temperature, pressure, and number of nips for uncoated paper. The surface, strength and printability properties of the paper tested. Data analyzed using Statistical Analyze System(SAS).

## Literature Survey

Soft-nip calendering is not only a new area of surface finishing but it is also becoming increasingly popular within the paper industry as an alternative to machine calendering or supercalendering.

The benefits of soft-nip calendering are preservıng high opacity and brightness, providing good gloss and smoothness, and improving surface uniformity and prinability. Soft-nip calenders with high-temperature mating rolls are also suitable for paper grades with high surface quality requirements(4). In addition, a soft-nip calender machine has less operating cost than a supercalender machine while providing a high quality paper. In general, supercalender has 5 to 18 nips. A soft-nip calender has a maximum of 4 nips. The surface temperature of a cast iron roll for supercalender has maximum 150 C°. However the surface temperature of iron roll for soft-nip calender has a maximum of 230 C°. Literature shows that "In a view of the high operating costs of supercalenders, soft-nip calenders with elastic and heated rolls represent an economic alternative"(5).

The soft calender nip consists of two types of rolls; a polymer covered roll and a heated iron roll. Compared with the cotton roll, the polymer roll nip uses a much hotter iron roll than the cotton roll. Peel(6) demonstrated with his experiment that increasing the temperature of the nips improves smoothness and gloss at the same thickness. Peel's data noted that the plastic compression in the paper sheet is not uniform in the z direction and is greater in the zones near the heated surfaces. This means certain surface properties can be produce at greater thickness. Literature also states that " In contrast to the machine calender where only the web is compressed within the nip, the soft nip compresses both the web and the polymer covering which ultimately widens the nip width and reduces the

specific nip pressure within the soft-nip for a given constant linear load"(7). Therefore soft-nip calendering preserves higher strength and bulk properties than hard-nip calendering (machine and supercalender) while producing high gloss and smoothness on the paper.

When soft-nip calendering operates at high temperature and pressure, gloss and smoothness values are increased. However strength, brightness, opacity, and porosity values are deceased when the soft-nip runs at high temperature. The following table shows the results of the Bresser and Schmitz(8) study:

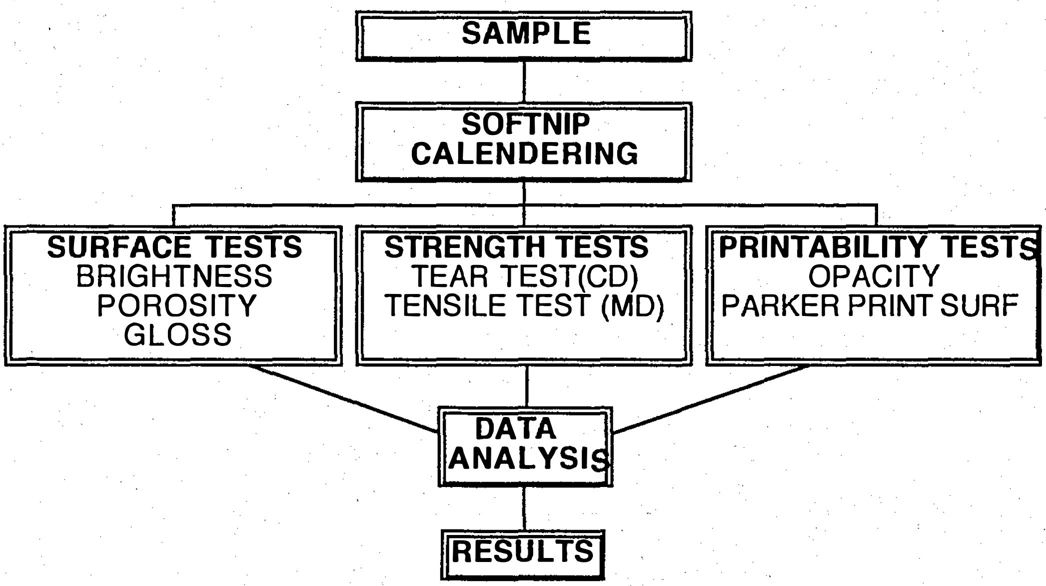
<u>The influential parameters of a soft calender and influenced paper properties.</u>

| | linear load | | Temperature | | cal. speed | | moisture | | roll hardness | |
|---|---|---|---|---|---|---|---|---|---|---|
| influence | low | high | low | high | low | high | low | high | low | high |
| paper properties | | | | | | | | | | |
| smoothness | - | + | - | + | + | - | - | + | - | + |
| gloss(75°) | - | + | - | + | + | - | - | + | + | - |
| bulk | + | - | + | - | - | + | + | - | + | - |
| strength | + | - | + | - | - | + | + | - | + | - |
| brightness/opacity | + | - | + | - | - | + | + | - | + | - |
| air-permeability | + | - | + | - | - | + | + | - | + | - |

## Methodology

Design of the study:

Flow chart of the experiments




**PILOT PLANT SOFT-NIP CALENDER MACHINE**

This study is a $3^K$ factorial design. There are three major parameters for the soft-nip calender machine, pressure, temperature and number of nips. Each parameter has three different running conditions low, medium and high. The following table is the experimental design for this study:

Table 1 shows the $3^K$ factorial design.

**$3^k$ Factorial Design**

| Conditions | Pressure(pli) | # of Nips | Temperature(F°) |
|---|---|---|---|
| Low | 500 | 1 | 120 |
| Medium | 1000 | 3 | 160 |
| High | 2000 | 5 | 200 |

Table 2 shows the combination of nine different factors which give twenty seven different conditions.

Temperature at 120 F°

| # of Nips | Pressure (pli) 500 | 1000 | 2000 |
|---|---|---|---|
| 1 | Sample #1 | Sample #4 | Sample #7 |
| 3 | Sample #10 | Sample #13 | Sample #16 |
| 5 | Sample #19 | Sample #22 | Sample #25 |

Temperature at 160 F°

| # of Nips | Pressure (pli) 500 | 1000 | 2000 |
|---|---|---|---|
| 1 | Sample #2 | Sample #5 | Sample #8 |
| 3 | Sample #11 | Sample #14 | Sample #17 |
| 5 | Sample #20 | Sample #23 | Sample #26 |

Temperature at 200 F°

| # of Nips | Pressure (pli) 500 | 1000 | 2000 |
|---|---|---|---|
| 1 | Sample #3 | Sample #6 | Sample #9 |
| 3 | Sample #12 | Sample #15 | Sample #18 |
| 5 | Sample #21 | Sample #24 | Sample #27 |

**Sampling for the pilot plant soft-nip calender machine:**

Under all possible combinations of the conditions of three control parameters(27), the samples were prepared for sample number 1 through 27. In order to achieve the target liner load pressure, each sample has 10 inch web size. In all trials surface, strength, and printability properties were tested to allow the drawing of graphs which track the relationships between properties as they are developed.

**Data:**

In order to evaluate the sample, there are three major properties to be considered surface, strength, and printability. The following measurement used for this study:

Surface : 1. Porosity
2. Hunter Gloss
3. Brightness meter (brightness)

Strength: 1. Tear test (CD)
2. Tensile test (MD)

Printabilty: 1. Parker print surf -1000 (Smoothness)
2. Opacity

**Test procedures:**

The following statements are the procedures for this project:

- All samples were conditioned for at least 48 hours in a humidity controlled room in order to achieve constant testing results.
- The results given in table 1 show the mean and standard deviation values achieved from the measurements made on three sheets per sample.
- The surface properties, porosity, gloss, and brightness, were measured at 5 locations on the calendered side of sheet.
- The strength properties are CD tear and MD tensile. The tear (CD) measurement was made at 5 different locations on each sheet. The tensile (MD) measurement was made at 6 different locations of each sheet.
- Printing properties of the samples were evaluated by using opacity and smoothness. These properties were measured at 5 different locations on the calendered side of each sheet.

**Sample(uncoated paper):**

The testing samples were produced by the pilot plant in Western Michigan University. The samples were part of trail from the Sequa chemical company. Basis weight of the sample was 71.68 g/m^2. The fiber furnish used was Canadian Northern Softwood and Eucalyptus form Brazil, 50/50. The paper was made at a wet end pH of 7.4, with 2.5 lbs/ton Hercon 75, 2.0 lbs/ton Nalco 7507(deformer) and 2.0 lbs/ton Nalco 7607 (cationic form. aid polymer). This was treated at the sizepress with a 8% Penford Gum 280 starch solution with 0.2 parts of Colloids 999 (deformer).

**Testing Methods:**

All necessary testing equipment was provided by the department and testing procedures followed the Tappi standard.

**Data Analysis**

The data was analyzed using the Statistical Analyze System(SAS). In SAS program, P-values from the analysis of variance have been used in order to evaluate the $3^K$ factorial design.

## Results and Discussion

Statistical Data Analysis

Table 3 is based on Appendix II. This table shows the mean and standard deviation values from different conditions. Table 3 also shows the base paper test results.

Table 4 shows the data analysis from Statistic Analyze System(SAS). The control parameters are shown in the Table 1 and the results of the optimization can be determined using P-values from the Analysis of Variance. According to the P-value from the Analysis of Variance, P-value less than 0.05 is a significant value which means acceptable data. P-values bigger than 0.05 are nonsignificient values which are rejected data. Three factors which include temperature, pressure, and number of nips can possibly have six different combinations. However according to the data analysis, there is only one interaction which is pressure*temperature. It means that both pressure and temperature are dependent values. According to Table 4, all conditions for both brightness and tensile energy absorbency(TEA) have P-values bigger than 0.05. This explains that soft-nip calendering did not affect all different conditions for brightness and TEA. Gloss and porosity have interactions for the temperature and pressure.

Surface Properties

Surface properties include three major tests which are brightness, porosity, and gloss. According to Table 4, all three different factors did not affect brightness. However different pressure, temperature, and number of nips have

significant effect on both gloss and porosity. In addition, both gloss and porosity have interactions for the temperature and pressure.

Figure 3 shows the effect of varying pressure on gloss. Compared with the base paper, pressure at 500(pli) has a 16.67% better gloss value. In addition, increased pressure increases the gloss. Compared with pressure at 500(pli), the pressure at 2000(pli) has a 5.31% improvement of the gloss value. Figure 4 describes the effect of varying temperature on gloss. Increased temperature increases the gloss values. However temperature at 160F° and 200F° show less than 1% difference. This means that medium temperature and high temperatures produce almost the same gloss values. Figure 5 shows the effect of varying nip conditions on gloss. According to the graph, increasing the number of nips increase the gloss values. Compared with after 3 nips, the gloss value after 5 nips did not change that much. There is only 0.63% difference. Therefore, medium and high nip conditions produce similar gloss results. Figure 6 shows the effect of varying pressure on gloss at different temperature. In Figure 6, increasing both pressure and temperature increase the gloss values. The slope at low temperature is much higher than the slope at the medium and high temperature. This means that pressure has a much greater effect at low temperature. There is a small difference between temperature at 160F° and 200F° when pressure is increased.

The porosity value of the base paper was 2655 ml/min. Applying soft-nip calendering significantly reduces porosity values for all three different factors, pressure, temperature, and number of nips. Figure 7 shows the effect of varying pressure on porosity. According to Figure 7, increased pressure decreases porosity. The effect of varying temperature on porosity is in Figure 8. Increased

temperature reduces porosity values. Compared with low (120F°) and medium (160F°) temperature, low temperature has 29 ml/min higher porosity than medium temperature. However, there is a small reduction occurring when the temperature increases from medium to high. Figure 9 shows that the effect of varying nip conditions on porosity. Increasing the number of nips decreases porosity values. However, there is not any difference between medium(after 3 nips) and high(after 5 nips). Figure 10 describes the effect of pressure on porosity at different temperature. This graph shows that, increasing temperature decreases porosity for all three different temperature ranges. The slope at low temperature (120F°) is high but the slope at medium(160F°) and high temperature(200F°) is almost horizontal line. This means that pressure does not have an effect at temperatures of 160F° and 200 F° for porosity.

According to the data, soft-nip calendering significantly improves the gloss value. The data also shows that increased pressure, temperature, number of nips increase the gloss values. All three factors, temperature, pressure, and number of nips significantly affect porosity. Increasing these three factors decreases porosity values for all three different conditions. However, pressure has a small effect on porosity at medium(160F°) and high(200F°) temperatures.

Strength Properties

There are two tests tear (CD) and tensile energy absorption (MD) considered as strength properties. These values are important for the printing machine runability. In general, soft-nip calendering increased strength properties when the temperature is increased.

Figure 13 shows the effect on varying temperature on tear(CD) index. Increased temperature slightly increased the tear(CD) index values. Data also shows that all three different ranges of temperature have lower tear(CD) values than the base paper tear(CD) index value. This means soft-nip calendering reduces strength properties.

According to the data analysis, there is not any effect of TEA for soft-nip calendering. In addition, pressure and number of nips do not effect the tear index (CD) values. Therefore soft-nip calendering has a minor effect on strength properties.

Printability Properties

Printability properties include opacity and parker print surface test. Parker Print Surf (PPS) measures the roughness of the paper. High PPS means low smoothness of the paper. PPS is an important measurement value for the print ability properties because it may indirectly indicate the level of print image. Data shows number of nips do not effect opacity. In addition, there is not any relationship between temperature and PPS for soft-nip calendering. In general, increased temperature increases smoothness of the paper.

Figure 1 shows the effect of different pressure on opacity. Compared with the base paper, all three different levels of pressure have low opacity values. Increased pressure reduces opacity values. However there is only 0.34% differences between pressure at 500(pli) and 1000(pli). Figure 2 describes the effect of varying temperature on opacity. Increased temperature slightly decreases opacity. The scale of y-axis of the this graph is only 8%. Even though graph shows decreasing trends, there is a very small difference.

Figure 11 shows the effect of varying pressure on PPS-1000. Compared with the base paper, all three different pressure have significantly low values. This shows that soft-nip calendering improves the smoothness of the paper. Increased pressure slightly decreases PPS values. Figure 12 shows the effect of different nip conditions on PPS-1000. In creased number of nips reduces PPS values. However, there is a only 0.01 micron differences between after 3 nips and after 5 nips. Therefore, there is not any difference between medium(after 3 nips) and high(after 5 nip) conditions.

Soft-nip calendering has disadvantages and advantages. Increased pressure and temperature reduce the opacity which means a reduction in prinability properties. However, increased number of nips and pressure, increases the smoothness which provides better print images.

Table 3. Mean & Standard Deviation Values from Raw data

| X1 | X2 | X3 | BRIGHTNESS | STDEV | OPACITY | STDEV | GLOSS | STDEV | POROSITY | STDEV |
|---|---|---|---|---|---|---|---|---|---|---|
| pli | F° | | % | | % | | % | | ml/min | |
| 500 | | | 90.84 | 0.13 | 86.53 | 0.64 | 22.58 | 0.88 | 54.18 | 3.68 |
| 1000 | | | 91.06 | 0.19 | 86.19 | 0.77 | 24.21 | 0.79 | 47.15 | 4.66 |
| 2000 | | | 90.49 | 0.19 | 84.90 | 0.74 | 27.89 | 0.70 | 38.92 | 2.53 |
| | 120 | | 91.16 | 0.15 | 86.95 | 0.75 | 21.20 | 0.71 | 69.24 | 5.26 |
| | 160 | | 90.53 | 0.18 | 85.86 | 0.62 | 26.43 | 0.58 | 37.19 | 2.98 |
| | 200 | | 90.71 | 0.18 | 84.81 | 0.78 | 27.05 | 1.09 | 33.83 | 2.63 |
| | | 1 | 90.69 | 0.13 | 86.15 | 0.61 | 22.32 | 0.69 | 55.64 | 4.09 |
| | | 3 | 90.79 | 0.12 | 85.57 | 0.72 | 25.86 | 0.99 | 42.75 | 3.86 |
| | | 5 | 90.91 | 0.26 | 85.90 | 0.82 | 26.49 | 0.69 | 41.87 | 2.92 |
| Base Paper | | | 90.70 | 0.11 | 89.33 | 0.09 | 5.91 | 0.03 | 2655 | 256 |

| X1 | X2 | X3 | PPS-1000 | STDEV | TEAR INDEX(CD) | STDEV | TEA(MD) | STDEV |
|---|---|---|---|---|---|---|---|---|
| pli | F° | | microns | | mNm^2/g | | J/m^2 | |
| 500 | | | 1.43 | 0.01 | 10.36 | 0.11 | 57.40 | 0.92 |
| 1000 | | | 1.37 | 0.01 | 10.07 | 0.14 | 62.17 | 1.04 |
| 2000 | | | 1.32 | 0.01 | 9.78 | 0.11 | 65.88 | 0.89 |
| | 120 | | 1.41 | 0.02 | 9.44 | 0.10 | 62.75 | 1.06 |
| | 160 | | 1.37 | 0.01 | 10.11 | 0.12 | 59.53 | 0.89 |
| | 200 | | 1.39 | 0.02 | 10.67 | 0.14 | 63.17 | 0.90 |
| | | 1 | 1.45 | 0.02 | 10.30 | 0.13 | 61.99 | 1.01 |
| | | 3 | 1.37 | 0.01 | 9.93 | 0.11 | 63.88 | 1.07 |
| | | 5 | 1.36 | 0.01 | 9.99 | 0.12 | 59.57 | 0.76 |
| Base Paper | | | 2.55 | 0.05 | 12.99 | 0.12 | 57.27 | 0.72 |

Table 4. Data Analysis from Statistic Analyze System

P-Values from Analysis of Varience

P-value < 0.05 (Significance)

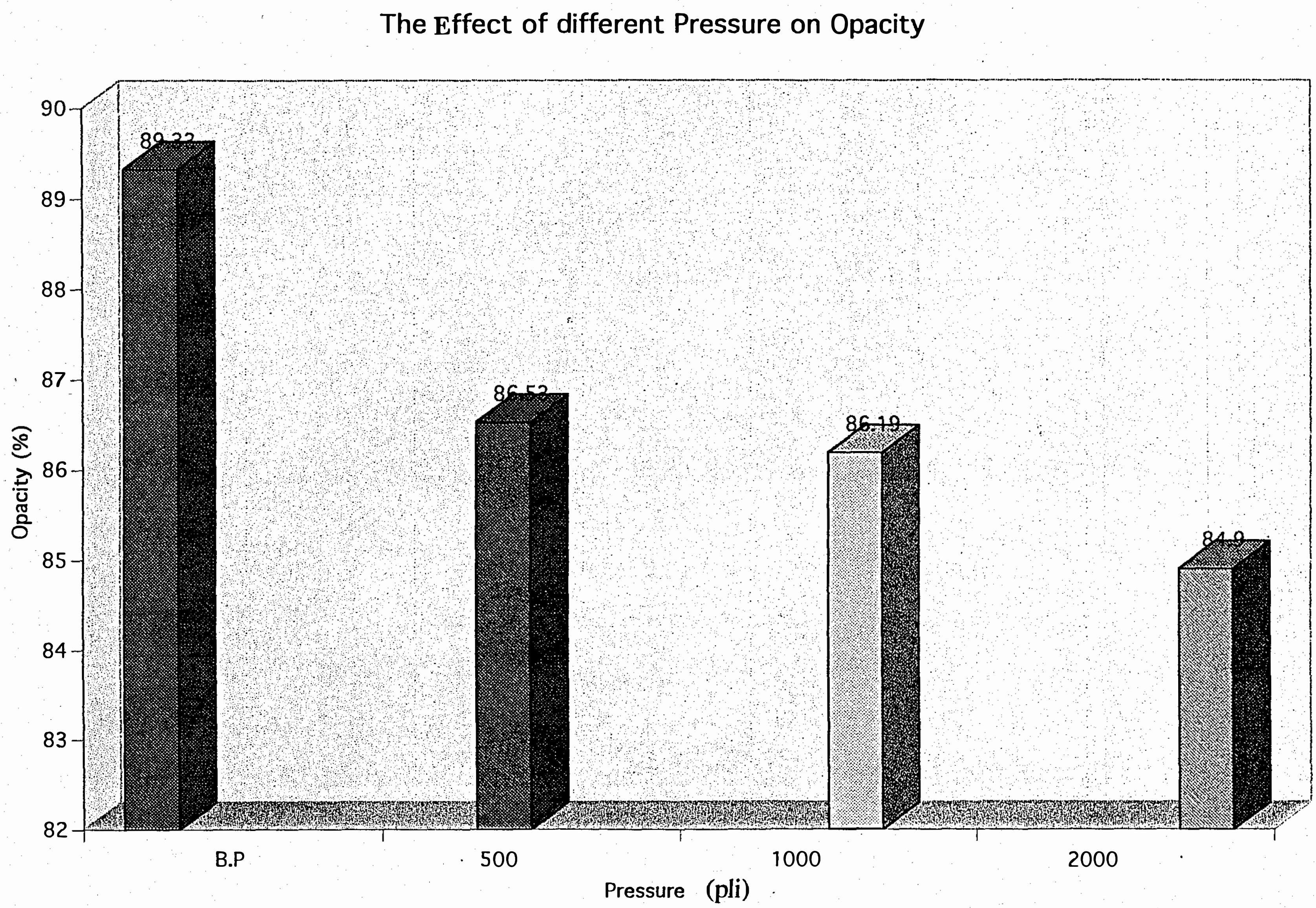
P-Value > 0.05 (nonsignificance)

Pressure * Temperature (Interaction)

| CONDITIONS | P-value Brightness % | P-value Opacity % | P-value Gloss % | P-value Porosity ml/min | P-value PPS-1000 microns |
|---|---|---|---|---|---|
| TEMPERATURE(F°) | 0.15 | 0.0006 | 0.0001 | 0.0001 | 0.5 |
| PRESSURE(pli) | 0.23 | 0.01 | 0.0001 | 0.005 | 0.024 |
| # of Nips | 0.81 | 0.65 | 0.0001 | 0.004 | 0.0005 |
| Pressure*Temperature | | | 0.016 | 0.001 | |

| CONDITIONS | P-value Tear Index (CD) mNm^2/g | P-value TEA(MD) J/m^2 |
|---|---|---|
| TEMPERATURE(F°) | 0.0001 | 0.55 |
| PRESSURE(pli) | 0.16 | 0.05 |
| # of Nips | 0.44 | 0.5 |

Figure 1.



The Effect of different Pressure on Opacity
90
89
88
87
86
85
84
83
82
Opacity (%)
89.33
86.52
86.19
84.9
B.P
500
1000
2000
Pressure (pli)

Figure 2.

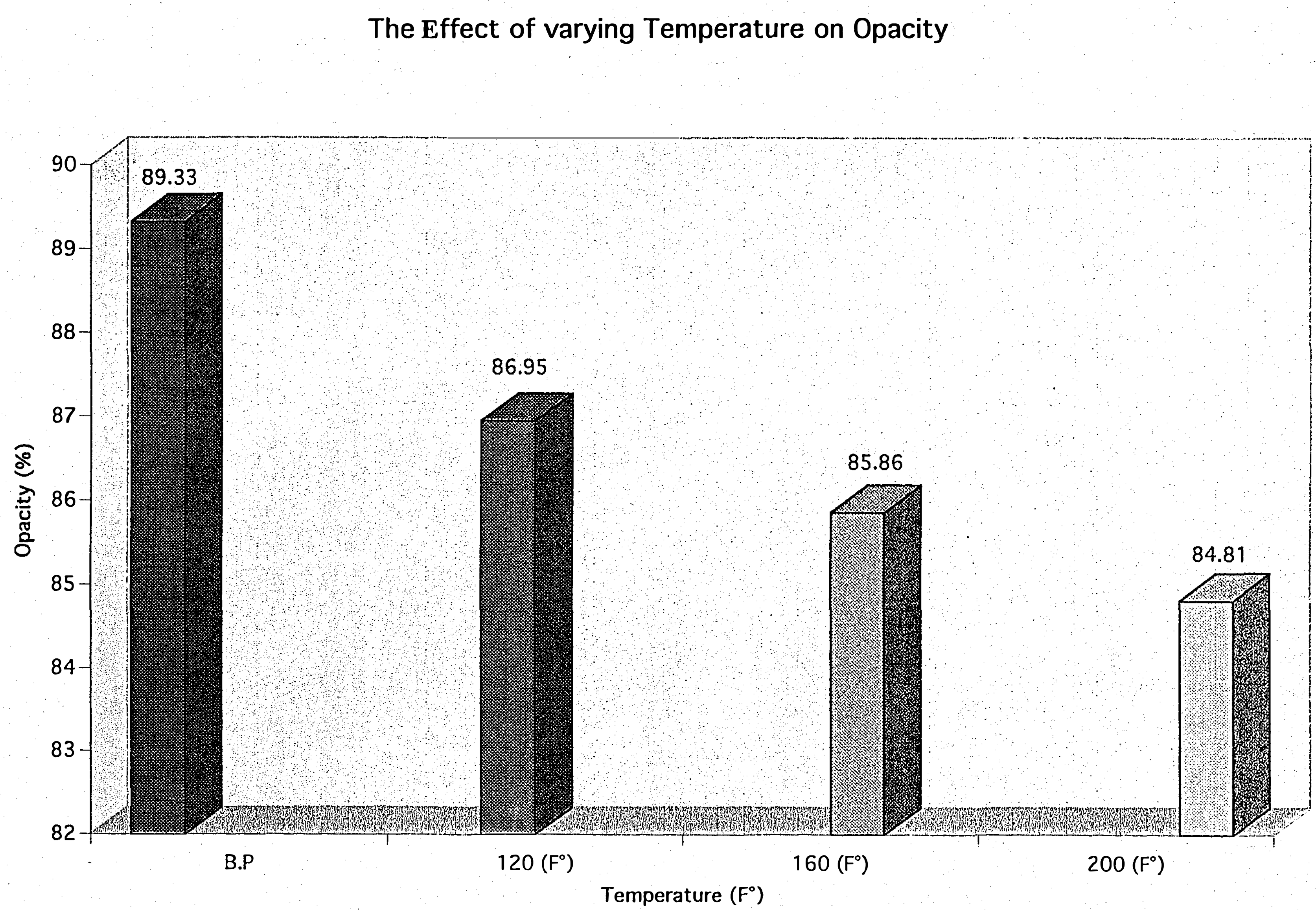

The Effect of varying Temperature on Opacity
90
89
88
87
86
85
84
83
82
Opacity (%)
89.33
86.95
85.86
84.81
B.P
120 (F°)
160 (F°)
200 (F°)
Temperature (F°)

Figure 3.

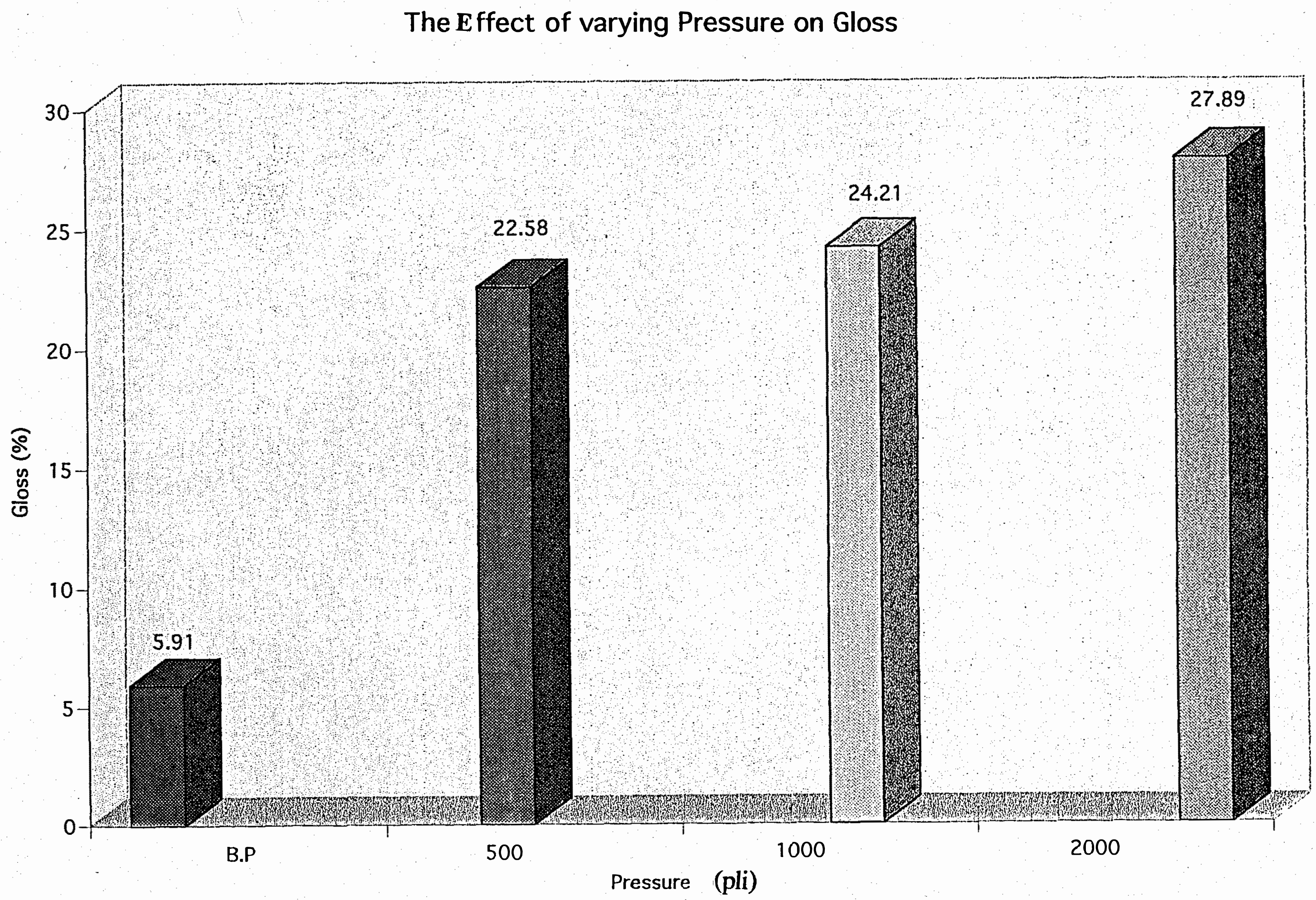
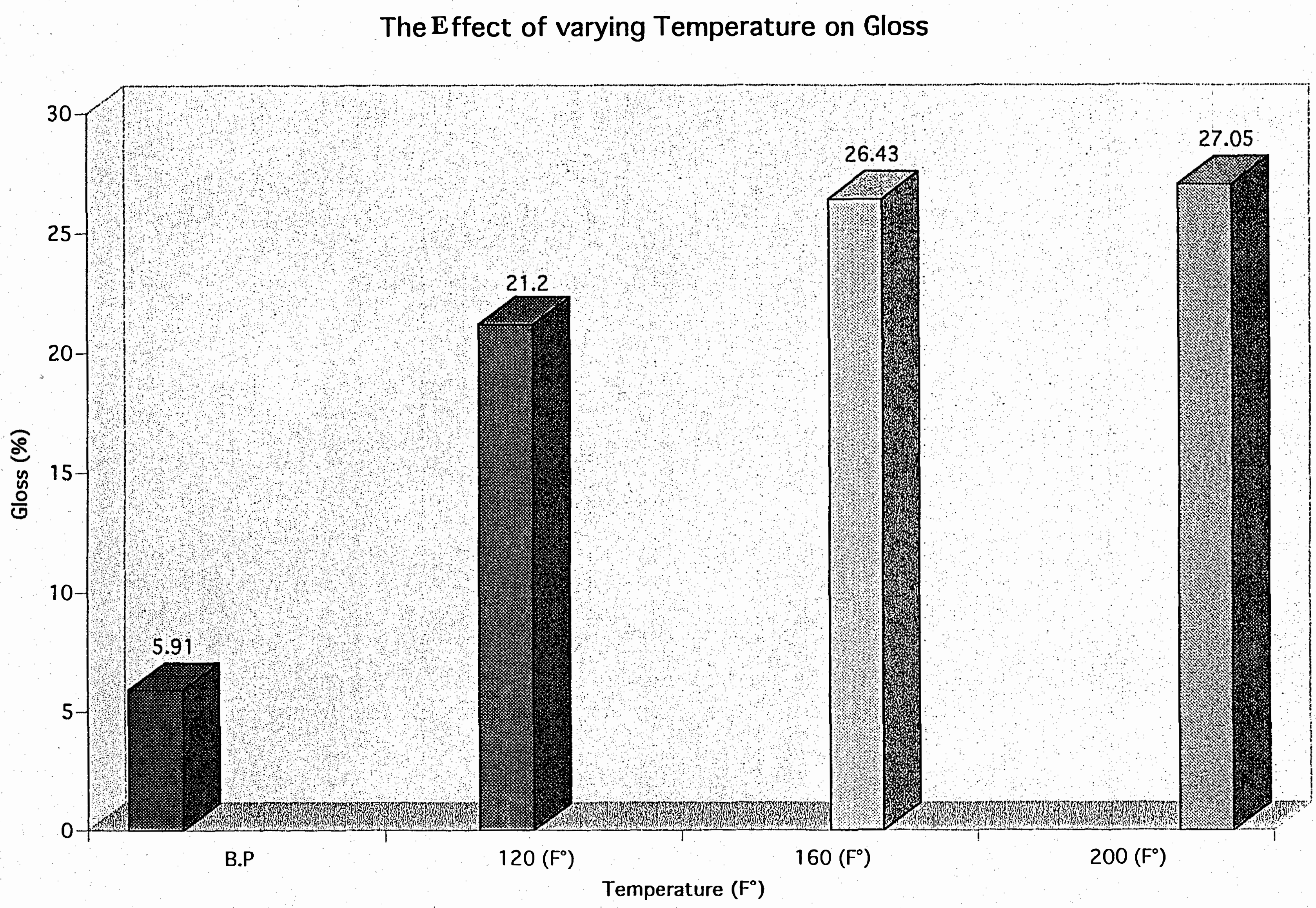
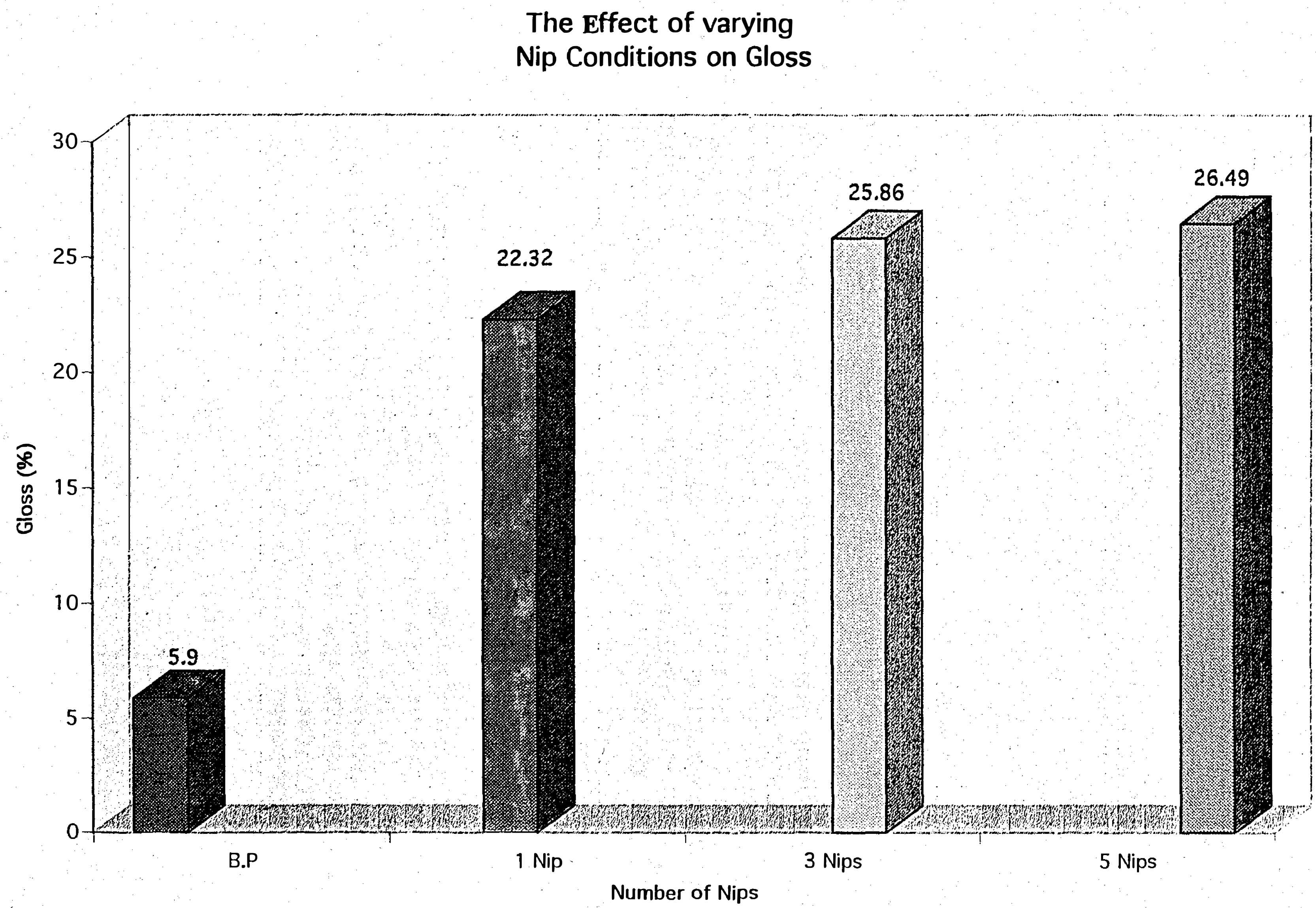

The Effect of varying Pressure on Gloss
Gloss (%)
30
25
20
15
10
5
0
5.91
22.58
24.21
27.89
B.P
500
1000
2000
Pressure (pli)

Figure 4.



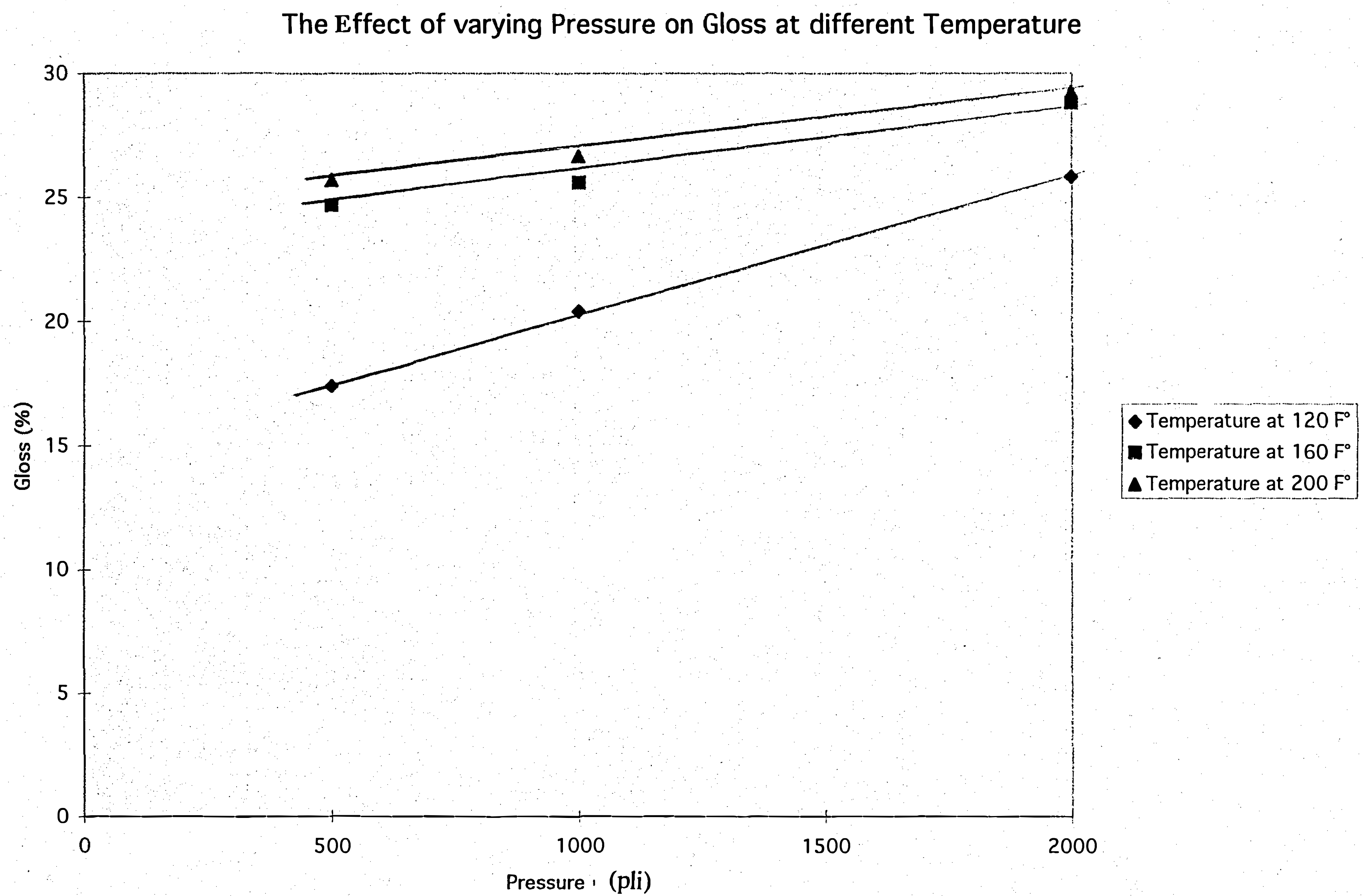
The Effect of varying Temperature on Gloss
30
25
20
15
10
5
0
Gloss (%)
5.91
21.2
26.43
27.05
B.P
120 (F°)
160 (F°)
200 (F°)
Temperature (F°)

Figure 5.



The Effect of varying
Nip Conditions on Gloss
30
25
20
15
10
5
0
Gloss (%)
5.9
22.32
25.86
26.49
B.P
1 Nip
3 Nips
5 Nips
Number of Nips

Figure 6.



The Effect of varying Pressure on Gloss at different Temperature
Gloss (%)
30
25
20
15
10
5
0
0
500
1000
1500
2000
Pressure (pli)
Temperature at 120 F°
Temperature at 160 F°
Temperature at 200 F°

Figure 7.

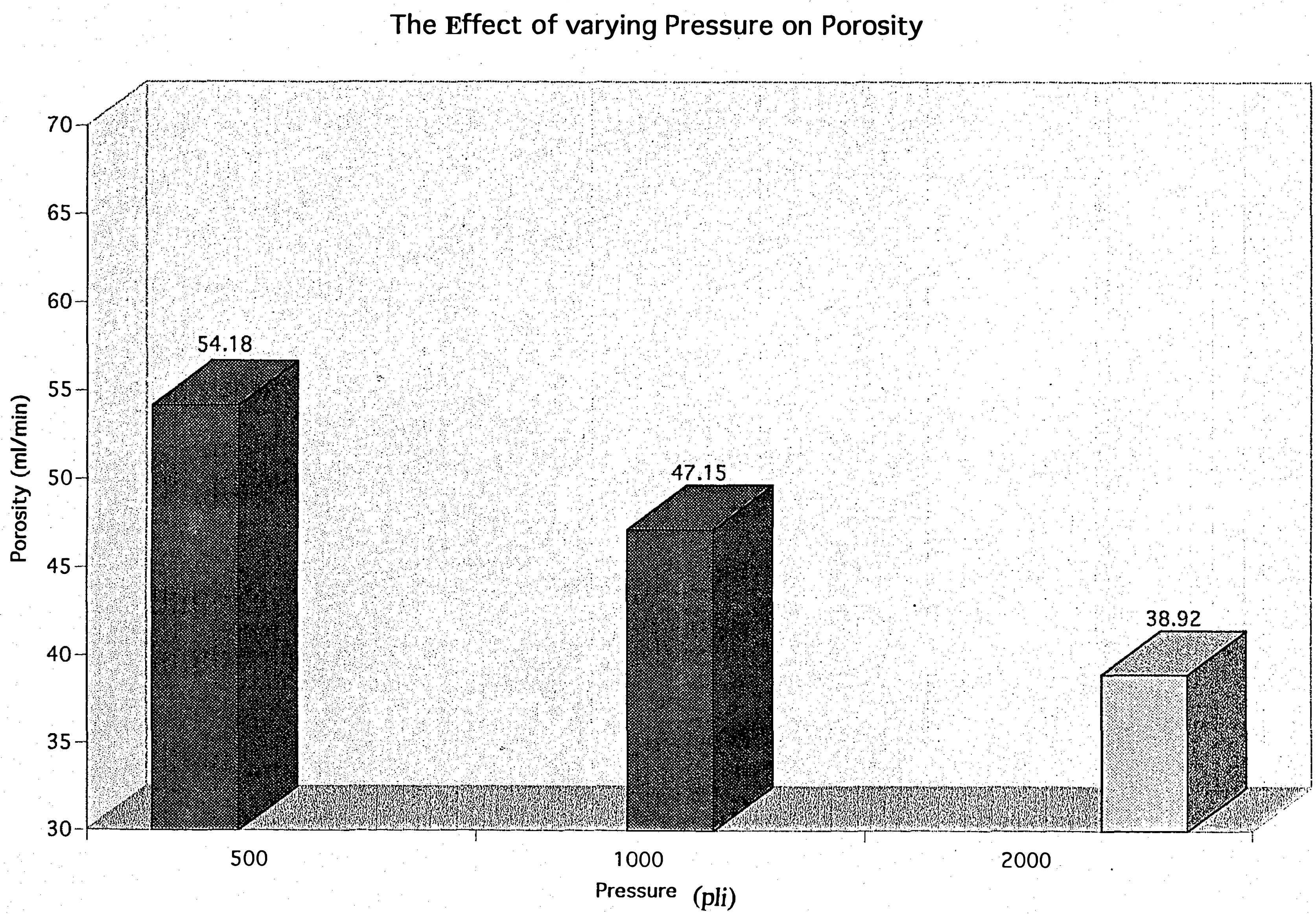

The Effect of varying Pressure on Porosity
70
65
60
55
50
45
40
35
30
Porosity (ml/min)
54.18
47.15
38.92
500
1000
2000
Pressure (pli)

Figure 8.

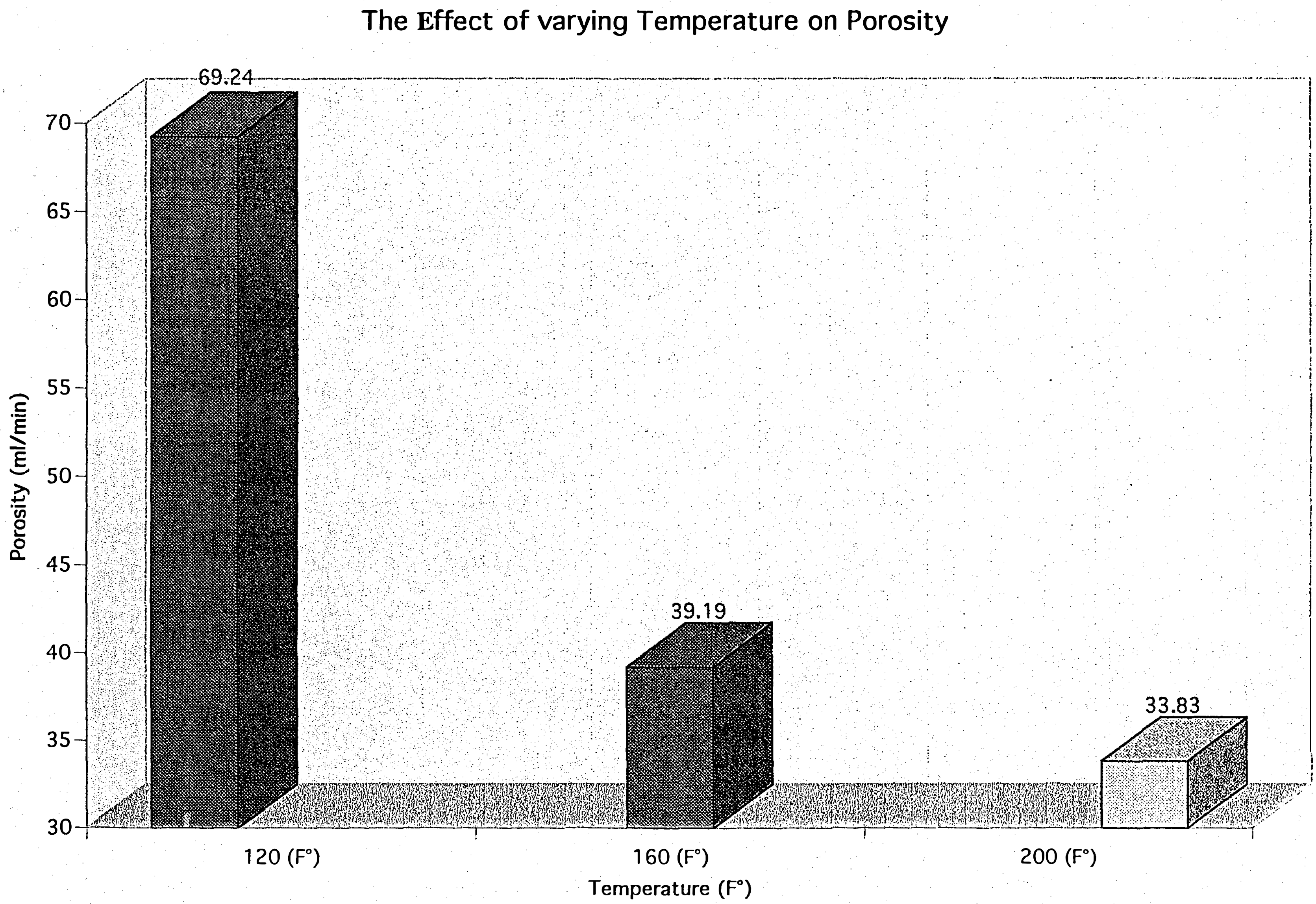

The Effect of varying Temperature on Porosity
69.24
39.19
33.83
70
65
60
55
50
45
40
35
30
Porosity (ml/min)
120 (F°)
160 (F°)
200 (F°)
Temperature (F°)

Figure 9.

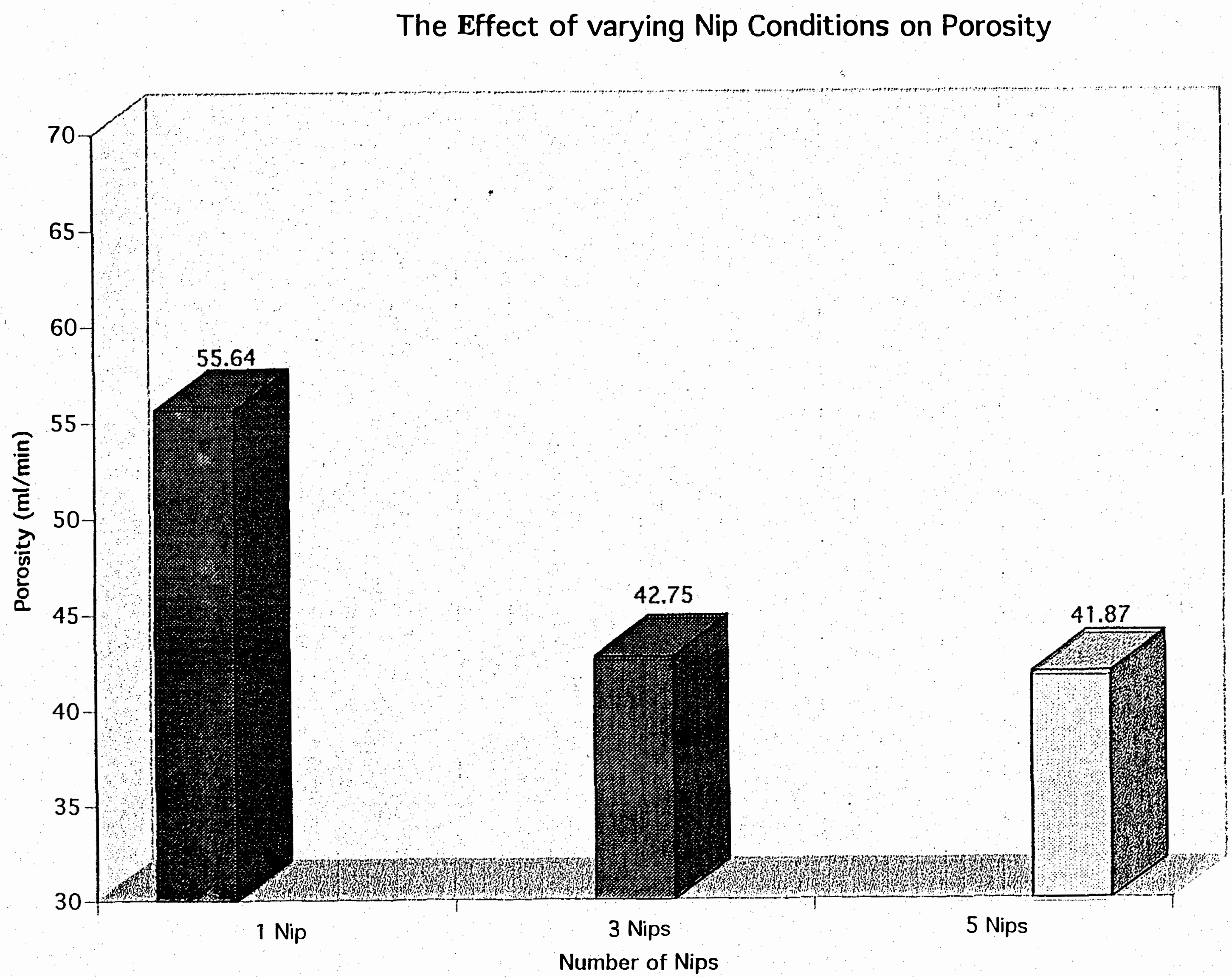
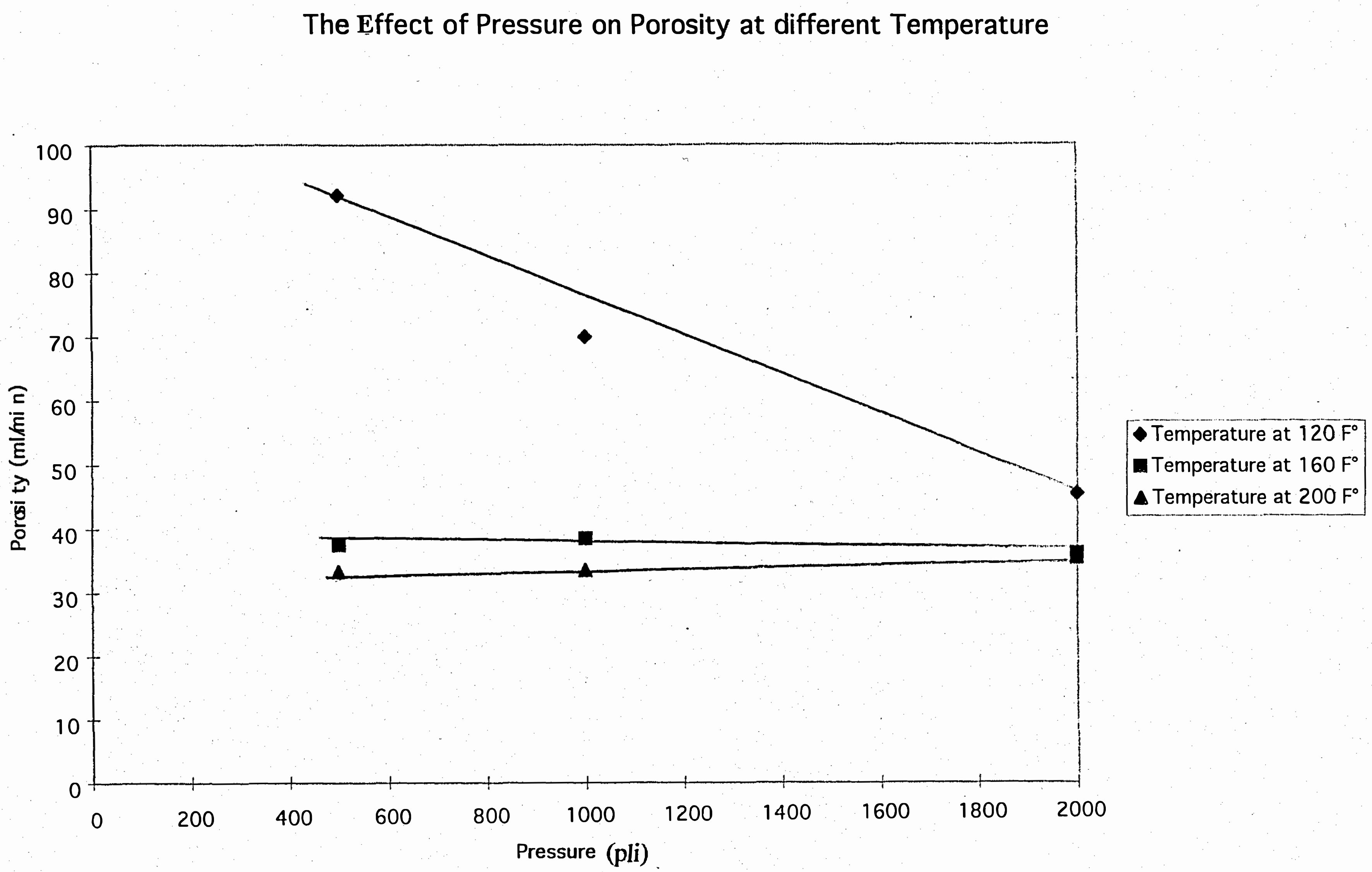

The Effect of varying Nip Conditions on Porosity
Porosity (ml/min)
70
65
60
55
50
45
40
35
30
55.64
42.75
41.87
1 Nip
3 Nips
5 Nips
Number of Nips

Figure 10.



The Effect of Pressure on Porosity at different Temperature
100
90
80
70
60
50
40
30
20
10
0
Porosity (ml/min)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Pressure (pli)
Temperature at 120 F°
Temperature at 160 F°
Temperature at 200 F°

Figure 11.

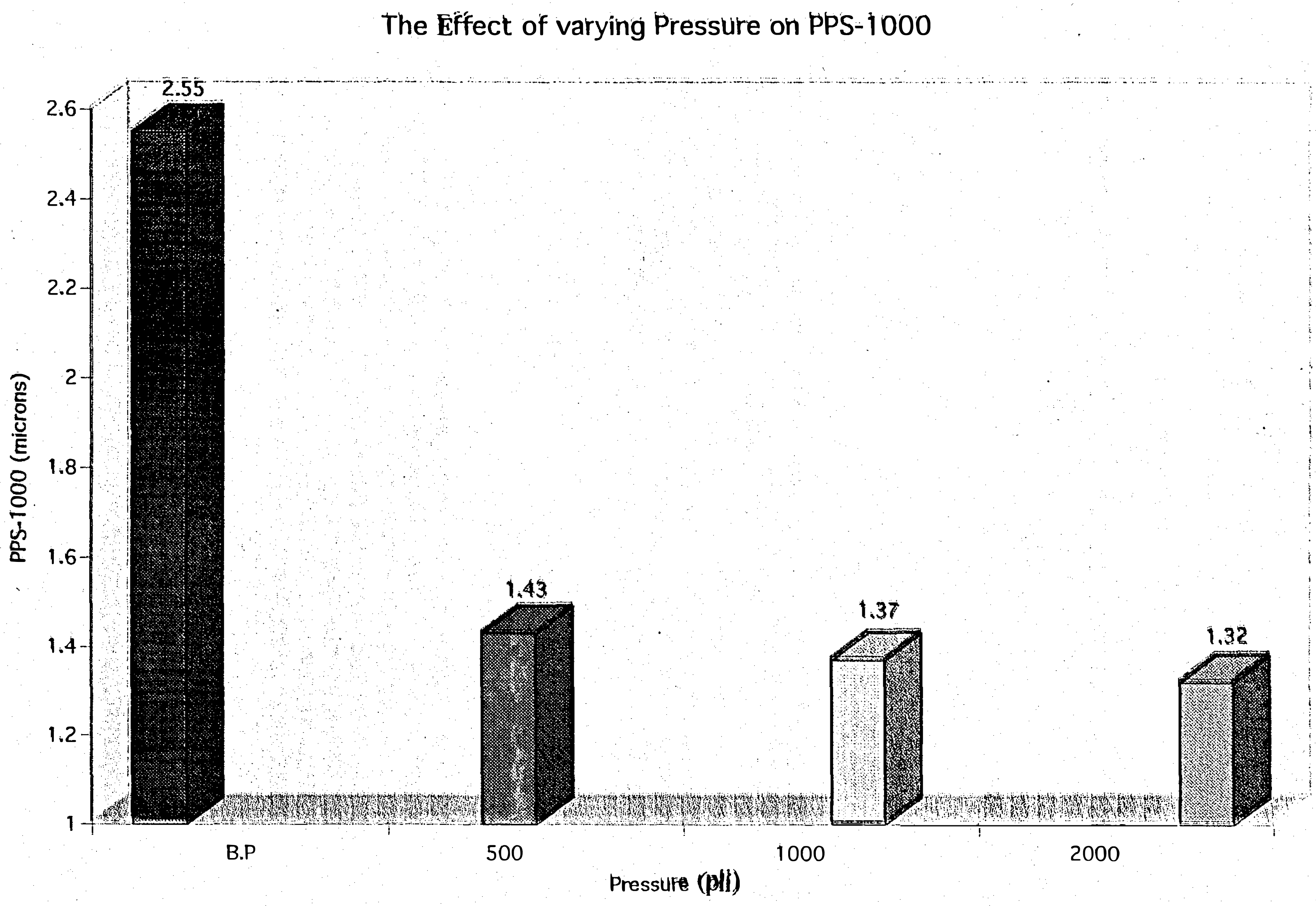
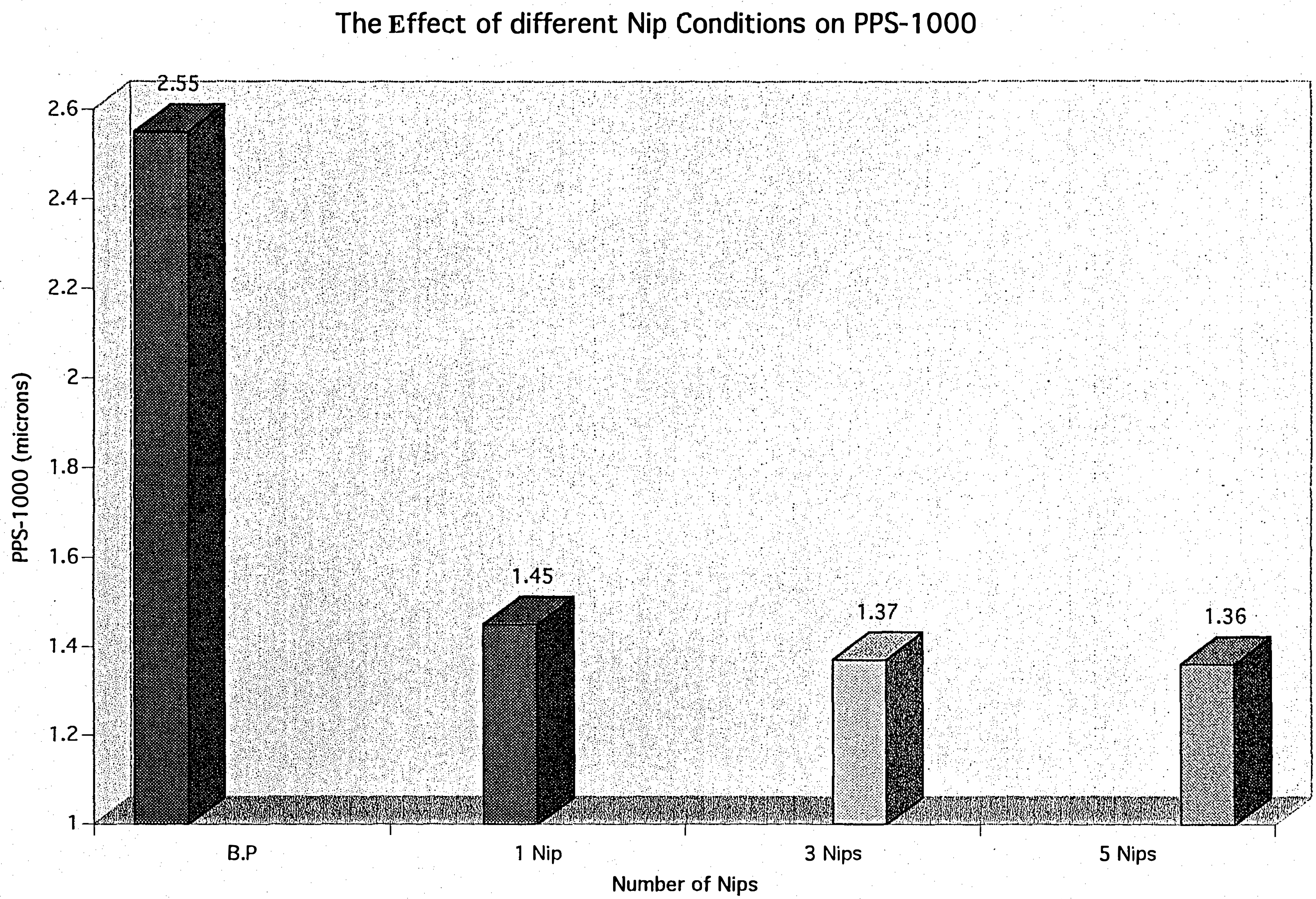
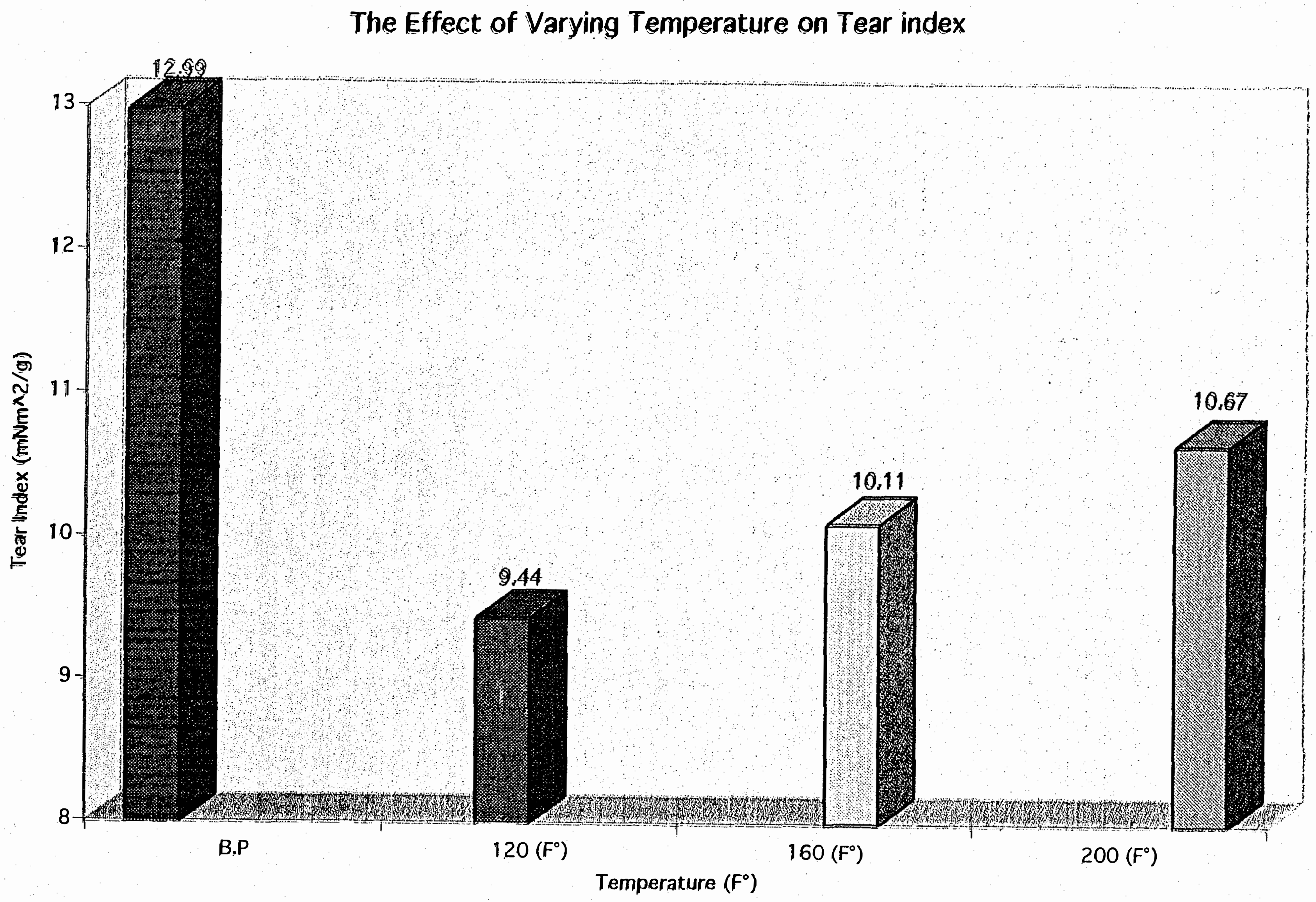

The Effect of varying Pressure on PPS-1000
PPS-1000 (microns)
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
2.55
1.43
1.37
1.32
B.P
500
1000
2000
Pressure (pli)

Figure 12.



The Effect of different Nip Conditions on PPS-1000
PPS-1000 (microns)
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
2.55
1.45
1.37
1.36
B.P
1 Nip
3 Nips
5 Nips
Number of Nips

Figure 13.


The Effect of Varying Temperature on Tear index
Tear Index (mNm^2/g)
13
12
11
10
9
8
12.99
9.44
10.11
10.67
B.P
120 (F°)
160 (F°)
200 (F°)
Temperature (F°)

## Conclusions

The optimization of the different conditions for soft-nip calendering was achieved using SAS. P-value less than 0.05 means significant values but bigger than 0.05 means nonsignificant values. According to the statistical data analysis, there are two interactions, gloss and porosity. Each condition has independent values except for these two values.

The following conclusions are made from the data analysis:

- Increasing temperature improves gloss and tear (CD) index but reduces opacity, and porosity.
- Increasing pressure improves gloss and smoothness but reduces opacity and porosity.
- Increasing number of nips improves gloss and smoothness but reduces porosity.
- Increasing both pressure and temperature improves gloss but reduces porosity.

**Recommendations**

Soft-nip calendering is a relatively new area of surface finishing. A major advantage of this study is the optimization of varying conditions of soft-nip calendering by using the statistical analyze system(SAS). Some limitations were encountered while using the pilot plant soft-nip calender machine. There are a lot of factors affecting soft-nip calendering. Three major factors, pressure, temperature, and number of nips, are applied in this study. However, other factors such as moisture content, degree of formation of paper, different furnishes in the paper, and speed of the soft-nip calender machine should be considered for further study.

This study gives a general idea of the optimizing conditions for soft-nip calendering. The results of this study could provide the guidance for further study.

**References**


1. Jay H. Vreeland, Eric R. Ellis, and Kenneth B. Jewett. , "Substrata thermal molding" Tappi 72 (7): 140 (1989).

2. Harald Hess. , "Supercalendering Uncoated Paper", Calendering and Supercalendering , TAPPI PRESS, Atlanta, p.32.

3. John D. Peel. , " Supercalendering and Soft-nip calendering compared", Tappi 44 (7) : 181 (1991).

4. Harald Hess. , "Soft Calenders-Can They Replace Supercalenders and Still Meet Technological Requirements?", Calendering and Supercalendering, TAPPI PRESS, Atlanta, p 242.

5. Harald Hess. , "Soft Calenders-Can They Replace Supercalenders and Still Meet Technological Requirements?", Calendering and Supercalendering, TAPPI PRESS, Atlanta, p 242.

6. John D. Peel. "Supercalendering and Soft-nip calendering compared", Tappi 44 (7) : 181 (1991).

7. Drier, T. , and Schuelke, T. , "Calendering of Newsprint with D.I.P" 1992 Finishing and Converting Conference p. 253-260.

8. Harald Hess. , "RESPONDING TO THE CHALLENGE TO RECYCLE PAPER CALENDERING RECYCLE PAPER GRADES", Calendering and Supercalendering, TAPPI PRESS, Atlanta, p 288.

Appendix I

Sample Calculations:

**Basis Weight:**

Area of the sample: $\pi r^2$ where r = 5 in and $\pi$ = 3.14

$\pi r^2$ = (3.14 * 25) in ^2 = 78.54 in ^2

(78.54 in ^2) * (2.54 cm/in)^2 = 506.7 cm^2

Weight of the sample: 3.632 g

Basis weight = Weight of the sample(g) / Area of the sample(m^2)

= (3.632 g/506.7 cm^2)(100 cm/m)^2

= 71.68 g/m^2

**Tear Index:**

Tear Index = Tear force / Basis weight

Average reading value for the tear force = 13

Tear Index = [(16*9.81*Ave reading value)/# of sample]/BW

= [(16*9.81*15)/3] / 71.68

= 10.94 mNm^2/g

**Tensile Energy Absorption(TEA):**

TEA = (98.07 * total energy(kgmm) / Area of the test specimen(cm^2))

Area of the test specimen: 15 cm^2

= (98.07*10.0234/15) = 65.53 J/m^2

# Raw Data from the Experiment

## Tempaeratue at 120 F°

| Sample Number | X1 | X2 | X3 | BRIGHTNESS | STDEV | OPACITY | STDEV | GLOSS | STDEV | TEA(MD) | STDEV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Unit | pli | F° | | % | | % | | % | | J/m^2 | |
| 1 | 500 | 120 | 1 | 90.91 | 0.22 | 87.22 | 0.54 | 15.61 | 0.32 | 50.95 | 0.95 |
| 4 | 1000 | 120 | 1 | 90.90 | 0.15 | 87.32 | 0.72 | 17.02 | 0.44 | 59.20 | 1.87 |
| 7 | 2000 | 120 | 1 | 90.31 | 0.13 | 86.43 | 1.13 | 21.83 | 0.71 | 70.72 | 0.65 |
| 10 | 500 | 120 | 3 | 91.79 | 0.13 | 87.68 | 0.85 | 17.50 | 2.53 | 64.73 | 1.24 |
| 13 | 1000 | 120 | 3 | 91.69 | 0.23 | 87.37 | 0.59 | 21.72 | 0.72 | 64.57 | 1.10 |
| 16 | 2000 | 120 | 3 | 89.90 | 0.10 | 84.96 | 0.72 | 27.31 | 0.54 | 64.06 | 0.80 |
| 19 | 500 | 120 | 5 | 91.74 | 0.14 | 87.89 | 0.64 | 19.00 | 0.24 | 60.71 | 0.79 |
| 22 | 1000 | 120 | 5 | 91.74 | 0.14 | 86.95 | 1.12 | 22.44 | 0.37 | 63.65 | 0.89 |
| 25 | 2000 | 120 | 5 | 91.42 | 0.11 | 86.74 | 0.49 | 28.31 | 0.49 | 66.17 | 1.23 |

| Sample Number | X1 | X2 | X3 | POROSITY | STDEV | PPS-1000 | STDEV | TEAR INDEX(CD) | STDEV |
|---|---|---|---|---|---|---|---|---|---|
| Unit | pli | F° | | ml/min | | microns | | mNm^2/g | |
| 1 | 500 | 120 | 1 | 111.7 | 6.2 | 1.45 | 0.03 | 10.36 | 0.10 |
| 4 | 1000 | 120 | 1 | 98.3 | 10.1 | 1.43 | 0.02 | 9.34 | 0.07 |
| 7 | 2000 | 120 | 1 | 55.54 | 3.24 | 1.33 | 0.02 | 9.34 | 0.12 |
| 10 | 500 | 120 | 3 | 82.54 | 5.33 | 1.40 | 0.01 | 9.49 | 0.07 |
| 13 | 1000 | 120 | 3 | 60.02 | 8.71 | 1.35 | 0.01 | 9.20 | 0.07 |
| 16 | 2000 | 120 | 3 | 42.38 | 3.6 | 1.34 | 0.02 | 9.20 | 0.08 |
| 19 | 500 | 120 | 5 | 81.81 | 5.23 | 1.39 | 0.01 | 9.34 | 0.08 |
| 22 | 1000 | 120 | 5 | 51.17 | 3.15 | 1.35 | 0.01 | 9.93 | 0.20 |
| 25 | 2000 | 120 | 5 | 39.69 | 1.78 | 1.33 | 0.01 | 8.76 | 0.08 |

# Temperature at 160 F°

| Sample Number | X1 | X2 | X3 | BRIGHTNESS | STDEV | OPACITY | STDEV | GLOSS | STDEV | POROSITY | STDEV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Unit | pli | F° | | % | | % | | % | | ml/min | |
| 2 | 500 | 160 | 1 | 90.59 | 0.11 | 87.46 | 0.41 | 21.84 | 0.71 | 43.98 | 2.9 |
| 5 | 1000 | 160 | 1 | 90.34 | 0.08 | 86.81 | 0.39 | 23.11 | 0.59 | 43.27 | 5.48 |
| 8 | 2000 | 160 | 1 | 89.97 | 0.09 | 84.53 | 0.47 | 25.47 | 0.50 | 41.4 | 1.98 |
| 11 | 500 | 160 | 3 | 90.36 | 0.07 | 86.67 | 0.76 | 26.78 | 0.40 | 33.25 | 2.28 |
| 14 | 1000 | 160 | 3 | 91.69 | 0.12 | 85.23 | 0.50 | 26.40 | 0.57 | 36.25 | 3.06 |
| 17 | 2000 | 160 | 3 | 89.60 | 0.09 | 84.65 | 0.61 | 29.94 | 0.64 | 33.75 | 2.62 |
| 20 | 500 | 160 | 5 | 90.25 | 0.13 | 86.55 | 0.66 | 25.42 | 0.49 | 35.02 | 3.19 |
| 23 | 1000 | 160 | 5 | 91.43 | 0.12 | 86.67 | 0.73 | 27.28 | 0.48 | 35.42 | 2.81 |
| 26 | 2000 | 160 | 5 | 90.57 | 0.78 | 84.19 | 1.02 | 31.67 | 0.80 | 32.36 | 2.48 |

| Sample Number | X1 | X2 | X3 | PPS-1000 | STDEV | TEAR INDEX(CD) | STDEV | TEA(MD) | STDEV |
|---|---|---|---|---|---|---|---|---|---|
| Unit | pli | F° | | microns | | mNm^2/g | | J/m^2 | |
| 2 | 500 | 160 | 1 | 1.48 | 0.01 | 10.66 | 0.13 | 60.63 | 0.52 |
| 5 | 1000 | 160 | 1 | 1.41 | 0.01 | 10.36 | 0.16 | 47.46 | 0.65 |
| 8 | 2000 | 160 | 1 | 1.31 | 0.01 | 10.07 | 0.12 | 68.80 | 1.34 |
| 11 | 500 | 160 | 3 | 1.40 | 0.01 | 10.36 | 0.07 | 53.86 | 1.21 |
| 14 | 1000 | 160 | 3 | 1.33 | 0.01 | 9.93 | 0.17 | 55.93 | 1.29 |
| 17 | 2000 | 160 | 3 | 1.32 | 0.02 | 9.34 | 0.12 | 69.93 | 0.78 |
| 20 | 500 | 160 | 5 | 1.41 | 0.01 | 10.36 | 0.07 | 50.24 | 1.09 |
| 23 | 1000 | 160 | 5 | 1.33 | 0.01 | 9.78 | 0.17 | 65.06 | 0.62 |
| 26 | 2000 | 160 | 5 | 1.31 | 0.01 | 10.07 | 0.07 | 63.88 | 0.52 |

# Temperature at 200 F°

| Sample Number | X1 | X2 | X3 | BRIGHTNESS | STDEV | OPACITY | STDEV | GLOSS | STDEV | POROSITY | STDEV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Unit | pli | F° | | % | | % | | % | | ml/min | |
| 6 | 1000 | 200 | 1 | 90.05 | 0.10 | 84.27 | 0.76 | 26.19 | 0.91 | 34.53 | 2.49 |
| 9 | 2000 | 200 | 1 | 91.26 | 0.11 | 85.11 | 0.59 | 26.08 | 1.20 | 34.45 | 2.25 |
| 12 | 500 | 200 | 3 | 90.06 | 0.10 | 84.59 | 0.75 | 25.18 | 0.88 | 30.07 | 3.35 |
| 15 | 1000 | 200 | 3 | 91.40 | 0.14 | 85.51 | 0.70 | 27.72 | 1.94 | 31.25 | 3.2 |
| 18 | 2000 | 200 | 3 | 90.65 | 0.11 | 83.43 | 0.99 | 30.20 | 0.69 | 35.24 | 2.59 |
| 21 | 500 | 200 | 5 | 90.00 | 0.14 | 84.51 | 0.66 | 28.08 | 1.56 | 31.72 | 2.52 |
| 24 | 1000 | 200 | 5 | 90.33 | 0.63 | 85.58 | 1.43 | 26.01 | 1.12 | 34.17 | 2.9 |
| 27 | 2000 | 200 | 5 | 90.74 | 0.15 | 84.04 | 0.65 | 30.19 | 0.68 | 35.51 | 2.25 |
| 27 | 2000 | 200 | 5 | 90.74 | 0.15 | 84.04 | 0.65 | 30.19 | 0.68 | | |

| Sample Number | X1 | X2 | X3 | PPS-1000 | STDEV | TEAR INDEX(CD) | STDEV | TEA(MD) | STDEV |
|---|---|---|---|---|---|---|---|---|---|
| Unit | pli | F° | | microns | | mNm^2/g | | J/m^2 | |
| 6 | 1000 | 200 | 1 | 1.45 | 0.02 | 10.80 | 0.12 | 66.33 | 0.84 |
| 9 | 2000 | 200 | 1 | 1.30 | 0.02 | 10.80 | 0.12 | 69.65 | 1.14 |
| 12 | 500 | 200 | 3 | 1.43 | 0.01 | 11.09 | 0.15 | 65.13 | 0.77 |
| 15 | 1000 | 200 | 3 | 1.36 | 0.02 | 10.80 | 0.13 | 66.55 | 1.87 |
| 18 | 2000 | 200 | 3 | 1.30 | 0.01 | 9.93 | 0.13 | 70.17 | 0.60 |
| 21 | 500 | 200 | 5 | 1.41 | 0.01 | 10.66 | 0.12 | 46.16 | 0.52 |
| 24 | 1000 | 200 | 5 | 1.35 | 0.01 | 10.51 | 0.17 | 70.74 | 0.28 |
| 27 | 2000 | 200 | 5 | 1.30 | 0.01 | 10.51 | 0.10 | 49.55 | 0.91 |
| 27 | 2000 | 200 | 5 | | | | | | |