IMPROVING QUALITY ON A NONWOVENS LINE

by

Brian Scott Platnick

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APPROVED:

C. P. Koelling, Chairman

Subhash C Sarin
Subhash Sarin

Marvin Agee
Marvin Agee

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(ABSTRACT)

This research develops and tests a methodology for improving quality on a continuous process line. A nonwovens line was chosen as the experimental environment to test this methodology. First the process variables were analyzed and classified and a screening experiment was run to determine which variables had a significant effect on the quality measures--air permeability, caliper, basis weight, and appearance--of the filter media. Then a second experiment was run to study fewer variables in more detail. The data were interpreted with ANOVA and regression models. This research makes three general contributions: a methodology for improving quality on a continuous process line, the cause-and-effect relationships between some of the independent and dependent variables, and the second-order and third-order effects show the complexity of the research environment.

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TABLE OF CONTENTS

1. Introduction 1

Research Objective 2

Overview of Experimental Environment 5

Testing the Material 7

  Basis Wt. 7

  Caliper 8

  Air Permeability 8

  Appearance 8

Nonwovens Overview 9

  Fibers 9

  Carding 10

  Parallel Laid Nonwovens 11

  Cross Laid Nonwovens 11

  Random Air Laid Nonwovens 12

  Bonding Nonwovens 12

  Finishing Processes 13

  End Use of Nonwovens 13

2. Review of Experimental Design Literature 15

3. Manufacturing Processes for 7395 Blue 20

Detailed Process Description 23

  Raw Fiber 24

Hoppers 24
Multimixer 25
Fine Opener 26
Vibrafeed 27
Feedrolls 28
Card 28
Crosslapper 30
Fehrer..31
Saturator 32
LESS Foamer 33
Latex 34
Dry Can.. 35
Calender 35
Accumulator 36
Winder 37
Menzel Slitter 37
Classification of Variables 38

4. Experimental Design Model 44
Screening Design 46
Preliminary Problems 46
Factors Examined 47
Fiber Weight 47
Saturator Speed 47
Saturator Gap 48
Compactor Roll 48

        Latex Flow 48
        Air Flow 48
        Can Speed 48
        Calender Pressure 48
    Experimental Procedures 49
    Tests for Linearity of Effects 50
    Problems During Experiment 51
    Testing/Calculations 51
    Results 55
    Summary of Screening Experiment 58
Second Experiment 59
    Factors Examined 61
    Statistical Analyses for Second Experiment 62
        ANOVA Tables 63
        Analyzing Interaction Effects 63
        Post-Hoc Comparisons 64

5. Analysis of the Results 66
CFM 66
Basis Weight 67
Caliper 69
Appearance 71
Regression Analysis 74
Summary of Second Experiment 75

6. Conclusion 76
Summary 76
Results of Research 77
Interpretation of Results 77
Critique of Methodology 80
Further Research 81

References 83

Appendix A. Screening Design 84

Appendix B. Second Experiment 98

Appendix C. Analysis of CFM 108

Appendix D. Analysis of Basis Weight 118

Appendix E. Analysis of Caliper 128

Appendix F. Analysis of Appearance 134

Appendix G. Regression Models 142

VITA 151

LIST OF TABLES

Table 1. Significant Effects From Screening Experiment .. 57

Table 2. ANOVA for CFM 68

Table 3. ANOVA for Basis Weight 70

Table 4. ANOVA for Caliper 72

Table 5. ANOVA for Appearance 73

Table 6. Summary of Results 78

LIST OF FIGURES

Figure 1. Flow Chart of Research Methodology 4

Figure 2. Schematic Drawing of Line #13 21

Figure 3. List of Variables on Line #13 42

Figure 4. Matrix for 16-run Fractional Factorial Design . 45

Figure 5. Linearity Test for Calender Pressure on CFM ... 52

Figure 6. Linearity Test for Calender Pressure on Caliper 53

Figure 7. Experimental Design Model for Second Experiment 60

Figure A-1. Values of Background Variables During Screening Design 85

Figure A-2. Results of Basis Weight Testing for Screening Design 87

Figure A-3. Results of Caliper Testing for Screening Design 88

Figure A-4. Results of CFM Testing for Screening Design . 89

Figure A-5. Results of Appearance Testing for Screening Design 90

Figure A-6. Caliper vs. Calender Pressure Linearity Testing 91

Figure A-7. CFM vs. Calender Pressure Linearity Testing . 92

Figure A-8. Factor Effects Computations for Basis Weight 93

Figure A-9. Factor Effects Computations for Caliper 94

Figure A-10. Factor Effects Computations for CFM 95

Figure A-11. Factor Effects Computations for Appearance . 96

Figure A-12. Standard Error Calculations for 16-run Fractional Factorial Design 97

Figure B-1. 3x3x2 Factorial Design 99

Figure B-2. Values of Background Variables For Second Experiment 100

Figure B-3. Random order of Treatment Combinations for Second Experiment 102

Figure B-4. Results of Basis Weight Testing for Second Experiment 103

Figure B-5. Results of Caliper Testing for Second Experiment 104

Figure B-6. Results of CFM Testing for Second Experiment 105

Figure B-7. Results of Appearance Testing for Second Experiment 106

Figure B-8. Foam Density Measurements for Second Experiment 107

Figure C-1. CFM vs. Saturator Gap at Two Levels of Fiber Weight 109

Figure C-2. CFM vs. Foam Density at Two Levels of Fiber Weight 110

Figure C-3. CFM vs. Saturator Gap at Three Levels of Foam Density 111

Figure C-4. CFM vs. Fiber Weight at Three Levels of Foam Density 112

Figure C-5. Tukey Test for CFM at Three Levels of Foam Density 113

Figure C-6. CFM vs. Fiber Weight at Three Levels of Saturator Gap 114

Figure C-7. CFM vs. Foam Density at Three Levels of Saturator Gap 115

Figure C-8. ANOVA Tables for CFM at Two Levels of Fiber Weight 116

Figure C-9. ANOVA Tables for CFM at Three Levels of Foam Density 117

Figure D-1. Basis Weight vs. Saturator Gap at Two Levels of Fiber Weight 119

Figure D-2. Basis Weight vs. Foam Density at Two Levels of Fiber Weight 120

Figure D-3. Basis Weight vs. Saturator Gap at Three Levels of Foam Density 121

Figure D-4. Basis Weight vs. Fiber Weight at Three Levels of Foam Density 122

Figure D-5. Tukey Test for Basis Weight at Three Levels of Foam Density 123

Figure D-6. Basis Weight vs. Fiber Weight at Three Levels of Saturator Gap 124

Figure D-7. Basis Weight vs. Foam Density at Three Levels of Saturator Gap 125

Figure D-8. ANOVA Tables for Basis Weight at Three Levels of Foam Density 126

Figure D-9. ANOVA Tables for Basis Weight at Two Levels of Fiber Weight 127

Figure E-1. Caliper vs. Saturator Gap at Two Levels of Fiber Weight 129

Figure E-2. Caliper vs. Foam Density at Two Levels of Fiber Weight 130

Figure E-3. Caliper vs. Fiber Weight at Three Levels of Saturator Gap 131

Figure E-4. Caliper vs. Foam Density at Three Levels of Saturator Gap 132

Figure E-5. ANOVA Tables for Caliper at Three Levels of Foam Density 133

Figure F-1. Appearance vs. Foam Density at Two Levels of Fiber Weight 135

Figure F-2. Appearance vs. Fiber Weight at Three Levels of Foam Density 136

Figure F-3. Appearance vs. Saturator Gap at Three Levels of Foam Density 137

Figure F-4. Appearance vs. Foam Density at Three Levels of Saturator Gap 138

Figure F-5. ANOVA Tables for Appearance at Two Levels of Fiber Weight 139

Figure F-6. ANOVA Tables for Appearance at Three Levels of Saturator Gap 140

Figure F-7. ANOVA Tables for Appearance at Three Levels of Foam Density 141

Figure G-1. Linear Regression Model for CFM 143

Figure G-2. Quadratic Regression Model for CFM 144

Figure G-3. Linear Regression Model for Basis Weight ... 145

Figure G-4. Quadratic Regression Model for Basis Weight 146

Figure G-5. Linear Regression Model for Caliper 147

Figure G-6. Quadratic Regression Model for Caliper 148

Figure G-7. Linear Regression Model for Appearance 149

Figure G-8. Quatratic Regression Model for Appearance .. 150

1. INTRODUCTION

In many industries, quality is measured by more than one parameter. In addition, the number of controllable variables which impact one or more of these quality measures can be very large. In these instances, technical personnel need a mechanism to affect product quality characteristics, but the relationship between controllable variables and product quality characteristics is often difficult to asses. Indeed controllable variables may interact with each other to further complicate this assesment.

In this research, a methodology is presented to assist in determining the relationships among controllable variables and quality characteristics. This methodology was applied to a nonwovens production line and evaluated as regards its effectiveness.

In this introductory section, a methodology for quality improvement and the experimental environment are discussed. Next, literature is reviewed on dry laid nonwovens and experimental design techniques. This is followed by an explanation of the machinery on the experimental production line and the associated independent variables. The experiments are then described and the results discussed. This research is concluded with a critical evaluation of the research methodology along with future research efforts into this important area of investigation.

RESEARCH OBJECTIVE

The objective of this research is to develop and test a methodology for improving quality on a continuous flow line. The overall strategy of this methodology is to develop a multivariate model, through designed experimentation and regression analysis, which equates the settings of independent variables to the quality characteristics (dependent variables) of the finished product. For example:

$f(\mathbf{x}) = a_1x_1 + a_2x_2 + \ldots + a_nx_n$

$g(\mathbf{x}) = b_1x_1 + b_2x_2 + \ldots + b_nx_n$

$h(\mathbf{x}) = c_1x_1 + c_2x_2 + \ldots + c_nx_n$

where,

$f(\mathbf{x})$, $g(\mathbf{x})$, and $h(\mathbf{x})$ are quality measures

$\mathbf{x} = x_1, x_2, \ldots, x_n$ are settings of independent variables

$a_1, \ldots, a_n; b_1, \ldots, b_n; c_1, \ldots c_n$ are parameters

Also, ANOVA is used to examine main and interaction effects of independent variables on quality characteristics.

The overall purpose of this research is to improve the quality of a product by gaining a better understanding of the cause and effect relationships between the operator controlled variables and the physical properties and appearance of the finished material. To accomplish this, an experimental environment was chosen and an experiment was designed to isolate the variables that have a significant impact on the finished material and determine how these variables affect its quality measures. The steps involved in this process are:

1) Choose dependent variables based on quality requirements of the customer.
2) Describe and analyze each stage in the production process to decide which inputs are considered fixed and which inputs are variable.
3) Document each independent variable and decide which are important and will be included in the screening design and which are secondary and will be held fixed.
4) Design a screening experiment.
5) Perform a screening experiment to determine which variables from the initial list have significant effects on the selected properties of the finished product.
6) Analyze the data from the screening design and decide how to proceed.
7) Perform a second experiment with a reduced number of variables.
8) Analyze data from the second experiment to determine which variables are significant and how they affect the selected properties of the finished product.
9) If the results are conclusive, provide operators and technical personnel with an operating guide for the product. This guide will help the operators trouble-shoot and predict the effect adjustments will have.

A flow chart of this methodology is shown in Figure 1.

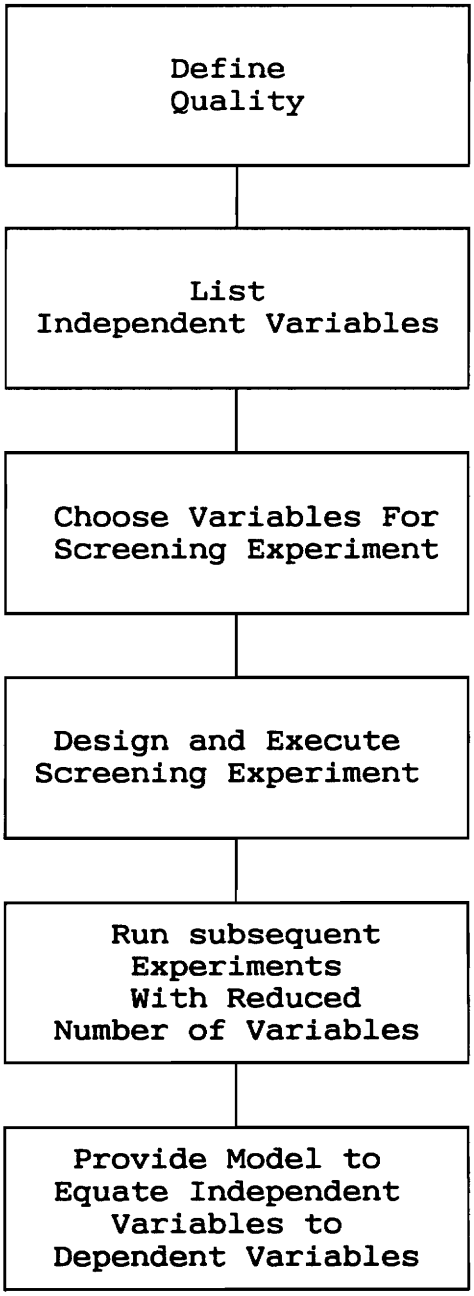

Figure 1. Flow Chart of Research Methodology

OVERVIEW OF EXPERIMENTAL ENVIRONMENT

To develop and test the quality improvement methodology, the researcher investigated the effects of certain control variables on the quality of an air filter media manufactured on a dry laid nonwovens line. This product, referred to as 7395 Blue, is manufactured on line #13 at Hollingsworth and Vose's Floyd, VA plant.

Hollingsworth and Vose produces latex bonded and thermally bonded nonwoven textiles for apparel interlinings and industrial purposes. One style which has been a problem for many years is 7395 Blue. The customer uses this product as a safety filter in an air filter for heavy duty farm and construction equipment. After receiving the 7395 Blue in roll form, the customer coats it with an oil which weighs roughly 85% as much as the original material. The coated filter is then cut into eight inch pieces and enclosed in cartridge form to be placed inside the primary air filter. It is essentially a safety filter in case the primary filter should fail.

Three physical properties must meet detailed customer specifications: thickness, basis weight, and air permeability. In addition, the material must be completely saturated with the latex binder in order to meet appearance criteria. Caliper (thickness) has a range of .044 to .054 inches with a target of .049. This is important because the customer's coating cannot be applied uniformly if there is too much variability in the caliper. The customer recently began testing the basis weight which has a specification of 80 to 88 pounds per 3000 square feet. Hollingsworth and Vose measures the basis weight in grams per square meter and has a quality standard of 128 to 145 g/m^2 (78.58 - 89.02 lbs/3000 ft^2). This specification is also important for the customer's coating process.

Historically, the most important parameter has been air permeability. It is measured in cubic feet of air which passes through one square foot of material in one minute at a pressure of .5 inches of water (CFM/ft^2 @ .5 in. H_2O). This parameter, which will be referred to as CFM, has tolerance limits of 200 and 270. In the past, the only reason shipments were rejected was due to poor CFM. The line operators at Hollingsworth and Vose would make adjustments on the line to meet the CFM without regard to caliper or finished weight because these were viewed by the customer as secondary criteria. Now, however, the customer has linked problems in their coating process to variation in caliper and basis weight. All three physical properties--CFM, caliper, and basis weight--are now considered critical. As far as appearance is concerned, the material must not have any white (unsaturated) areas, dark spots (from being squeezed too much in the saturating process) or any hard latex particles in the web.

Line operators and technical personnel at Hollingsworth & Vose have a basic understanding of cause and effect relationships on the production line. They feel they know what to do to influence one physical property at a time, but it is unknown how this adjustment will affect other properties. It is important that the line operator know what effects an adjustment will have on every physical property of the material. For instance, there may be two ways to raise CFM--one which will lower caliper and one which will raise caliper. Based on the current measure of caliper, the operator can select the appropriate adjustment.

TESTING THE MATERIAL

In this research, three physical properties (response variables) were examined: basis weight, caliper, and air permeability (CFM). In addition, the appearance of the material was considered as a fourth physical property and judged by a quality control inspector. The customer has procedures, for testing each parameter, that Hollingsworth and Vose has followed in their quality control testing procedures. The appearance of the material, however, is more subjective. White, unsaturated areas of fiber, hard latex crumbs, and dark areas in the material (saturator marks) are not acceptable. Following are summaries of the testing procedures.

BASIS WEIGHT

To measure the basis weight, a full-width (50") sample of fabric at least 12 inches in length was folded twice in the cross direction. A 9x9 inch section was die cut from the four layers and weighed on an electronic balance. The weight was measured in grams to two decimal places. This number was then multiplied by 19.136 and divided by four to convert the weight to grams per square meter.

CALIPER

To measure caliper, a strip approximately six inches wide was cut across the width. The C & R thickness gauge with a 1.129 inch diameter (one square inch) two ounce pressure foot was used to test four equally spaced points across the material. The dial reading was recorded to the third decimal in inches (whole number in mils). For simplicity, the measurements were taken from the four 9x9 basis weight samples.

AIR PERMEABILITY

The Frazier air permeability tester consists of two manometers (oil–filled pressure gauges): one for airflow, the other for water pressure. Both were zeroed before testing. After an 11 millimeter orifice was inserted, the material was clamped into position and the machine switched on. The flow control dial was turned clockwise until the manometer read 0.50 inches of water pressure. Then the airflow manometer reading was recorded and the CFM/ft^2 read from an accompanying chart. Each sample was tested in four places: once on each of the four 9x9 basis weight samples.

APPEARANCE

The appearance of 7395 Blue is another important characteristic. There is no structured method for measuring the appearance other than visual inspection. For this experiment, a scale from zero to ten was used to rate the material. Zero was recorded if the material was not saturated with latex and ten was recorded if the material was full of saturator marks and latex crumbs. Ratings of the material were scaled between these two extreme cases with five being recorded if the appearance was perfect. An experienced quality control inspector rated the material.

NONWOVENS OVERVIEW

Nonwovens is a vague term that encompasses many diverse manufacturing processes and end products. "Nonwovens are fabric–like materials consisting of a conglomeration of fibers that are bonded in some way or other" (Wagner, 1982, p. 3). 7395 Blue is a resin bonded, dry laid nonwoven used in air filters. Hollingsworth & Vose also manufactures a variety of resin and thermally bonded nonwovens used for apparel interlinings, floppy disk liners, soap wrappers, and many other purposes. The following is an overview of nonwovens, with an emphasis on the processes at Hollingsworth & Vose's Floyd Plant, taken from J. Robert Wagner's booklet Nonwoven Fabrics.

FIBERS

Most fibers used in nonwovens today are man–made. Rayon, Nylon, Polyester, and Vinyon are low in cost, require no cleaning, are uniform in their physical properties, and are readily available. Fifteen years ago Rayon accounted for 70% of the man–made fiber used in nonwovens, now Polyester has surpassed Rayon as the most widely used fiber.

CARDING

Fibrous webs can be produced by three methods--dry laid, wet laid, or spun bonded. The Floyd, VA plant manufactures dry laid nonwovens which are produced from ordinary textile cards. Wagner (1982, p.12) describes carding as "the process of opening, disentangling, or separating and straightening individual fibers, parallelizing, blending, and cleaning or extracting foreign matter and delivering the opened mass of fibers for further processing in a uniform manner." A card consists of a series of cylinders covered with a wire clothing which resembles a band saw blade. Wagner (1982, pp. 14–15) explains the carding process:

> There are two actions possible in the carding process. One is carding and the other is stripping. A carding action can occur when two adjacent card wire clothed surfaces have their wire or points inclined in opposite directions, and their metallic surface speed such that the points of one surface travels at a faster surface speed than the surface speed of the other set of points. The two surfaces may be traveling in opposite directions, the same direction or one surface may even be stationary, so long as there is a relative speed differential between the two surfaces. The action of carding serves to open, straighten and separate fibers and in the case of natural fibers, to clean foreign matter from the stock. A stripping action can occur when two adjacent card wire clothed surfaces have their wire or points inclined in the same direction. The card clothing having surface speed will remove or strip the fiber from the other surface. In so doing, it may transfer the fiber for further working or it may serve to doff the final fiber web.
>
> The feed roll of the card feeds the fiber at a controlled rate. The fiber is gripped between the feed roll and the curved portion of the feed plate which sometimes is called a nose bar. The metallic clothing of the licker–in roll, travelling at a high rate of speed, picks at individual fibers and thus separates them from other fibers and carries the fibers around to the main cylinder. The main cylinder then

picks up the fiber from the licker–in and further opening is accomplished by flats, stationary granular or metallic wire top or sets of workers and strippers operating together.

In all cases, it is the rotational direction of the rolls, the direction of the wire and the relative speeds of adjacent surfaces which determines whether there is working or stripping taking place. The working action may be either internal, that is within the opening formed by the cylinder, worker and stripper, or external, and again is dependent on rotation and wire direction. In a worker–stripper arrangement, the worker operates in close proximity to the main cylinder to provide a working action and the stripper removes the fiber from the worker and then deposits the fiber back on the main cylinder for further processing.

The settings on the card between working surfaces are between 0.18 and 0.25 mm and tend to be set further apart on the initial rolls and closer on following rolls. In this manner, the fiber is opened or separated gently with less fiber breakage occurring.

PARALLEL LAID NONWOVENS

Fibers in a parallel laid web are oriented in the machine direction and lay parallel to each other. A card can produce only a limited weight web, so cards are frequently placed in tandem with their webs produced onto a common conveyor to increase the weight and strength of the web. Parallel laid nonwovens have high machine direction strength and low cross directional strength. They are used in diaper cover stock, wiping cloths, shoe shine rags and other areas where high strength is desired in only one direction.

CROSS LAID NONWOVENS

Wagner (1982, p. 16) explains how crosslaid nonwovens are produced and discuses their end uses:

> Sometimes it is desirable to produce a carded nonwoven with less directional and more homogeneous properties. To do so, the web exiting the card is picked up by a conveyor and then gently laid down on another conveyor travelling perpendicular to the initial conveyor. The relative speed of the second conveyor in conjunction to the rate that the web is laid down in a back and forth motion, causes the web to have bi-directional fiber formation and the product that it produces is known as a cross laid nonwoven. Because the fibers are laid down in a crossed manner, the property of the product after bonding tends to be bi-directional in strength and elongation properties with an overall improvement in the average properties in all directions about an x,y plane. Some uses of cross laid nonwovens are blankets, papermaker's felts, indoor-outdoor carpeting, interlining and thermal lining, carpet underlay, automotive products, road support membranes or geotechnic fabrics, furniture padding and many other products.

RANDOM AIR LAID NONWOVENS

To produce an air laid nonwoven, fibers are carried by an air stream and collected on a screen to produce the web. Wagner (1982, p. 17) explains this process in detail:

> Because the fibers are orientated [sic] in a more random fashion in an air laid web, the tensile and elongation properties are remarkably uniform in all directions in an x,y plane. The web produced tends to have a lower density than most carded webs; that is, they are soft, lofty and porous making them especially suitable for thermal interlining, padding and air or liquid filtration.

BONDING NONWOVENS

"Once the fibers are formed into a fibrous web, it is necessary to bond the structure by some means in order to make a useful nonwoven. The various methods of bonding nonwovens can be grouped into four different basic methods. These are inherent, thermal, mechanical and chemical bonding" (Wagner, 1982, p. 28). One type of chemical binder, which is used in 7395 Blue, is epoxy resin, usually referred to as latex binder. The web is passed through nip rolls which hold a reservoir of latex foam. These rolls squeeze the binder into the web of fibers. The bonded material is then dried by an oven or dry cans.

FINISHING PROCESSES

The many finishing processes for nonwovens can be grouped into three categories – mechanical finishing, chemical finishing, and high energy finishing. One of the most common mechanical finishing processes is calendering. Calendering or pressing is used to soften the material, compress the web, and make the thickness more uniform. Some chemical finishing treatments are dying, fireproofing, and sterilization. Ethylene oxide gas (ETO) was the primary method of sterilizing nonwovens in the 1970's. However, because of physical hazards inherent in ETO, it is anticipated that radiation will supersede ETO sterilization.

END USE OF NONWOVENS

Wagner (1982, pp. 46–47) lists some of the different end uses of dry laid nonwovens by market area:

> The end use market for nonwovens can be divided into two broad types, that is

disposable and durable nonwovens. Disposable nonwovens are generally used once and at most a half dozen times, before they are discarded. Examples of disposable nonwovens are wiping cloths, filters, personal products, diapers and etc. Durable nonwovens on the other hand last for extended periods of time and maybe indefinitely. Typical examples of durable nonwovens are stiffening for cuffs or collars, interfacing, shoe uppers, book covers, wall paper and geotechnic fabrics. Interfacing may last for only a few years, whereas geotechnic fabrics for soil stabilization in road construction is an example where the life of the nonwoven is permanent.

In the United States, the consumption of nonwovens can be grouped into five different market categories. The market distribution is 45 percent in industrial, 20 percent in the household, 20 percent in the hospital, 10 percent in apparel and 5 percent in other areas.

In industrial end uses some typical end uses for nonwovens are gas and liquid filters, book covers, abrasive fabric, gowns, wipes, coating base, wrapping, tarpaulins, road support membranes and mailing envelopes.

In the household, nonwovens are used as kitchen towels, table cloths, napkins, curtains, furniture covers, carpet underlay, carpet underlay backing, air filters, tea bags, lamp shades, indoor–outdoor carpeting, carpet primary backing and artificial wash leathers and pads. In the hospital, nonwovens are used for sheets, absorbent pads and bibs, surgical dressing, gowns, hats, shoe covers, face masks, surgical sponges and many other items.

In the apparel trade, nonwovens have been used for dresses, blouses, trousers, overalls, gowns, personal products, hair nets, caps, underwear, handkerchiefs, shoe uppers, interfacing, interlining and swim suits.

2. REVIEW OF EXPERIMENTAL DESIGN LITERATURE

Designing an experiment takes careful planning and preparation so the results and subsequent decisions will be based on good information and analyses. A review of textbooks and industry literature on experimental design has brought out details on how to set up the model, collect data, and interpret the results. The most important part is setting up the model, since poorly designed experiments will result in a waste of time and money.

Dupont (1988) states the first step in planning an experiment is to list the independent and dependent variables, then choose which independent variables will be controlled as part of the experiment. Bartee (1968) explains that an experiment usually contains only one response variable, however, several responses may be measured in the same experiment with the data treated as if separate experiments were run. Bartee (1968, p. 74) continues by discussing the various ways of treating independent variables (factors) in an experiment.

> (1) The factor can be held constant and, therefore, become a part of the boundary conditions of the experiment; (2) the factor can be allowed to vary without any control and, thus, can become a part of the error in the experiment; and (3) the factor can be measured in the experiment and, thus, become a variable that is considered important in the investigation. The number of factor levels should be selected at the minimum level that will accomplish the goals of the experiment but not contribute to an excessively large experiment. If the investigator limits his

interest in a qualitative factor to a linear effect, two levels will serve very well.

One of the most popular classes of designed experiments is the factorial design. In a factorial experiment, as Juran (1988, p. 26.1) describes, several factors are controlled at two or more levels and the response variable is measured at every possible combination of the factors. Each combination of the factor levels is a "treatment combination."

Duncan (1986) and Walpole & Myers (1972) both note that a fractional factorial, which would require only 1/2, 1/4, or even 1/16 of the factor combinations, is useful when higher order interactions of factors are not important. Thus, a priori knowledge of the system can save time and money when running an experiment. Juran (1988, pp. 26.7–26.8) sums up the full factorial and fractional factorial experiments by stating that a full factorial is used to study a few variables in detail while a fractional factorial studies more variables in less detail.

Frequently, fractional factorial designs are used as "screening designs" to reduce a list of independent variables to a manageable number. Box, Hunter, & Hunter (1978) note that in the preliminary stages of an experiment, screening designs can eliminate a lot of future effort by isolating important variables early in the experimental process. Belz (1973) sees a screening design as an exploratory exercise to rapidly acquire information about important factors with the intention of running a follow–up experiment of these factors. Dupont (1988) strongly recommends a screening design to pick the important variables from a large list of possible variables with a minimum of testing effort. Box, Hunter, & Hunter (1978, p. 304) believe "as a rough general rule, not more than one quarter of the experimental effort (budget) should be invested in a first design."

A design known as a 2^k factorial design is the most popular in literature and research because of the simplicity in setting up the model and analyzing the data. Each factor is measured at only two levels, low and high, and all combinations are run. In a fractional design, only part of the treatment combinations are run. An inherent assumption in a 2^k design is linear effects of the factors. If the effects are actually quadratic, cubic, etc., a 2^k factorial design will not be sensitive to the curvature of the effects. The primary reason a factorial design is better than a "one factor at a time" analysis is all of the observations are used to supply information on each of the main effects.

The most common methodology in dealing with the data is to set up a matrix of all possible combinations with the high levels of each factor denoted by a (+) and low levels by a (–). When a factor is controlled at three levels, the middle level is denoted by a (0). Dupont (1988, pp. 21–22) mentions "a bold approach, using widely spaced (+) and (–) levels, is a hallmark of good experimental strategy. The (+) and (–) levels should be far enough apart so that the 'effects' of factor x is clearly larger than the experimental error. In control engineering terminology this guarantees a large signal–to–noise ratio."

Experimental error comes in many different forms. Equipment needs to be calibrated to avoid "accuracy error" and measurements read correctly to avoid "precision error" (Bartee, 1968). Dupont (1986) describes two other kinds of error: bias error and random error. Bias error will either remain constant over a period of time, like seasons of the year, or follow a consistent pattern over experimental runs, such as differences in machine operators. The statistical tools for dealing with bias error are randomization--collecting samples in a random order--and blocking--running the experiment in two or more separate blocks. Random error changes from one run to the next, or even from one sample to the next. The principal statistical tool for dealing with random error is replication.

Nearly every author has something to say regarding replication, however, Bartee (1968) gives the simplest and possibly the most accurate definition: replication is repeated measurements. Many experimental design professionals think of replication as repeating an experiment. It is only necessary to repeat observations, not repeat the experiment. Box, Hunter, & Hunter (1978, p. 322) suggest that it is better to add a variable and run a 2^4 factorial design than repeat a 2^3 factorial. Dupont (1988, p. 23) states that precision is increased for an experiment by increasing the number of observations. It does not matter if the number of observations is increased by replicating a design or by including additional factors. Juran (1988, 26.4) defines replication as the "repetition of an observation or measurement in order to increase precision or to provide the means for measuring precision." Though everyone has different ideas on how to replicate an experiment, they all agree on one thing: replication means repeated measurements.

After the experiment has been run, the data must be interpreted. This entails statistically comparing the high levels of a factor with the low levels. Individual factors can be interpreted as well as interactions of two or more effects, however, in a fractional experiment, many of the higher order effects are not included. This is the cost of not running all possible treatment combinations. Confounding higher order interactions should not cause a problem because, as Walpole & Myers (1972) state, the experimenter usually knows in advance that many of the interaction effects are negligible and should not be included in the model. Box, Hunter, & Hunter (1978) point out that the main effect of a factor cannot be interpreted if the factor interacts with other variables. Interacting variables must be considered jointly. Keppel (1973) explains that by plotting the data, it may be possible to interpret the main effect separate from the interaction effect.

The experimental model was developed from this information. In addition, some more specific details about experimental design will be brought out as the model and experimental results are discussed.

3. MANUFACTURING PROCESS FOR 7395 BLUE

Figure 2 is a schematic drawing of line 13, including the various manufacturing processes used to produce 7395 Blue. Following is a brief explanation of each process, the raw materials, and the finished product for each stage on the production line. A more detailed analysis of the variables at each phase will follow.

Bales of raw fiber are transferred from inventory to the production line where the fiber is manually loaded into hoppers. The Nematron computer, which is connected to the hopper weigh pans, controls the amount of each fiber type that is dumped according to a target weight input by the line operator. If one pan is overfilled or underfilled, the Nematron automatically adjusts the target weight so that over a period of several dumps, the blend will be correct. The fiber travels through suction pipes to the Multi–Mixer where it is stored in one of three chambers before it travels to the Fine Opener. The hoppers, multi–mixer, and fine opener all aid in "opening" and blending the fiber as it passes to the vibrafeed and into the card. The vibrafeed compacts the fiber into a uniform batt that is fed through feedrolls to the card. The feedroll speeds are adjusted automatically by the Servolap computer which accounts for small changes in the density of the fiber batt to ensure that the card receives a consistent mass of fiber. The card consists of many metal cylinders covered with a wire similar to saw–teeth. These rolls work the fiber to produce a parallel web which then travels up a conveyor to the

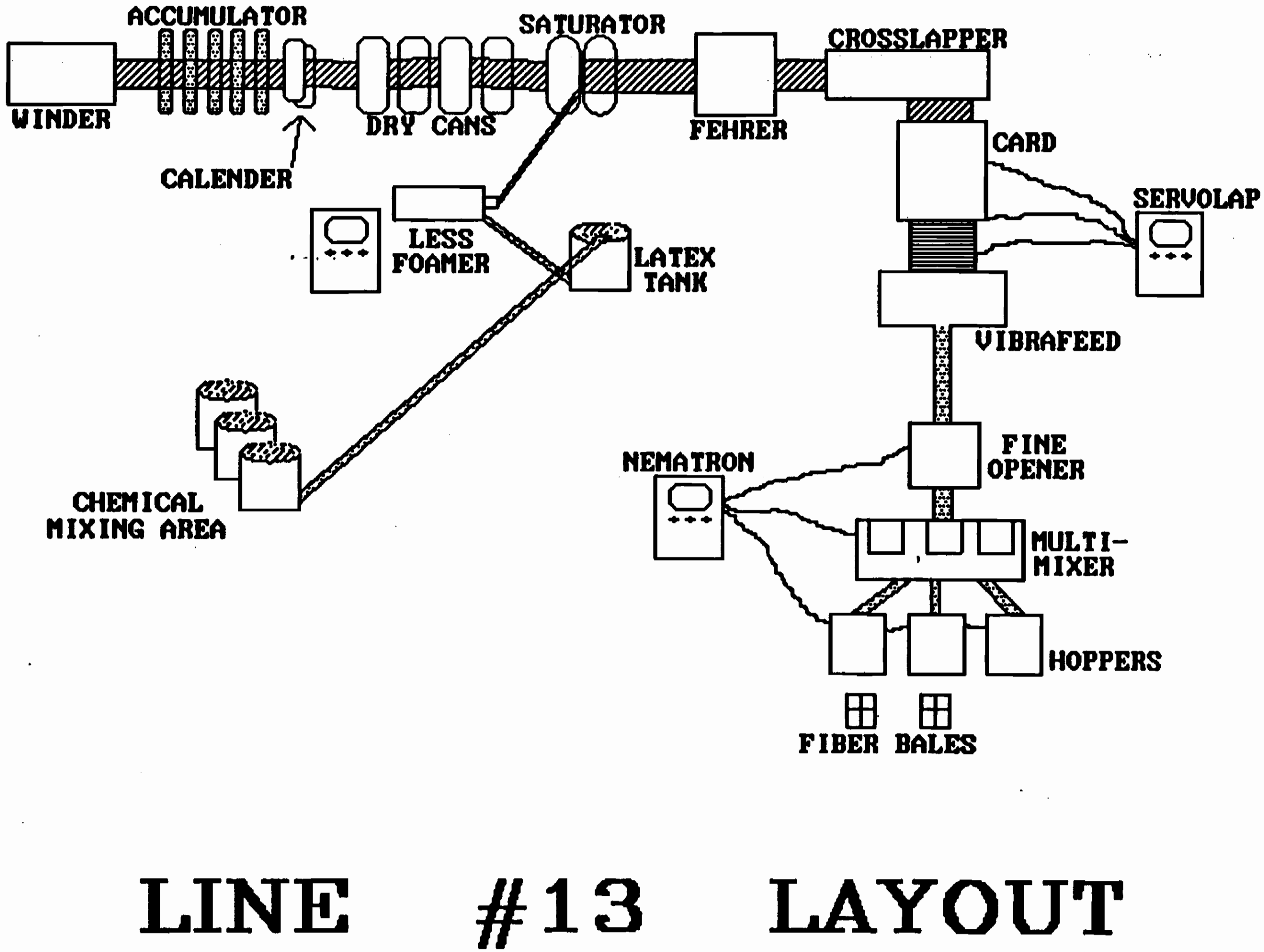

Figure 2. Schematic Drawing of Line #13

crosslapper. The crosslapper moves back and forth laying the fiber onto a belt which is oriented 90 degrees from the machine direction of the card thus changing the direction of material flow. The belt under the crosslapper moves much slowerthan the crosslapper carriage in order to produce a web which is roughly 10 layers thick. This thick web travels by conveyor to the Fehrer (a small version of a card) which works the fiber and air-lays it onto a belt so the fibers are oriented in random directions.

The web travels by conveyor and then up carrier rolls to the saturator where latex foam is applied through a transverse nozzle onto two rolls. The web is pressed through these rolls and the latex foam squeezed into the web. The web is now completely saturated with the latex binder and is in a much more stable form.

Latex is made in the chemical mixing area and pumped through a hose to the latex tank on the line. The foamer adds air to the latex to produce foam with the desired density. The LESS Foamer, like the Nematron and Servolap, is a closed-loop process. The parameters are entered and the computer makes adjustments to stay within the desired tolerances.

The web now passes through a series of drying cylinders referred to as dry cans. These cylinders are heated with steam to roughly 300 degrees Fahrenheit. The dry material may pass through calender rolls if the caliper is too high; if not, the calender is by-passed. An accumulator is used to take up slack in the line so finished product can be removed in roll form or on an A–frame (for work–in–process) at the winder.

The final product is either cut to finished size on the line or transferred by A–frame to a slitting line where it is cut to widths of 12" to 18" depending on the customer order and shipped in rolls of 500 lineal yards. The material on the production line is produced continuously, unless there is a problem, at a width of roughly 50 inches. Since the slitting operation has never been a problem for this product, it was not analyzed in this study.

DETAILED PROCESS DESCRIPTION

In this section, each process in the manufacture of 7395 Blue is discussed and the meaningful variables listed. After compiling a list of variables, each was analyzed to determine experimental treatment.

There are many complex manufacturing processes and pieces of equipment on line #13. The following will give a brief description of each step so the importance of the variables listed will be understood. In a later section, these variables are analyzed to determine which are considered unimportant and which are important. The important variables are either held constant, controlled as part of the experimental design, or uncontrolled and considered part of the error term.

RAW FIBER

Polyester fiber is taken from inventory in bale form to the hopper area. Bale straps are cut and the fiber "opens" up, allowing the temperature and humidity to match that of the room. 7395 Blue consists of two types of fiber:

40% – 3d x 1.5" Barnett Polyester

60% – 1.5d x 1.5" T54W Dacron Polyester

The "d" stands for denier which is defined as the weight, in grams, of 9,000 meters of fiber. The size in inches is the length of an individual fiber. T54W refers to the finish on the fiber and Barnett and Dacron are trade names. The fiber is also crimped so it can be carded.

VARIABLES:

Fiber length

Fiber denier

Length of time bale sits after being opened

Fiber blend percentage

Fiber type/finish

HOPPERS

Fiber is manually removed from the bales, partially broken up, and placed on the hopper feed belts. Because 7395 Blue is made up of only two fiber types, only two of the three hoppers are used--one hopper per fiber type. The belt pulls the fiber inside the hopper where a spiked apron pulls the fiber vertically and a beater roll transfers it into the weigh pan. These pans, one per hopper, are weighed by load cells which are wired to the Nematron computer. The Nematron monitors the weight of each pan dump and automatically adjusts the set points to keep the desired fiber blend. When both pans are filled to the set point, they dump simultaneously onto a belt. Fiber travels on this belt to a beater roll and then through suction pipes to the multimixer. The vertical spiked apron and beater rolls are the first stage in "opening" or pulling apart the fiber.

VARIABLES:

Speed of spiked apron

Gap between apron and beater roll

MULTIMIXER

The multimixer is a buffer between the hoppers and the rest of the line. Its primary purpose is to aid in opening and blending the various fiber types so it is especially useful for styles which contain three or four fiber types. While the multimixer consists of six independently fed chambers, fiber is taken out of all chambers simultaneously to get a better blend. The Nematron computer can be set to fill either three or six chambers, but, experience has shown three to be adequate.

The Nematron computer controls the speed that fiber is fed into and out of the multimixer. Adjustments made to the multimixer or the speed settings are maintenance actions, not operator adjustments.

VARIABLES:

Number of chambers used

FINE OPENER

Fiber travels from the multimixer through suction pipes to the fine opener where two sets of feedrolls and beater rolls continue "opening" the fiber. Sometimes during the opening process, the fiber is worked too much resulting in small balls of fiber or "neps." If neps are forming, either one or both sections of the fine opener can be by-passed. After passing through the fine opener, fiber travels through suction pipes to the traveling condenser above the vibrafeed.

VARIABLES:

Feedroll speeds

One section / both sections / by-pass

VIBRAFEED

The line 13 operator's manual (1988) describes the processes involved in the vibrafeed. A travelling condenser fan drops fiber into the feedbox, which serves as a buffer, until a limit switch is tripped. Two feedrolls then drop the fiber into a second chamber where it is grabbed by a spiked apron and delivered to the vibrating box. A doffer roll is used to comb the fiber from the spiked apron and an evener roll returns large pieces of fiber. An electric eye stops the feed when the vibrating box is full. The vibrating box compacts the fiber into a mat which travels by apron to the card. The purpose of this continuous process is to produce a consistent matt of fiber for carding.

The hoppers, multimixer, fine opener, vibrafeed, and all the suction pipes are considered the opening and blending equipment. Their function is to provide the card with blended fiber which has been worked enough to allow for carding.

VARIABLES:

- Frequency of vibration (3 gears available)
- Width of vibrating box (6 settings)
- Intensity of vibration
- Apron speed
- Beater roll speed
- Feed roll speed

Evener roll / doffer roll speed

Gap between evener roll and spiked apron

FEEDROLLS

There are feedrolls in many locations throughout the fiber opening and blending system. However, if someone refers to "the" feedrolls, he is referring to the ones that feed the mat of fiber from the vibrafeed to the card. The Servolap computer measures the density of fiber coming out of the vibrafeed and automatically adjusts the feedroll speed to ensure that the fiber weight entering the card stays uniform. The vibrafeed can deliver a fairly uniform mat of fiber, but the Servolap is able to adjust the amount which enters the card to keep the grams per square meter output from the card stable.

VARIABLES:

Calibrate density for the Servolap

Calibrate distance from Servolap measuring point to the feedrolls

Desired fiber weight out of card (g/m^2)

CARD

The card is the most important piece of equipment in producing 7395 Blue. A card consists of rollers (drums) covered with a wire clothing that has the appearance of saw–teeth. Fibers are processed through a combing action as they pass through the card. Carding occurs when two rolls, which have carding points (teeth) in opposing directions at the nip (where two rolls meet), comb the fiber as the rolls turn in opposite directions.

The card on line #13 consists of a lickerin roll, a main cylinder, doffer, worker rolls, stripper rolls, and a doffing comb. The lickerin removes excess clumps of fiber from the feedrolls. The main cylinder, the largest diameter roll in the card, carries fibers through the card and deposits them on the doffer. Workers rotate backward to "work" the fiber and get the desired web quality while stripper rolls remove the fiber from the workers and carry it back to the main cylinder. The doffer, which removes the fibers from the card, plays a significant role in web appearance, and therefore its speed is very important. The doffing comb "combs" the fibers from the doffer and the fibers continue in web form to the crosslapper.

VARIABLES:

Worker speed
Stripper speed
Doffer speed
Main cylinder speed
Doffing comb angle
Comb frequency

Gap between each nip point

Clothing wire type (tooth configuration for each individual roll)

- Front angle of teeth
- Back angle of teeth
- Tooth height
- Overall wire height

CROSSLAPPER

The crosslapper's function is to build up web weight, loft, and add cross-directional strength. Two endless conveyor belts layer the web onto a floor apron than runs 90 degrees to the machine direction of the card. This floor apron runs much slower than the crosslapper resulting in a thick, layered web of fibers. The direction of this crosslaid web is at a right angle from the direction that the parallel web travelled through the card and crosslapper.

The line 13 operator's manual (1988) describes some of the important settings on the crosslapper. The operator sets the pitch (distance the floor apron travels while the web make one complete lap) and adjusts the width. There are two separate adjustments for the width, the Traverse which sets the overall width and the Axis which is used to center the web on the apron.

VARIABLES:

Pitch (web width/# of layers)

Width of web

Axis (center point of web on belt)

Delivery apron speed; outlet apron speed

Up/down setting on outlet apron

FEHRER

The fehrer is basically a small card with only two sets of workers and strippers and a main cylinder. The web from the crosslapper travels up an apron to a set of feedrolls at the fehrer inlet. After passing through the system, fibers are doffed by an air stream from the transversal blower onto a moving wire screen running over a suction system. A cleaning roll keeps the screen clean from fiber build-up. Fibers are oriented in the parallel direction when coming off the card and cross-directional after the crosslapper. The fehrer breaks apart the web and individual fibers are air-laid onto the screen randomly oriented in the x and y planes with a very small portion in the z plane (Wagner, 1982). The random orientation of the fibers produces a low density web that is soft, lofty, and porous, making it especially useful for air filtration.

VARIABLES:

Transversal blower speed

Main cylinder speed

Worker/stripper speed

Inlet conveyor speed; outlet conveyor speed

2–stage suction system (one or both stages)

Wire on rolls (angle, teeth, etc. like card)

SATURATOR

Before reaching the saturator, the web travels down a triangle apron from the fehrer outlet and onto a floor apron. From the floor apron, the web travels up carrier rolls to the saturator.

The saturator consists of two rolls, one smooth and one knurled, which hold a reservoir of foamed latex binder. The foam is pumped from the "LESS" foamer through a hose and out a transverse nozzle. The web of fiber passes through the reservoir while the rolls squeeze the latex into it. The web is more stable once the binder has been applied and it will have even more stability once the latex is dried and cured.

VARIABLES:

Saturator speed

Triangle apron speed

Floor apron speed

Carrier roll speed

Transverse nozzle speed

Saturator Gap

Compactor roll (yes/no)

LESS FOAMER

The LESS foamer is a computer controlled machine that controls the density (air/latex ratio) of the latex foam and the mass flow output to the saturator. The operator enters the setpoints and the foamer automatically makes adjustments to keep the density and flow of the latex at the desired level. In general, a foamer consists of a pump and a rotor. The pump sends latex to the rotor where it is converted to foam by adding air. A soap dispenser must be kept full to lubricate the rotor. On most foamers, the latex/air ratio and the flow are controlled manually, however the LESS foamer continually adjusts these inputs to maintain the desired set points.

VARIABLES:

Foam density setpoint

Output flow setpoint

Reservoir height

Humidity of air entering rotor

NOTE: When a manually controlled foamer is used, the variables are:

- Air flow
- Latex flow
- Rotor speed

LATEX

Latex is used as a chemical binder to give strength to the web of fibers. 7395 Blue is composed of 60% -70% fiber and 30% - 40% latex binder by weight. The latex mixture is prepared in the chemical mix area and pumped into a tank near the saturator. A different latex formulation, made up of many ingredients, is used for each product. Each batch of latex produced for 7395 Blue will be slightly different, so adjustments are frequently necessary after a new batch is pumped to the line.

VARIABLES:

- Quantity of each ingredient
- Mixing time
- Quantity of water in latex (% solids)
- Variation in individual ingredients

DRY CANS

The dry cans are a series of drums or cylinders, heated by steam, which dry and cure the latex as the saturated material winds through them. Each of the two sets of cans are controlled by a single chain so their speeds are basically uniform within each set. The first set contains 19 cans and the second set contains 10 cans. Above the first set of dry cans are nine infrared heaters which can be turned on and off individually. There are also three separate steam pressure valves on the first set which control four, eight, and seven cans respectively. The group of four cans--the first four after the saturator--are the most important in the drying and curing process. The second set of cans has only one steam pressure gauge.

VARIABLES:

Infrared heaters (on/off)
Speed of cans
Steam pressure on cans (four groups)

CALENDER

There are many places on the line where the web can be calendered (pressed). The primary calender has an adjustment to set the desired pressure in pounds per lineal inch. This calender is usually by-passed for 7395 Blue, but the operator sometimes uses it if the caliper is high. If only a small amount of calendering is required, either the pressure is turned down very low, the web is run through a smaller calender, or the web is only run through a set of nip rolls.

VARIABLES:

Calender speed

Calender pressure

Selection of calender (large/small/nip rolls)

ACCUMULATOR

The accumulator consists of two sets of rolls –an upper set and a lower set with the web threaded between them. When the winder is stopped, the distance between the two sets of rolls increases to take up slack in the line. This allows the process to continue until the winder is restarted. On some light weight styles, weights are placed on the top rolls of the accumulator to avoid stretching the web. 7395 Blue is one of the heavier styles produced on line 13, so stretching is not usually a problem at this stage of the process.

VARIABLES:

Accumulator outfeed speed

Nip roll (open/closed)

Amount of counter weight placed on accumulator

WINDER

Two winders can be used on line #13. One for finished rolls and one for work-in-process material stored on A-frames. 7395 Blue is usually rolled onto an A-frame and taken to the Menzel Slitter (line 81) to be cut into 500 yard rolls in widths of about 12 to 18 inches. Roughly 1500 yards of material can be rolled onto an A-frame at a width of up to 52 inches.

VARIABLES:

- Tension during winding
- Winder speed
- A-frame/finished rolls
- Width on A-frame/finished rolls

MENZEL SLITTER

The Menzel slitter is used to cut material from A-frames into 500 yard finished rolls with a width of 11.91, 13.91, 15.91, or 17.91 inches depending on the customer order. Material is unwound from the A-frame, passed over a few rolls to even the material out, and slit to the required width. Finished material is rolled onto 3" diameter cores and packed for shipment.

VARIABLES:

- Line speed
- Actual Width
- Tension on finished roll
- Slitter blade speed

CLASSIFICATION OF VARIABLES

One of the most important steps in designing an experiment is deciding which variables to include. Each variable in the process must be defined and analyzed so the experimenter will be aware of the variables which are excluded from the design to aid further investigations. The process description contains 79 variables and could be increased considerably if each worker, stripper, dry can, etc. were considered separately. However, the task at hand was to reduce this list to those variables which are most important by interviewing line operators, maintenance personnel, and technical personnel. The variables were divided into three functional groups: fiber, latex, and finishing process.

The fiber blending system has never been a problem on line 13. In fact, this line has more opening and blending equipment than any other production line in the plant. The only variable dealing with fiber which was included in the experiment was the weight in grams per meter of the web coming off the card's doffer roll. This weight is controlled by the Servolap computer. The same generalization can be made for the crosslapper and fehrer. Everything from the fiber bales to the fehrer has one purpose: to produce a uniform web of opened, blended fibers. Studies in the past have shown the web to be consistent when the Servolap is working properly. Within a normal operating range, opening and blending equipment have little affect on the final product, thus they were not included in the experiment. The Servolap measures fiber batt density and controls the amount of fiber which enters the card. By adjusting the Servolap's setpoint, the basis weight of the web is adjusted. Therefore, the only variable in the fiber system that was included in the experiment was the desired fiber weight out of card (fiber weight).

The types of wire clothing used in the card and fehrer are fixed because of the time and cost involved to rewire a card. Line 13 runs many different styles; some are very light in weight, others like 7395 Blue are very heavy. The card and fehrer are not wired for any particular style, but to run many diverse styles, therefore, all of the settings dealing with the card and fehrer were held fixed.

The most critical part in the manufacture of 7395 Blue is the latex saturation process. Variables involving latex and the saturator are very important. The saturator speed--the surface velocity of the saturator roll--and the saturator gap--the distance between the two saturator rolls--were included in the experiment. Thickness of the web entering the saturator can also play a part in the saturation process. Sometimes the operator places a roll on top of the web between the floor apron and carrier rolls to compact the web of fibers, therefore, compactor roll (yes/no) was included. The foam density setpoint and the output flow setpoint are controlled by the Less Foamer. These two variables refer to the air/latex ratio of the foam and the actual amount of latex pumped to the saturator. Since the LESS foamer was not working during the experiment, the air flow and latex flow were used in place of the foam density setpoint and the output flow setpoint. Enough latex was prepared initially to last throughout the study, therefore, variation in ingredients, mixing time, etc. was not considered.

From beginning to end, line 13 has many speed controls; the speeds of the card, vibrafeed, crosslapper, fehrer, and their belts and conveyors must be synchronized to produce a uniform web. Speeds during and after saturation can be varied to alter physical properties of the material without causing damage as it would to an unbonded web of fibers. Dry can speed (relative to saturator speed) can be adjusted to stretch the material or reduce the draw. The dry can speed and the saturator speed are the most sensitive, as stretching has a greater impact on wet material than dry material. Speeds after drying were set to avoid excessive tension and not varied during the experiment.

Only one variable dealing with finishing processes was included in the screening design--calender pressure. The material can be pressed at different points in the line by any of the many sets of nip rolls (two rolls which press the material) and three different calender rolls. For simplicity, only one was included; namely, the primary calender roll was used to show the effects of pressing the material. It is assumed that calendering has the same effect no matter where it is performed; the difference depends upon the amount of pressure applied. From the original list of 79 variables, eight were chosen for inclusion in the screening design. They are:

Desired fiber weight out of card (fiber weight)
Saturator speed
Saturator gap
Compactor roll yes/no
Latex flow
Air flow
Speed of cans
Calender pressure

Most of the other variables were held constant during the screening design. Some variables were constant during the experiment, such as the wire type on a given roll. Other variables, such as the doffer speed, have a setpoint and were considered constant though they may fluctuate somewhat. Randomizing the order of treatment combinations alleviated this problem. The variables listed in Figure 3 have one of four designations:

Independent Variable – part of the experiment

Constant – truly constant during the experiment

Setpoint – considered constant

After Sampling – after point where sample is taken

VARIABLES ON LINE 13

AREA	VARIABLE	CLASSIFICATION	VALUE
Raw fiber	Fiber length	SETPOINT	
	Fiber denier	SETPOINT	
	Length of time bale sits after being opened	CONSTANT	
	Fiber blend percentage	SETPOINT	
	Fiber type/finish	CONSTANT	
Hoppers	Speed of spiked apron	SETPOINT	
	Gap between apron and beater roll	CONSTANT	
Multimixer	Number of chambers used	CONSTANT	
Fine opener	Feedroll speeds	SETPOINT	
	One section / both sections/ by-pass	CONSTANT	
Vibrafeed	Frequency of vibration (3 gears available)	SETPOINT	
	Width of vibrating box (6 settings)	SETPOINT	
	Intensity of vibration	SETPOINT	
	Apron speed	SETPOINT	
	Beater roll speed	SETPOINT	
	Feedroll speed	SETPOINT	
	Evener roll/doffer roll speed	SETPOINT	
	Gap between evener roll and spiked apron	CONSTANT	
Feedrolls	Calibrate density for the Servolap	CONSTANT	
	Calibrate distance from Servolap measuring point to the feedrolls	CONSTANT	
	Desired fiber weight out of card (g/m^2)	IND. VARIABLE	
Card	Worker speed	SETPOINT	
	Stripper speed	SETPOINT	
	Doffer speed	SETPOINT	
	Main cylinder speed	SETPOINT	
	Doffing comb angle	CONSTANT	
	Comb frequency	CONSTANT	
	Gap between each nip point	CONSTANT	
	Clothing wire type	CONSTANT	
	(tooth configuration for each individual roll)	CONSTANT	
	Front angle of teeth	CONSTANT	
	Back angle of teeth	CONSTANT	
	Tooth height	CONSTANT	
	Overall wire height	CONSTANT	
Crosslapper	Pitch (web width/# of layers)	CONSTANT	
	Width of web	SETPOINT	
	Axis (center point of web on belt)	SETPOINT	
	Delivery apron speed	SETPOINT	
	Outlet apron speed	SETPOINT	
	Up/down setting on outlet apron	CONSTANT	

Figure 3. List of Variables on Line #13

Fehrer	Transversal blower speed	SETPOINT	
	Main cylinder speed	SETPOINT	
	Worker/stripper speed	SETPOINT	
	Inlet conveyor speed	SETPOINT	
	Outlet conveyor speed	SETPOINT	
	2-stage suction system (one/two stages)	CONSTANT	
	Wire on rolls (angle, teeth, etc. like card)	CONSTANT	
Saturator	Saturator speed	IND. VARIABLE	
	Triangle apron speed	SETPOINT	
	Floor apron speed	SETPOINT	
	Carrier roll speed	SETPOINT	
	Transverse nozzle speed	SETPOINT	
	Saturator gap	IND. VARIABLE	
	Compactor roll on carrier rolls (yes/no)	IND. VARIABLE	
Less Foamer	Foam density setpoint	IND. VARIABLE	
	Output flow setpoint	IND. VARIABLE	
	Reservoir height	SETPOINT	
	Humidity of air entering rotor	CONSTANT	
Latex	Quantity of each ingredient	CONSTANT	
	Mixing time	CONSTANT	
	Quantity of water in latex (% solids)	CONSTANT	
	Variation in individual ingredients	CONSTANT	
Dry cans	Infrared heaters (on/off)	CONSTANT	
	Speed of cans (relative to saturator)	IND. VARIABLE	
	Steam pressure on cans	SETPOINT	
Calender	Calender speed	SETPOINT	
	Calender pressure	IND. VARIABLE	
	Selection of calender (large/small/cooling rolls)	CONSTANT	
Accumulator	Accumulator outfeed speed	SETPOINT	
	Nip roll (open/closed)	CONSTANT	
	Amount of counter weight on accumulator	CONSTANT	
Winder	Tension during winding	AFTER	
	Winder speed	AFTER	
	A-frame/finished rolls	AFTER	
	Width on A-frame/finished rolls	AFTER	
Menzel slitter	Line speed	AFTER	
	Actual width	AFTER	
	Tension on finished roll	AFTER	
	Slitter blade speed	AFTER	

Figure 3. (Continued)

4. EXPERIMENTAL DESIGN MODEL

One of the first decisions made was whether to use a fixed model, random model, or mixed model. A fixed model is one where the levels of each factor are selected arbitrarily and systematically. A random model is one in which any outcome in the population has an equal chance for each of the factors. A mixed model includes both fixed factors and random factors. For this experiment, a fixed model was used.

It was assumed that the factors being studied have linear effects on the response variables. During the first experiment, one factor--calender pressure--was measured at several different levels to test this assumption on CFM and caliper; the calender was not expected to have an effect on basis weight. All the factors were controlled within the normal operating range of line #13. The first experiment used to study 7395 Blue was, as suggested by the literature, a screening design. A 16-run fractional factorial, recommended by Dupont (1988) for an experiment with six, seven, or eight factors, was used for the screening design. Figure 4 shows the table used to collect and analyze the data, where x(1) through x(8) are the factors with no interaction effects and E(1) through E(7) represent the various interaction effects between the variables which were pooled as the error term. Belz (1973) and Dupont (1988) both suggest that the experimenter use his prior knowledge of the system to relegate some of the effects to residual effects. Also, if only six or seven factors were studied, the additional x-columns would be

FACTOR EFFECT COMPUTATIONS
16–RUN FRACTIONAL FACTORIAL

SCREENING DESIGN

VARIABLE: ________________

TRIAL	MEAN	X(1)	X(2)	X(3)	X(4)	X(5)	X(6)	X(7)	X(8)	E(1)	E(2)	E(3)	E(4)	E(5)	E(6)	E(7)	RESPONSE
1	+	−	−	−	+	+	+	−	+	+	+	−	−	−	+	−	
2	+	+	−	−	−	−	+	+	+	−	−	−	−	+	+	+	
3	+	−	+	−	−	+	−	+	+	−	+	+	−	+	−	−	
4	+	+	+	−	+	−	−	−	+	+	−	+	−	−	−	+	
5	+	−	−	+	+	−	−	+	+	+	−	−	+	+	−	−	
6	+	+	−	+	−	+	−	−	+	−	+	−	+	−	−	+	
7	+	−	+	+	−	−	+	−	+	−	−	+	+	−	+	−	
8	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	
9	+	+	+	+	−	−	−	+	−	+	+	−	−	−	+	−	
10	+	−	+	+	+	+	−	−	−	−	−	−	−	+	+	+	
11	+	+	−	+	+	−	+	−	−	−	+	+	−	+	−	−	
12	+	−	−	+	−	+	+	+	−	+	−	+	−	−	−	+	
13	+	+	+	−	−	+	+	−	−	+	−	−	+	+	−	−	
14	+	−	+	−	+	−	+	+	−	−	+	−	+	−	−	+	
15	+	+	−	−	+	+	−	+	−	−	−	+	+	−	+	−	
16	+	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	
SUM +																	
SUM -																	
CHECK																	
DIFF.																	
EFFECT																	
LCL																	
UCL																	

Figure 4. Matrix for 16–run Fractional Factorial

included with the residual error.

SCREENING DESIGN

On Tuesday, Jan. 22, 1991, the screening experiment for 7395 Blue was run. Enough raw materials were procured to last for the duration of the experiment. One batch of latex and the same bales of fiber were used throughout to avoid any error due to changing raw materials. The order of treatment combinations was randomly chosen by computer. Before the experiment began, factor levels were chosen for all eight independent variables and a small experiment was run to test for linearity of one of the variables--calender pressure--on CFM and caliper. At the beginning of the experiment, all of the background variables that were not fixed over the long run were documented in Figure A-1. Overall the experiment went well with only a few minor problems.

PRELIMINARY PROBLEMS

Two automated process control systems--the LESS Foamer and the Servolap--were not functioning properly. In place of the LESS Foamer, the Campen Foamer was used. This is a manually controlled latex foamer which works much like the LESS. The two primary variables on the Campen foamer, air flow and latex flow, are both controlled by the operator. The Servolap system was operational in manual, but not in automatic. In manual, the operator controls the feedroll speed which is in percent of available output.

Running the Servolap in manual and using a manual foamer are not major problems. The main drawback is that increased variance in the physical properties of the final product would be expected. Line #13 is the only line in the plant with this type of equipment; all of the other lines have manual foamers and feedrolls.

FACTORS EXAMINED

Eight factors were included in the screening design: Fiber wt., Saturator speed, Saturator gap, Compactor roll, Latex flow, Air flow, Can speed, and Calender pressure. By using previous technical information for 7395 Blue and interviewing line #13 operators, high and low limits were chosen for each factor. Following are discussions of each factor and their high/low setpoints.

Fiber weight. This is a setpoint on the Servolap Computer. Inautomatic, the Servolap would make small adjustments to the feedroll speeds to account for variation in the fiber batt, thus reducing the variation in the fiber web weight. In manual this setting is the feedroll speed in percent output. The high and low setpoints were 45% and 35%.

Saturator Speed. This is the difference in yards per minute between the carrier roll speed and the saturator speed. The high and low setpoints were 1.2 and .5 yds/min. Running faster would damage the web, while a slower speed would prevent the fiber from entering the saturator uniformly.

Saturator gap. The gap between the two saturator rolls was not precisely measured. The low point was the maximum the rolls could be apart and still saturate the web with latex. The high point was the tightest the saturator could be without breaking the material. These two points were recorded on the wheels which open and close the saturator. They were four complete turns apart.

Compactor roll. A roll on the conveyor just before the carrier rolls was the high setpoint. No roll was the low setpoint.

Latex flow. The high and low setpoints on the Campen Foamer latex pump were 47% and 43%. Any lower would cause the latex reservoir in the saturator to get too low while a higher setpoint would cause an overflow of latex.

Air flow. The setpoints for the air on the Campen Foamer were 26% and 20%. Acceptable latex foam could not be produced at more extreme settings.

Can speed. This represented the difference between the saturator speed and the dry can speed in yards per minute. The operator felt that 1.5 and 0.5 would be acceptable, but extreme limits.

Calender pressure. The finishing calender on line #13 will provide uniform calendering at a pressure of 500 psi or more. The high point for calendering was set at 500 psi and the low point at 0 psi (uncalendered). Experience has shown that calendering has a great impact on caliper, therefore, 500 psi should be plenty of pressure to show any effects. Although 7395 Blue is not calendered, it could be in the future, therefore, this variable was included to see how it affected the final product.

EXPERIMENTAL PROCEDURES

Accuracy of the test data is very important. Since the experiment was run on a continuous flow process, collecting many samples at each factor combination did not require much additional effort. This replication provided much more accurate information than single sampling. Before beginning the experiment, the line was started and allowed to run for a 30 – 40 minutes to ensure that everything was in proper working order. All the measurable background variables were recorded in Figure A–1 so they can be duplicated in subsequent experiments. Many of the variables included in this list were not easily measurable and although theoretically variables are in practice constant. Therefore, not all of the variables have values listed. Each factor was set to either its high or low point according to the randomized matrix. When the setpoints were changed to a new treatment combination, the line was allowed to run for 10 to 15 minutes before sampling to ensure that the changes took effect. For example, after the fiber weight was adjusted on the Servolap computer, it took about 10 minutes for the material to reach the saturator. Some extra time was also allowed for the material to equilibrate after the adjustment.

At each sampling interval, three pieces were cut approximately 18 inches in the machine direction, completely across the cross direction. Four 9x9 inch samples were die cut across each piece providing a total of 12 samples per sampling interval. The samples were tested 24 hours after the experiment, as past studies have shown this to be enough time for the caliper to rebound to its equilibrium point. Each 9x9 piece was tested according to the testing procedure outlined. The appearance was judged when the other testing was performed.

In a laboratory setting, the entire experiment could be replicated without much difficulty, however, in a manufacturing environment, it is too costly and time consuming. Therefore, replication was limited to repeated sampling at each treatment combination during the experiment.

TESTS FOR LINEARITY OF EFFECTS

Before starting the screening experiment, a small experiment was run to test for linearity of effects. The calender was chosen for this test as adjustments have an immediate effect on the material; it would not be necessary to wait for the material to equilibrate for several minutes. The material was tested for CFM and caliper at seven different calender pressures. The material was tested 24 hours after the experiment to allow the caliper to rebound to its equilibrium point. The linearity assumption proved valid in both cases at a 95% confidence level. Figures 5 and 6 show these results.

PROBLEMS DURING THE SCREENING EXPERIMENT

At each treatment combination, the factors were adjusted to their appropriate setpoints, at least 10 minutes passed to allow the material to equilibrate, then a sample was taken. Some small problems were encountered during the actual experiment. Can speed was not a variable that could be included in the experiment. At the slow setpoint, the material would sag in the dry cans and eventually fall to the floor. At higher speeds, the material was stretched so much that it almost broke in two. The researcher chose to fix this variable at 1.0 yds/min (the operator's advice) faster than the saturator and not adjust it during the experiment. When determining effects, the column in the design matrix for this variable became part of the error term.

Two other problems caused some inconvenience. While adjusting for the fifth treatment combination, the material broke and wrapped the saturator. During the seventh treatment combination, the material wrapped one of the dry cans. Both of these problems required only a brief delay for cleaning and threading the line.

TESTING/CALCULATIONS

After 24 hours, the material was tested for basis wt., caliper, CFM, and appearance. The measurements were recorded on forms and totaled for each treatment combination. These measurements, as well as the data from the "linearity" tests are included in Appendix A

```
The regression equation for CFM vs. calender pressure is

 CFM  =   237   -  0.0706 calender

 Predictor        Coef        Stdev     t-ratio        p
 Constant       237.16        10.18       23.30    0.000
 calender     -0.07055      0.01034       -6.83    0.001

 s = 10.94       R-sq = 90.3%     R-sq(adj) = 88.4%

 Analysis of Variance

 SOURCE       DF         SS          MS         F        p
 Regression    1     5575.1      5575.1     46.60    0.001
 Error         5      598.3       119.7
 Total         6     6173.4
```

FIGURE 5. Linearity Test for Calender Pressure on CFM

```
The regression equation for caliper vs. calender pressure is

caliper  =   50.5   -  0.0179 calender

Predictor         Coef          Stdev     t-ratio        p
Constant        50.500          1.067       47.33    0.000
calender     -0.017857       0.001083      -16.48    0.000

s = 1.146       R-sq = 98.2%     R-sq(adj) = 97.8%

Analysis of Variance

SOURCE       DF         SS          MS         F         p
Regression    1     357.14      357.14    271.74     0.000
Error         5       6.57        1.31
Total         6     363.71
```

FIGURE 6. Linearity Test for Calender Pressure on Caliper

(A–2 through A–7). The results were inspected for reasonableness before measuring the effects. Only the sixteenth treatment combination seemed unreasonable. This treatment combination was run fifth in the experiments random order. The finished weight was extremely high, but the fiber weight and latex flow were both at their low points. The explanation for this is the feedrolls were at their high level for the previous treatment combination and the sample was taken before the adjustment took affect. Point #16 was discarded and in its place is the average of the other 15 points.

Figures A–8 through A–11 were used to calculate the results. A separate table was used for each of the four response variables. The average response for the variable goes under the column labeled "response." The effects were determined by the following procedure outlined by Dupont (1988):

(1) Add all of the responses on the lines with "+" signs and write the total on the "sum +" line.

(2) Add all of the responses on the lines with "–" signs and write the total on the "sum –" line.

(3) Subtract "sum –" from "sum +" to get the difference and write this number on the "diff." line.

(4) Divide the "diff" by the number of "+" signs in the column to get the "effect."

These effects were compared to 95% confidence limits of the standard error to determine which effects were significant. Figure A–12 contains the calculations for the standard error of all four response variables. The confidence intervals were determined by the following procedure, also outlined by Dupont (1988), and compared to the effects for each factor in Table 1.

(1) Square the effects of all unassigned factor effects. This includes E(1) through E(7) plus x(7) which was unassigned.

(2) Divide the sum of squares by the number of unassigned effects and take the square root to get the "standard error."

(3) Find the t-value for 95% confidence with degrees of freedom equal to the number of unassigned effects.

(4) Multiply the t-value by the standard error to get the magnitude of the confidence limits.

(5) If the absolute value of the effect is greater than the confidence limit, then the effect was significant.

RESULTS

Three factors--saturator speed, compactor roll, and latex flow--had no effect on any of the response variables. The other four factors each significantly affect two response variables. The fiber weight (feedroll speed) affected the basis weight and caliper; the calender affected the caliper and CFM; the saturator gap affected the basis weight and appearance; and the air flow affected the CFM and appearance. Most of the significant effects observed are explained intuitively, in fact, none of the results ran contrary to expectations.

As the feedroll speed (fiber weight) increased, the basis weight and caliper both increased. This is reasonable as increasing the feedroll speed will send more fiber through the card and more fiber in a given area of material should cause the basis weight and caliper to increase.

Calendering the material caused the caliper and CFM to decrease. Squeezing the material will obviously lower caliper and the CFM dropped because as the material is compressed, it becomes less porous and will not allow as much air to pass through.

Tightening the saturator caused the basis weight to drop. The saturator must be tight enough to squeeze the latex into the material, but it reaches a point where latex may be squeezed back out of the material. This is why the saturator gap was controlled at three levels for the second experiment. A tighter saturator also caused saturator marks while a loose saturator resulted in white, unsaturated areas in the material. The saturator affected the appearance the same way it affected basis weight--by the quantity of latex it squeezed into the material.

Table 1. Significant Effects From Screening Experiment

	Basis Wt.	Caliper	CFM	Appearance
Confidence Interval:	11.96	6.79	30.52	1.24
Factors				
Fiber Wt.	17.38 *	8.71 *	−10.10	1.00
Sat. Speed	−2.38	1.33	20.60	0.50
Sat. Gap	−12.38 *	−3.29	19.63	2.25 *
Comp. Roll	−4.63	−3.69	−3.90	0.25
Latex Flow	4.38	3.52	2.10	1.00
Air Flow	−2.88	3.94	30.90 *	−2.00 *
Can Speed	------	------	------	-----
Cal. Pres.	0.88	−16.06 *	−71.10 *	−0.75

Significant are denoted by an asterisk (*).

The air flow was significant for appearance and CFM. Increasing the air flow caused white, fuzzy areas and a higher CFM. An increase in air flow produced lighter foam so the material did not get saturated as well, thus affecting the appearance and CFM. It was unexpected that the air flow had an effect while the latex flow did not. The most reasonable answer is that the levels of air flow were comparatively wider than the levels for latex flow. Thus the effects of air flow were significant while the effects of latex flow were not greater than the noise in the line. In the second experiment, these two variables were combined into one variable: foam density.

SUMMARY OF SCREENING EXPERIMENT

The goal of the first experiment was to screen eight variables to determine which were most important. A 16–run fractional factorial design was used to measure the effects of these eight factors on four response variables––CFM, basis weight, caliper, and appearance. Can speed had to be held constant during the experiment and saturator speed, compactor roll, and latex flow had no effect on any of the response variables. Calender pressure had a significant effect on CFM and caliper, but since the calender is not normally used on 7395 Blue, it was not included in the second experiment.

Three other factors had a significant effect on two of the four response variables. Air flow, fiber weight, and saturator gap will be included in the second experiment. Air flow affected appearance and CFM, fiber weight affected basis weight and caliper, and saturator gap affected basis weight and appearance. Two of these variables--saturator gap and air flow--are part of the latex saturation process and fiber weight was expected to have some influence on latex saturation. The second experiment, therefore, took a closer look at the latex saturation process.

SECOND EXPERIMENT

For the second experiment, the latex saturation process was studied in detail. Two of the three factors in the experiment--foam density and saturator gap--are applied to line #13 at the same physical location. The saturator squeezes the latex foam into the material, therefore, these two variables were controlled at three levels each so interaction relationships could be better determined. Fiber weight, the other factor in the experiment, was controlled at two levels. A full 3x3x2 factorial design (Figure 7) was employed to measure the main and interaction effects of foam density, saturator gap, and fiber weight on CFM, basis weight, caliper and appearance on 7395 Blue.

The only significant factor from the screening design not included in the second design was calender pressure. The primary reason for this is that 7395 Blue is not usually calendered. Also the second experiment was intended to focus on the latex saturation process and the calender, located at the very end of line #13, does not affect the material until it is completely dry. It is unlikely that there would be any interaction effects between the calender and other factors.

EXPERIMENTAL DESIGN MODEL FOR SECOND EXPERIMENT

TREATMENT COMBINATION	FIBER WEIGHT	FOAM DENSITY	SATURATOR GAP
1	+	+	+
2	+	+	0
3	+	+	-
4	+	0	+
5	+	0	0
6	+	0	-
7	+	-	+
8	+	-	0
9	+	-	-
10	-	+	+
11	-	+	0
12	-	+	-
13	-	0	+
14	-	0	0
15	-	0	-
16	-	-	+
17	-	-	0
18	-	-	-

Figure 7. Experimental Design Model for Second Experiment

FACTORS EXAMINED

The same procedures were used for the second experiment as the first experiment. The background variables were set to the same levels as before (Figure B–2), the order of the treatment combinations was chosen randomly (Figure B–3), and a minimum of 10 minutes passed after each adjustment before sampling to allow the material to equilibrate. Since the Servolap was working, the fiber weight could be better controlled. As in the screening experiment, previous technical data and interviews with line #13 operators determined the levels of each factor. The two levels for fiber weight were 78 (–) and 94 (+) grams/m^2. The three levels for saturator gap were 0.030" (–), 0.037" (0), and 0.045" (+). The foam density is a combination of the air flow and latex flow on the Campen foamer. The three levels for foam density were: latex = 42.5, air = 24 (–); latex = 44.5, air = 22 (0); and latex = 46.5, air = 20 (+). Both the air and latex are set according to percent of maximum output on the manually controlled Campen foamer. The computer controlled LESS foamer was still not functioning during this experiment.

The actual foam density was also measured during the second experiment. At each treatment combination, a 260 ml cup was filled with latex foam from the saturator reservoir and weighed. The material was marked so that a sample could be taken at the same location where the foam density was measured. This process was repeated three times at each treatment combination.

During this experiment, line #13 ran without any downtime and all of the adjustments were made without problems. After 24 hours, samples were die cut and measured exactly as in the screening design. Appendix B (B–4 through B–8) contains the results of all the testing. The appearance was again judged by a quality control inspector. Figure B–8 shows the foam density measurements. The tare weight was subtracted later and the gross weight converted to grams/ml.

The four measurements across each sample cannot be considered independent, therefore, they were averaged to give one result per sample. Averaging four measurements will provide a more accurate representation than just measuring at one location as there may be inconsistencies in the material's cross–direction.

STATISTICAL ANALYSES FOR SECOND EXPERIMENT

The same procedures will be used to analyze the data for each of the four response variables. First ANOVA tables were produced to see which factors and interactions significantly affect the response variables. For these and all subsequent ANOVA tables, a 95% confidence level was used to determine significance. Higher order effects were interpreted before main effects as a main effect cannot be interpreted without first examining all interactions involving that factor. Significant two–factor interactions were analyzed and post–hoc comparisons made. For convenience, the numbers 1, 2, and 3 will be used instead of "–", "0", and "+" for the levels of each factor.

All three-factor interactions were significant. If three-factor interaction effects actually exist, analysis becomes considerably more complex. The effects cannot reasonably be explained and the main and two-factor effects cannot be interpreted. If three-factor effects exist, the line #13 operators and technical personnel at Hollingsworth & Vose will have a difficult time trying to control the process. Therefore, the three-factor interactions were ignored and the other effects interpreted.

ANOVA TABLES

The ANOVA table shows which factors and interactions significantly affect the response variable. For example, Table 3 (which will be interpreted shortly) shows the ANOVA results for caliper. At the 95% confidence level, a factor is significant if the "p-value" is less than .05. For caliper, all effects are significant except foam density, which has a p-value of 0.113. Main effects may be interpreted directly only if the interaction effects for that factor are not significant. All of the ANOVA tables which follow have significant interaction effects, therefore, these interactions must be analyzed before any conclusion can be drawn for the main effects.

ANALYZING INTERACTION EFFECTS

If an interaction effect is significant, interpreting the main effects becomes more complex.

The simplest way to analyze the interaction effect is to graph the two factors which interact against the response variable. Figure C–3 is a graph of CFM vs. the saturator gap for the three levels of foam density. Since the three lines do not cross, the interaction is ordinal. This means that the effect foam density has on CFM can be interpreted separately from the effect of the saturator gap, i.e. as the foam density increases, the CFM decreases irrespective of the level of saturator gap. Figure C–6 is a graph showing a disordinal interaction. The effect of saturator gap on CFM varies depending on the level of fiber weight. A general conclusion cannot be reached for disordinal interactions.

To gain more insight into a disordinal interaction, separate ANOVA tables are produced for each individual level of the interacting variable. For example, for the disordinal interaction in Figure C–6, ANOVA tables for each level of fiber (Figure C–8) are produced. The two ANOVA tables show that the effect of saturator gap is significant at both levels of fiber. The nomenclature of the factors is different for these ANOVA tables. For example, sat(d–1) is the effect of saturator gap when the foam density is at level one and den(f–2) is the foam density when the fiber weight is at level two.

POST–HOC COMPARISONS

If a main effect can be interpreted, it is important to know at which levels of this factor the response variable is significantly different. For example, if a factor has five levels, it is possible that the response variable will not change significantly at four of the levels, but will be significantly differently at the fifth level. To compare the means of each level, the Tukey test was used.

To perform the Tukey test, a critical range is calculated and all of the differences between means are compared to this range. The critical range has the formula:

$$CR_T = q(r_{max}, df_{S/A}) * SQRT(MS_{S/A}/s)$$

where,

q = the studentized range statistic obtained from a chart

r_{max} = the number of treatment groups

$df_{S/A}$ = error degrees of freedom from the ANOVA chart

$MS_{S/A}$ = mean squared error of the factor from ANOVA chart

s = sample size in each group

For a factor with only two levels, a Tukey test need not be performed. If the difference between two means is greater than the critical range, then the means are significantly different.

5. ANALYSIS OF THE RESULTS

CFM

At a 95% confidence level, Table 2 shows that all main and interaction effects are significant. Figure C–1 is a graph of CFM vs saturator gap at different levels of fiber weight. The lines for fiber = 1 and fiber = 2 do not cross, therefore, the interaction is ordinal. The CFM is higher at fiber = 1 than at fiber = 2 for all levels of saturator gap, therefore, the main effect of fiber weight can be interpreted separately from the saturator gap. Figure C–2 shows CFM vs. foam density at the two levels of fiber weight. Again the interaction is ordinal and the fiber weight can be interpreted separately from the foam density. Thus as the fiber weight increases, the CFM will decrease. This result is reasonable. Increasing the quantity of fiber in the product allows less air to pass through, thus decreasing the CFM.

Figures C–3 and C–4 show CFM vs saturator gap and fiber weight at the three levels of foam density. Both of these interactions are ordinal so the main effect of foam density can be interpreted. As the foam density increases, the CFM will decrease. This also makes sense. More latex binder will make the material less porous and the CFM will decrease. Figure C–5 presents a Tukey test illustrating that at a 95% confidence level, the CFM is not significantly different when the foam density at its two lower levels, but the CFM decreases significantly at foam density = 3.

Figures C–6 and C–7 show that saturator gap interaction is disordinal with respect to both fiber weight and foam density. To gain more insight into the saturator gap, ANOVA tables were produced for each individual level of fiber weight and foam density to see when the saturator gap significantly affected CFM. ANOVA Tables in Figures C–8 and C–9 show that the saturator gap is significant at both level of fiber weight, but only at one level of foam density––foam density = 2. The effect of saturator gap on CFM is very complex and cannot be interpreted separately from fiber weight or foam density.

BASIS WEIGHT

Table 3 shows that all main and interaction effects are significant for basis weight. Figures D–1 and D–2 show that fiber weight interacts ordinally with both saturator gap and foam density. As the fiber weight increases, the basis weight will increase for all levels of saturator gap and foam density. This result is intuitive. More fiber in the product will obviously cause the basis weight to increase.

Figure D–3 shows that foam density interaction is ordinal with respect to saturator gap. Figure D–4 shows that foam density would be ordinal with respect to fiber weight except for the two points at fiber = 2 and foam density = 1 & 2. As foam density increases, the basis weight increases. This result is similar to that for fiber weight. More latex in the

Table 2. ANOVA for CFM

Factor	Type	Levels	Values		
fiber	fixed	2	1	2	
foam-den	fixed	3	1	2	3
sat-gap	fixed	3	1	2	3

Analysis of Variance for CFM

Source	DF	SS	MS	F	P
fiber	1	2386.7	2386.69	69.93	0.000
foam-den	2	8807.4	4403.72	129.03	0.000
sat-gap	2	225.3	112.67	3.30	0.048
fiber*foam-den	2	808.9	404.46	11.85	0.000
fiber*sat-gap	2	754.4	377.19	11.05	0.000
foam-den*sat-gap	4	393.2	98.31	2.88	0.036
fiber*foam-den*sat-gap	4	2188.9	547.21	16.03	0.000
Error	36	1228.7	34.13		
Total	53	16793.5	316.86		

material will cause the basis weight to increase. A Tukey test (Figure D–5) compares the different levels of foam density on basis weight. The weight is significantly higher at the high level of foam density than the two lower levels.

Figures D–6 and D–7 show that saturator gap interaction is disordinal with respect to both fiber weight and foam density. The ANOVA tables for each individual level of fiber weight and foam density (Figures D–8 and D–9) show that the effects of saturator gap are significant at all levels of foam density, but only at the low level of fiber. The saturator gap will not influence the basis weight at the high level of fiber weight. As with CFM, saturator gap is complex and its effect on basis weight cannot be interpreted apart form fiber weight or foam density.

CALIPER

Table 4 shows that all effects for caliper are significant except foam density. The foam density had no main effect on caliper, but it interacted with the other factors resulting in significant effects. This is reasonable as the latex fills in pores in the fiber web and should not cause the caliper to change. Figures E–1 and E–2 show that fiber weight interaction is ordinal with respect to both saturator gap and foam density. As the fiber weight increases, the caliper increases. Unlike the latex foam, increasing the fiber weight will result in a more lofty web, thus the caliper will increase as the fiber weight increases.

Table 3. ANOVA For Basis Weight

Factor	Type	Levels	Values		
fiber	fixed	2	1	2	
foam-den	fixed	3	1	2	3
sat-gap	fixed	3	1	2	3

Analysis of Variance for WEIGHT

Source	DF	SS	MS	F	P
fiber	1	1223.1	1223.13	212.05	0.000
foam-den	2	1236.3	618.14	107.16	0.000
sat-gap	2	184.4	92.20	15.98	0.000
fiber*foam-den	2	215.9	107.97	18.72	0.000
fiber*sat-gap	2	215.7	107.84	18.70	0.000
foam-den*sat-gap	4	204.2	51.06	8.85	0.000
fiber*foam-den*sat-gap	4	697.5	174.38	30.23	0.000
Error	36	207.7	5.77		
Total	53	4184.8	78.96		

Saturator gap interaction is ordinal for fiber weight (Figure E–3), but disordinal for foam density (Figure E–4). Figure E–5 shows the ANOVA results for saturator gap at each level of foam density. In fact, the saturator gap has a significant effect on caliper at all levels of foam density. Again the effect of saturator gap cannot be interpreted separately from foam density.

APPEARANCE

Table 5 shows that all effects for appearance are significant except the fiber weight–saturator gap interaction. All other two–factor interactions are disordinal as shown in Figures F–1, F–2, F–3, & F–4. Inspecting the ANOVA results in Figures F–5, F–6, & F–7 for the individual levels of each factor show that fiber weight is not significant when foam density is at its middle level, but all other effects are significant. All of the factors affect appearance, but these effects are very complex and difficult to quantify. The closest the results come to allowing a main effect to be interpreted is for saturator gap. Except for low levels of foam density, as the saturator gap decreases, saturator marks are more likely to appear and as the saturator gap increases, white spots will result.

Adjusting the appearance is very complex. With the two–factor interactions being disordinal, changing the appearance is primarily trial–and–error. The best way to change the appearance is by adjusting the saturator gap. A wider gap will reduce saturator marks while a tighter gap will help eliminate white, fuzzy areas in the web.

Table 4. ANOVA For Caliper

Factor	Type	Levels	Values		
fiber	fixed	2	1	2	
foam-den	fixed	3	1	2	3
sat-gap	fixed	3	1	2	3

Analysis of Variance for CALIPER

Source	DF	SS	MS	F	P
fiber	1	312.96	312.963	130.00	0.000
foam-den	2	11.15	5.574	2.32	0.113
sat-gap	2	179.15	89.574	37.21	0.000
fiber*foam-den	2	81.15	40.574	16.85	0.000
fiber*sat-gap	2	28.04	14.019	5.82	0.006
foam-den*sat-gap	4	89.85	22.463	9.33	0.000
fiber*foam-den*sat-gap	4	137.85	34.463	14.32	0.000
Error	36	86.67	2.407		
Total	53	926.8	17.487		

Table 5. ANOVA For Appearance

Factor	Type	Levels	Values		
fiber	fixed	2	1	2	
foam-den	fixed	3	1	2	3
sat-gap	fixed	3	1	2	3

Analysis of Variance for APP

Source	DF	SS	MS	F	P
fiber	1	0.667	0.6667	7.20	0.011
foam-den	2	24.111	12.0556	130.20	0.000
sat-gap	2	122.333	61.1667	660.60	0.000
fiber*foam-den	2	20.333	10.1667	109.80	0.000
fiber*sat-gap	2	0.333	0.1667	1.80	0.180
foam-den*sat-gap	4	89.222	22.3056	240.90	0.000
fiber*foam-den*sat-gap	4	47.667	11.9167	128.70	0.000
Error	36	3.333	0.0926		
Total	53	308.000	5.8113		

REGRESSION ANALYSIS

The research initially had an objective of developing a regression relationship between the factors and the response variables. The results of the ANOVA tables and subsequent analyses show that producing 7395 Blue on line #13 is a very complex process and developing adequate regression equations may not be a realistic goal. Figures G-1 through G-8 show linear and second-order regression models for CFM, basis weight, caliper, and appearance in all three factors. The second-order models include all interaction effects between the factors.

The linear models for CFM, basis weight, caliper, and appearance had R-sq values of 58.6%, 64.6&, 49.7%, and 40.0%. These values do not lend significant confidence to the linear models developed. This follows from the ANOVA results. With virtually all of the two-factor interactions being significant, a linear regression model would be expected to be inadequate.

The second-order models for caliper and appearance had R-sq values of 58.7% and 45.3%. Again these values are too low to use the models. The R-sq values for CFM and basis weight, however, were 73.3% and 73.6%. These values offer some hope that a regression model can be developed to reflect the actual physical environment. Unfortunately the models were rather complex. Fiber weight, saturator gap, and foam density all have negative coefficients for CFM, but all of the two-factor interactions have positive coefficients. The second–order regression model for basis weight is similar. Fiber weight, saturator gap, and foam density all have positive coefficients, yet three of the second–order terms have negative coefficients. Line #13 operators would have a difficult time using these models to control the line. Therefore, no regression model can be recommended.

SUMMARY OF SECOND EXPERIMENT

The second experiment was designed to investigate the latex saturation process in detail. An 18–run full factorial design measured the effects of fiber weight at two levels and foam density and saturator gap at three levels each on CFM, basis weight, caliper, and appearance of 7395 Blue. ANOVA showed that considerable interaction between factors existed, but further analysis enabled some of the main effects to be interpreted. Increasing fiber weight will increase the basis weight and caliper while decreasing the CFM. Raising the foam density will increase the basis weight and lower the CFM. Tightening the saturator causes saturator marks and loosening the saturator causes white, fuzzy areas in the material. These results, which were consistent with the results of the screening experiment, will be discussed further in the conclusion.

6. CONCLUSION

SUMMARY

The purpose of this research was to develop and test a methodology for improving quality on a continuous flow line. In the experimental environment studied, quality was measured by the four response variables CFM, basis weight, caliper, and appearance. First, all of the variables were listed, then by interviewing line operators and technical personnel at Hollingsworth & Vose, the list was reduced to eight variables: fiber weight, saturator speed, saturator gap, compactor roll, latex flow, air flow, can speed, and calender pressure. A 16–run fractional factorial design measured the main effects of these eight variables. This screening experiment helped narrow the list of important factors to saturator gap, fiber weight and foam density.

A full factorial experiment was designed to measure the effects of saturator gap, fiber weight, and foam density on CFM, basis weight, caliper, and appearance. ANOVA revealed the significant effects and further analysis enabled some of the main effects to be interpreted. There was too much complex interaction between factors to develop adequate regression equations.

RESULTS OF RESEARCH

The main effect of fiber weight can be interpreted separately from the other factors for CFM, basis weight, and caliper. As the fiber weight increases, the basis weight and caliper increase and the CFM decreases. This is logical as more fiber in the material results in a heavier, thicker product which does not allow as much air to pass through.

The foam density has no effect by itself on caliper, but it does interact with other factors to significantly affect the caliper. As foam density increases, the basis weight will increase and the CFM will decrease. Again these results are logical as more latex in the final product will increase the weight and not allow as much air to pass through the material.

The only main effect for saturator gap that can be interpreted is for the appearance. A tight saturator will cause saturator marks to form in the material and a loose saturator will result in white, unsaturated areas. Table 6 summarizes these results.

INTERPRETATION OF RESULTS

All of the main effects which could be interpreted apart from interaction effects are intuitive results. Increasing the fiber weight or foam density will result in a higher basis

Table 6. Summary of Results

	FIBER WEIGHT	**FOAM DENSITY**	**SATURATOR GAP**
CFM:			
	negative correlation	negative correlation	main effect cannot be interpreted
BASIS WEIGHT:			
	positive correlation	positive correlation	main effect cannot be interpreted
CALIPER:			
	positive correlation	no main effect only interaction effects	main effect cannot be interpreted
APPEARANCE:			
	main effect cannot be interpreted	main effect cannot be interpreted	increase gap to remove sat. marks decrease gap to remove white spots

weight and lower CFM. Increasing the fiber weight will result in a higher caliper. Tightening the saturator will cause saturator marks. These statements are obvious to those experienced in the field of latex bonded nonwovens. However, the fact that virtually all of the two–factor interactions were significant is unexpected. The interaction effects are so significant that trying to get the CFM, basis weight, caliper, and appearance within specifications is essentially no more than trial–and–error. If the three–factor interactions which were ignored actually reflect the real world, even the few interpretations of main effects may be without merit. Following are the basic guidelines for line #13 operators to follow when producing 7395 Blue:

CFM. To increase CFM, lower the fiber weight and/or foam density. To decrease CFM, raise the fiber weight and/or foam density.

Basis weight. To increase basis weight, increase the fiber weight and/or foam density. To decrease basis weight, decrease the fiber weight and/or foam density.

Caliper. To increase caliper, increase the fiber weight. To decrease caliper, decrease the fiber weight.

Appearance. To reduce saturator marks, loosen the saturator. To reduce white, fuzzy areas, tighten the saturator.

All other adjustments are trial–and–error. If the operator desires an increase in CFM and basis weight, he will have to experiment with other variables keeping in mind that the same adjustment may not work every time. The disordinal two–factor interactions reveal that the effect of adjusting a variable may change depending on the settings of other variables.

CRITIQUE OF METHODOLOGY

The methodology of designed experimentation and regression analysis provided the researcher with insight into the experimental environment, but failed to produce a quantitative model which was useful in controlling the dependent variables. The reasons a useful model could not be produced are hypothesized to be:

(1) Too much noise in the independent variables

(2) Complex interactions between the independent variables

(3) The background variables fluctuate even when "fixed."

For this methodology to be more useful, the independent variables in the experiment and background variables must be better controlled. Once better control is established over the variables, accurate regression models can be developed.

In general, however, this methodology is useful. Documentation of all variables on the line is necessary so the experimental conditions can be duplicated. Running a screening experiment will save time and money. Frequently the screening experiment will reveal that variables which are believed important are not actually significant. In an environment where the independent variables can be well controlled, this methodology will result in an accurate operating model.

In an environment where a deterministic model cannot be developed (as in this research), it may be possible to employ computer simulation. ANOVA can be utilized to determine the parameters for a computer simulation model which may provide additional analysis of the system at less cost. Taking this concept one step further, an automated gauging system could be installed on a continuous flow line to provide real-time quality measurements and automatically adjust the inputs to further improve quality. Before automated process control is installed, however, an analysis similar to this research must be undertaken to understand the cause-and-effect relationships on the line, i.e. the researcher must determine which variables a gauging system would control. Therefore, the methodology outlined in this research is necessary to develop a deterministic model, a simulation model, or real-time process control.

FURTHER RESEARCH

The latex saturation process on Hollingsworth and Vose's line #13 is very complex and involved. The LESS foamer should provide more control over this process by reducing variance in the foam density. In order to understand the saturation process, an analysis similar to this research should be performed, but at more levels of the independent variables. For example, a 24–run fractional factorial experiment for the same three variables used in this research, each at six levels, may provide the researcher with an idea of the best ranges for each independent variable. Before attempting this, it would be wise to calibrate the Servolap and LESS foamer to ensure a consistent fiber weight and foam density as better control over the independent variables will yield better results. It is, however, unlikely that better results can be obtained unless the two–factor and three–factor interactions can be understood and explained. Future researchers must also be careful not to design too large an experiment. Problems such as the size of the latex tank, changing bales of fiber, changing operators, and environmental changes will limit the length of the experiment. Future researchers at Hollingsworth and Vose as well as those researching similar problems should consider computer simulation techniques and real–time process control as two options to follow the methodology outlined in this research.

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APPENDIX A. SCREENING DESIGN

VARIABLES ON LINE 13

AREA	VARIABLE	CLASSIFICATION	VALUE	
Raw fiber	Fiber length	SETPOINT	1.5	1.5
	Fiber denier	SETPOINT	1.5	3
	Length of time bale sits after being opened	CONSTANT		
	Fiber blend percentage	SETPOINT	60%	40%
	Fiber type/finish	CONSTANT	Dic. T54	Burett Poly
Hoppers	Speed of spiked apron	SETPOINT		
	Gap between apron and beater roll	CONSTANT		
Multimixer	Number of chambers used	CONSTANT	3	
Fine opener	Feedroll speeds	SETPOINT		
	One section / both sections/ by-pass	CONSTANT		
Vibrafeed	Frequency of vibration (3 gears available)	SETPOINT	middle	
	Width of vibrating box (6 settings)	SETPOINT	1/2 (lowest)	
	Intensity of vibration / stroke	SETPOINT	6 / 5 1/2	
	Apron speed	SETPOINT	—	
	Beater roll speed	SETPOINT	—	
	Feedroll speed	SETPOINT	—	
	Evener roll/doffer roll speed	SETPOINT	—	
	Gap between evener roll and spiked apron	CONSTANT	—	
Feedrolls	Calibrate density for the Servolap	CONSTANT	—	
	Calibrate distance from Servolap measuring point to the feedrolls	CONSTANT	—	
	Desired fiber weight out of card (g/m^2)	IND. VARIABLE		
Card	Worker speed	SETPOINT	116	
	Stripper speed	SETPOINT	617	
	Doffer speed	SETPOINT	59.2	
	Main cylinder speed	SETPOINT	133	
	Doffing comb angle	CONSTANT	0	
	Comb frequency	CONSTANT	—	
	Gap between each nip point	CONSTANT	—	
	Clothing wire type	CONSTANT	—	
	(tooth configuration for each individual roll)	CONSTANT	—	
	Front angle of teeth	CONSTANT	—	
	Back angle of teeth	CONSTANT	—	
	Tooth height	CONSTANT	—	
	Overall wire height	CONSTANT	—	
Crosslapper	Pitch (web width/# of layers)	CONSTANT	—	
	Width of web	SETPOINT	96 .97/.95	
	Axis (center point of web on belt)	SETPOINT	L	
	Delivery apron speed	SETPOINT	575	
	Outlet apron speed	SETPOINT	1.9	
	Up/down setting on outlet apron	CONSTANT	—	

Figure A-1. Values of Background Variables During Screening Experiment

Fehrer	Transversal blower speed	SETPOINT	—
	Main cylinder speed	SETPOINT	—
	Worker/stripper speed	SETPOINT	60
	Inlet conveyor speed	SETPOINT	1.2
	Outlet conveyor speed	SETPOINT	4.8
	2-stage suction system (one/two stages)	CONSTANT	2 stgs
	Wire on rolls (angle, teeth, etc. like card)	CONSTANT	—
Saturator	Saturator speed	IND. VARIABLE	—
	Triangle apron speed	SETPOINT	3.0
	Floor apron speed	SETPOINT	3.0
	Carrier roll speed	SETPOINT	6.0
	Transverse nozzle speed	SETPOINT	—
	Saturator gap	IND. VARIABLE	\
	Compactor roll on carrier rolls (yes/no)	IND. VARIABLE	\
Less Foamer	Foam density setpoint	IND. VARIABLE	—
	Output flow setpoint	IND. VARIABLE	—
	Reservoir height	SETPOINT	—
	Humidity of air entering rotor	CONSTANT	—
Latex	Quantity of each ingredient	CONSTANT	—
	Mixing time	CONSTANT	—
	Quantity of water in latex (% solids)	CONSTANT	—
	Variation in individual ingredients	CONSTANT	—
Dry cans	Infrared heaters (on/off)	CONSTANT	
	Speed of cans (relative to saturator)	IND. VARIABLE	+1.5 (P
	Steam pressure on cans	SETPOINT	90/70/75 90/60
Calender	Calender speed	SETPOINT	
	Calender pressure	IND. VARIABLE	0 - 700
	Selection of calender (large/small/cooling rolls)	CONSTANT	Perkins
Accumulator	Accumulator outfeed speed	SETPOINT	8.3
	Nip roll (open/closed)	CONSTANT	—
	Amount of counter weight on accumulator	CONSTANT	—
Winder	Tension during winding	AFTER	
	Winder speed	AFTER	
	A-frame/finished rolls	AFTER	
	Width on A-frame/finished rolls	AFTER	
Menzel slitter	Line speed	AFTER	
	Actual width	AFTER	
	Tension on finished roll	AFTER	
	Slitter blade speed	AFTER	

Figure A-1. Continued

BASIS WEIGHT OF 7395 BLUE

SCREENING DESIGN

	1				2				3					
	1	2	3	4	1	2	3	4	1	2	3	4	AVG	
1	6.20	6.39	6.88	6.09	6.18	6.27	6.08	6.06	6.53	6.78	6.40	5.80	6.27 ~~120~~	120
2	6.39	6.43	6.41	6.37	6.28	6.29	6.30	6.67	6.56	6.70	6.57	6.47	6.45	124
3	7.93	7.92	7.85	8.02	7.97	7.45	7.56	7.78	7.91	7.83	7.89	7.23	7.78	149
4	7.53	7.83	7.37	7.34	7.76	7.60	7.72	7.67	7.67	7.68	7.65	7.60	7.62	146
5	6.14	6.16	6.25	6.39	6.29	6.01	6.00	6.18	6.35	6.38	6.23	6.28	6.22	119
6	6.87	6.71	6.74	6.84	7.25	6.89	7.00	7.17	7.28	7.31	6.97	7.33	7.03	135
7	6.00	5.56	5.74	6.28	5.78	5.83	5.58	5.85	5.55	5.89	5.93	5.93	5.89	113
8	5.11	5.33	4.50	5.33	5.78	5.79	5.18	5.01	5.62	5.21	5.09	5.44	5.31	102
9	5.58	5.65	5.61	5.61	5.79	5.90	5.65	5.60	5.86	5.63	5.57	5.53	5.66	108
10	5.19	5.20	4.70	5.20	5.14	5.33	5.25	5.37	4.97	4.74	4.85	4.96	5.10	98
11	6.30	6.39	6.23	6.31	6.04	6.35	6.12	6.52	6.18	6.02	6.07	5.99	6.22	119
12	6.60	6.47	6.47	6.16	6.73	6.76	6.63	6.69	6.88	6.84	6.62	6.65	6.63	127.4
13	5.85	6.62	6.14	6.13	5.58	5.59	5.48	5.75	5.91	5.81	5.82	6.00	5.89	112
14	5.81	5.98	5.89	6.23	6.31	6.33	5.95	5.96	6.07	5.97	6.15	6.42	6.09	117
15	6.11	5.97	6.09	6.24	6.19	5.87	5.74	5.90	6.18	6.12	6.07	6.16	6.06	116
16	7.60	7.90	7.71	7.84	7.24	7.50	7.33	7.74	7.29	7.55	7.23	7.65	7.55	146

Figure A-2. Results of Basis Wt. Testing for Screening Design

CALIPER OF 7395 BLUE

SCREENING DESIGN

	1				2				3				
	1	2	3	4	1	2	3	4	1	2	3	4	AVG
1	42	33	30	29	42	34	28	29	43	34	29	26	33.25
2	50	45	43	42	50	46	43	42	52	48	48	44	46.08
3	48	41	36	39	46	34	35	39	53	39	33	35	41.33
4	65	62	60	59	64	58	59	56	68	62	62	58	61.08
5	49	45	41	42	46	44	41	42	49	43	41	43	43.83
6	50	49	48	46	52	48	46	46	54	52	46	47	48.5
7	39	30	24	26	36	31	23	25	36	30	23	24	28.92
8	45	38	35	41	43	44	38	40	42	43	41	44	41.17
9	48	49	43	42	50	48	47	45	51	44	43	44	46.17
10	35	28	21	24	35	30	24	24	32	27	21	24	27.08
11	46	36	28	29	43	35	28	29	39	35	27	29	33.67
12	40	36	28	25	41	36	28	28	43	38	30	29	33.5
13	53	51	52	51	49	45	44	46	48	46	44	44	47.75
14	37	31	24	25	37	31	27	27	38	28	25	26	29.67
15	35	31	24	26	36	28	22	23	35	30	24	25	28.25
16	78	75	73	71	71	69	68	69	70	69	67	68	70.67

Figure A-3. Results of Caliper Testing for Screening Design

AIR PERMEABILITY OF 7395 BLUE

SCREENING DESIGN

	1				2				3				
	1	2	3	4	1	2	3	4	1	2	3	4	AVG
1	251	214	158	209	254	222	203	191	266	176	170	217	211
2	243	242	243	246	242	228	237	238	246	230	228	230	238
3	176	180	128	125^-	193	163	138	144	180	165^-	153	122	156
4	231	203	235^-	217	198	186	188	176	215^-	210	226	194	207
5	261	254	243	248	252	257	264	265^-	257	238	251	276	255
6	228	238	254	227	214	242	224	214	223	228^-	224	230	229
7	217	215^-	191	158	242	235^-	198	198	237	222	176	153	204
8	277	290	333^+	306	264	273	282	333^+	277	294	323	312	297
9	311	297	281	278	288	280	297	294	293	285^-	298	291	291
10	281	242	243	230	268	248	219	220	310	278	222	251	251
11	237	194	172	176	234	191	174	184	240	212	186	201	200
12	194	196	180	162	227	182	170	147	217	209	151	182	184
13	304	282	281	290	312	300	305^-	278	284	278^-	281	268	289
14	234	214	174	165^-	196	172	152	210	245^-	203	158	163	194
15	198	172	147	167	191	184	161	163	203	186	156	184	176
16	309	305^-	306	304	313	306	313	309	331	325^-	324	311	313

Figure A-4. Results of CFM Testing for Screening Design

APPEARANCE OF 7395 BLUE
SCREENING DESIGN

	RATING	COMMENTS
1	7	Sat marks, color O.K.
2	8	Sat marks, color O.K.
3	3	white spots, fuzzy, dark
4	7	Sat. marks, dark
5	9	heavy sat marks, color O.K.
6	8	Sat marks, color O.K.
7	8	Sat marks, a little dark
8	4	a little white, color O.K.
9	5	dark
10	~~4~~ 6	a few sat. marks, color O.K.
11	9	heavy sat marks dark
12	5	dark
13	7	Sat marks color OK
14	6	a few Sat. marks very dark
15	3	no sat marks, white on back, dark
16	7	Sat marks, a little light

0 = WHITE, FUZZY
5 = O. K.
10 = SATURATOR MARKS

Figure A-5. Results of Appearance Testing for Screening Design

TEST FOR LINEARITY OF CALENDER PRESSURE
SCREENING DESIGN

PSI	1	2	3	4	5	6	7	8	9	10	AVG
300	53	54	51	51	43	43	41	37	32	34	44
500	55	49	48	45	39	37	39	37	39	39	43
700	51	46	43	38	32	30	35	35	38	40	39
900	36	36	37	34	30	29	31	30	29	33	33
1100	34	32	35	32	30	29	28	31	29	29	31
1300	29	31	33	31	26	24	27	24	24	22	27
1500	21	25	27	25	24	26	25	26	21	23	24

Figure A-6. Caliper vs. Calender Pressure Linearity Testing

TEST FOR LINEARITY OF CALENDER PRESSURE

SCREENING DESIGN

PSI	1	2	3	4	5	6	7	8	9	10	AVG
300	202	214	200	256	234	261	237	257			232.6
500	172	174	189	191	202	191	209	218			193.3
700	156	161	170	181	185	195	176	214			179.8
900	142	163	163	163	163	175	172	187			166
1100	139	159	149	151	156	154	152	178			154.1
1300	123 ~~159~~	137	147	142	157	178	170	181			154.4
1500	113	120	134	139	144	147	147	139			135.4

Figure A-7. CFM vs. Calender Pressure Linearity Testing

FACTOR EFFECT COMPUTATIONS
16-RUN FRACTIONAL FACTORIAL

SCREENING DESIGN VARIABLE: Basis Weight

TRIAL	MEAN	X(1)	X(2)	X(3)	X(4)	X(5)	X(6)	X(7)	X(8)	E(1)	E(2)	E(3)	E(4)	E(5)	E(6)	E(7)	RESPONSE	
1	+	-	-	-	+	+	+	-	+	+	+	-	-	-	+	-	116	(15)
2	+	+	-	-	-	-	+	+	+	-	-	-	-	+	+	+	149	(3)
3	+	-	+	-	-	+	-	+	+	-	+	+	-	+	-	-	117	(14)
4	+	+	+	-	+	-	-	-	+	+	-	+	-	-	-	+	127	(12)
5	+	-	-	+	+	-	-	+	+	+	-	-	+	+	-	-	113	(7)
6	+	+	-	+	-	+	-	-	+	-	+	-	+	-	-	+	119	(11)
7	+	-	+	+	-	-	+	-	+	-	-	+	+	-	+	-	98	(10)
8	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	120	(1)
9	+	+	+	+	-	-	-	+	-	+	+	-	-	-	+	-	124	(2)
10	+	-	+	+	+	+	-	-	-	-	-	-	-	+	+	+	119	(5)
11	+	+	-	+	+	-	+	-	-	-	+	+	-	+	-	-	112	(13)
12	+	-	-	+	-	+	+	+	-	+	-	+	-	-	-	+	108	(9)
13	+	+	+	-	-	+	+	-	-	+	-	-	+	+	-	-	146	(16)
14	+	-	+	-	+	-	+	+	-	-	+	-	+	-	-	+	102	(8)
15	+	+	-	-	+	+	-	+	-	-	-	+	+	-	+	-	135	(6)
16	+	-	-	-	-	-	-	-	-	+	+	+	+	+	+	+	*120*	(4)
SUM +	1925	1032	953	913 ~~1012~~	944	980	951	968	959	974	930	937	953	996	981	964		
SUM -	—	893	972	1012 ~~915~~	981	945	974	957	966	951	995	988	972	929	944	961		
CHECK	–	1925	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
DIFF.	1925	139	-19	-99	-37	35	-23	11	-7	23	-65	-51	-19	67	37	3		
EFFECT	120.31	17.38	-2.38	-12.38	-4.63	4.38	-2.88	1.38	.88	2.88	-8.13	-6.38	-2.38	8.38	4.63	.38		
LCL	▨																	
UCL	▨																	

Figure A–8. Factor Effects Computations for Basis Wt.

FACTOR EFFECT COMPUTATIONS
16-RUN FRACTIONAL FACTORIAL

SCREENING DESIGN VARIABLE: CALIPER

TRIAL	MEAN	X(1)	X(2)	X(3)	X(4)	X(5)	X(6)	X(7)	X(8)	E(1)	E(2)	E(3)	E(4)	E(5)	E(6)	E(7)	RESPONSE	
1	+	–	–	–	+	+	+	–	+	+	+	–	–	–	+	–	28.25	(15)
2	+	+	–	–	–	–	+	+	+	–	–	–	–	+	+	+	41.33	(3)
3	+	–	+	–	–	+	–	+	+	–	+	+	–	+	–	–	29.67	(14)
4	+	+	+	–	+	–	–	–	+	+	–	+	–	–	–	+	33.5	(12)
5	+	–	–	+	+	–	–	+	+	+	–	–	+	+	–	–	28.92	(7)
6	+	+	–	+	–	+	–	–	+	–	+	–	+	–	–	+	33.67	(11)
7	+	–	+	+	–	–	+	–	+	–	–	+	+	–	+	–	27.08	(10)
8	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	~~41.17~~ 33.25	(4)
9	+	+	+	+	–	–	–	+	–	+	+	–	–	–	+	–	46.08	(2)
10	+	–	+	+	+	+	–	–	–	–	–	–	–	+	+	+	43.83	(5)
11	+	+	–	+	+	–	+	–	–	–	+	+	–	+	–	–	47.75	(13)
12	+	–	–	+	–	+	+	+	–	+	–	+	–	–	–	+	46.17	(9)
13	+	+	+	–	–	+	+	–	–	+	–	–	+	+	–	–	70.67	(16)
14	+	–	+	–	+	–	+	+	–	–	+	–	+	–	–	+	41.17	(8)
15	+	+	–	–	+	+	–	+	–	–	–	+	+	–	+	–	48.50	(6)
16	+	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	*39.99*	(4)
SUM +	639.80	354.75	325.25	306.75	305.17	339.01	335.67	315.09	255.67	326.83	299.83	305.91	323.25	335.41	308.31	312.91		
SUM –	—	285.00	314.58	333.08	334.66	303.82	309.16	324.74	384.16	313.00	340.00	333.92	316.58	304.45	331.54	326.94		
CHECK		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	.41 ✓		
DIFF.		69.67	10.67	-26.53	-29.49	28.19	31.51	-9.65	-128.49	13.83	-40.17	-28.01	6.67	30.96	-23.21	-14.01		
EFFECT	39.99	8.71	1.33	-3.29	-3.69	3.52	3.94	-1.21	-16.06	1.73	-5.02	-3.50	.83	3.87	-2.90	-1.75		
LCL																		
UCL																		

Figure A-9. Factor Effects Computations for Caliper

FACTOR EFFECT COMPUTATIONS
16-RUN FRACTIONAL FACTORIAL

SCREENING DESIGN VARIABLE: CFM

TRIAL	MEAN	X(1)	X(2)	X(3)	X(4)	X(5)	X(6)	X(7)	X(8)	E(1)	E(2)	E(3)	E(4)	E(5)	E(6)	E(7)	RESPONSE	
1	+	−	−	−	+	+	+	−	+	+	+	−	−	−	+	−	176	(15)
2	+	+	−	−	−	−	+	+	+	−	−	−	−	+	+	+	156	(3)
3	+	−	+	−	−	+	−	+	+	−	+	+	−	+	−	−	194	(14)
4	+	+	+	−	+	−	−	−	+	+	−	+	−	−	−	+	184	(12)
5	+	−	−	+	+	−	−	+	+	+	−	−	+	+	−	−	204	(7)
6	+	+	−	+	−	+	−	−	+	−	+	−	+	−	−	+	200	(11)
7	+	−	+	+	−	−	+	−	+	−	−	+	+	−	+	−	251	(10)
8	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	211	(1)
9	+	+	+	+	−	−	−	+	−	+	+	−	−	−	+	−	238	(2)
10	+	−	+	+	+	+	−	−	−	−	−	−	−	+	+	+	255	(5)
11	+	+	−	+	+	−	+	−	−	−	+	+	−	+	−	−	289	(13)
12	+	−	−	+	−	+	+	+	−	+	−	+	−	−	−	+	291	(9)
13	+	+	+	−	−	+	+	−	−	+	−	−	+	+	−	−	313	(16)
14	+	−	+	−	+	−	+	+	−	−	+	−	+	−	−	+	297	(8)
15	+	+	−	−	+	+	−	+	−	−	−	+	+	−	+	−	229	(6)
16	+	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	* 233 *	(4)
SUM +	3721	1820	1993	1939	1895	1869	1984	1820	1576	1850	1838	1882	1938	1855	1749	1827		
SUM −		1901	1778	1782	1876	1862	1737	1901	2195	1871	1883	1839	1783	1866	1972	1894		
CHECK		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
DIFF.		-81	165	157	-31	17	247	81	.569	-21	-45	43	155	-11	-225	67		
EFFECT	232.5	-10.1	20.6	19.63	-3.9	2.1	30.9	10.1	-71.1	-2.6	-5.6	5.4	19.4	-1.4	-27.9	-8.4		
LCL																		
UCL																		

Figure A–10. Factor Effects Computations for CFM

FACTOR EFFECT COMPUTATIONS
16-RUN FRACTIONAL FACTORIAL

SCREENING DESIGN VARIABLE: APPEARANCE

TRIAL	MEAN	X(1)	X(2)	X(3)	X(4)	X(5)	X(6)	X(7)	X(8)	E(1)	E(2)	E(3)	E(4)	E(5)	E(6)	E(7)	RESPONSE	
1	+	−	−	−	+	+	+	−	+	+	+	−	−	−	+	−	3	(15)
2	+	+	−	−	−	−	+	+	+	−	−	−	−	+	+	+	3	(3)
3	+	−	+	−	−	+	−	+	+	−	+	+	−	+	−	−	6	(14)
4	+	+	+	−	+	−	−	−	+	+	−	+	−	−	−	+	5	(12)
5	+	−	−	+	+	−	−	+	+	+	−	−	+	+	−	−	8	(7)
6	+	+	−	+	−	+	−	−	+	−	+	−	+	−	−	+	9	(11)
7	+	−	+	+	−	−	+	−	+	−	−	+	+	−	+	−	6	(10)
8	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	7	(1)
9	+	+	+	+	−	−	−	+	−	+	+	−	−	−	+	−	8	(2)
10	+	−	+	+	+	+	−	−	−	−	−	−	−	+	+	+	9	(5)
11	+	+	−	+	+	−	+	−	−	−	+	+	−	+	−	−	7	(13)
12	+	−	−	+	−	+	+	+	−	+	−	+	−	−	−	+	5	(9)
13	+	+	+	−	−	+	+	−	−	+	−	−	+	+	−	−	7	(16)
14	+	−	+	−	+	−	+	+	−	−	+	−	+	−	−	+	4	(8)
15	+	+	−	−	+	+	−	+	−	−	−	+	+	−	+	−	8	(6)
16	+	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	5	(4)
SUM +	100	54	52	59	51	54	42	49	47	48	49	49	54	52	49	47		
SUM -		46	48	41	49	46	58	51	53	52	51	51	46	48	51	53		
CHECK		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
DIFF.		8	4	18	2	8	-16	-2	-6	-4	-2	-2	8	4	-2	-6		
EFFECT	6.25	1.0	.50	2.25	.25	1.0	-2.0	-.25	-.75	-.50	-.25	-.25	1.0	.50	-.25	-.75		
LCL																		
UCL																		

Figure A–11. Factor Effects Computations for Appearance

$t(95\%\ \text{CI}, 8\ \text{df}) = 2.31$

Basis Wt.

$S_{FE} = \text{SQRT}[(1.38^2 + 2.88^2 + 8.13^2 + 6.38^2 + 2.38^2 + 8.38^2 + 4.63^2 + 0.38^2)/8] = 5.18$

95% Confidence Interval = $t^*S_{FE} = 2.31^*5.18 = 11.96$

Caliper

$S_{FE} = \text{SQRT}[(1.21^2 + 1.73^2 + 5.02^2 + 3.50^2 + 0.83^2 + 3.87^2 + 2.90^2 + 1.75^2)/8] = 2.94$

95% Confidence Interval = $t^*S_{FE} = 2.31^*2.94 = 6.79$

CFM

$S_{FE} = \text{SQRT}[(10.1^2 + 2.6^2 + 5.6^2 + 5.4^2 + 19.4^2 + 1.4^2 + 27.9^2 + 8.4^2)/8] = 13.2$

95% Confidence Interval = $t^*S_{FE} = 2.31^*13.2 = 30.52$

Appearance

$S_{FE} = \text{SQRT}[(0.25^2 + 0.5^2 + 0.25^2 + 0.25^2 + 1.0^2 + 0.5^2 + 0.25^2 + 0.75^2)/8] = 0.54$

95% Confidence Interval = $t^*S_{FE} = 2.31^*0.54 = 1.24$

Figure A-12. Standard Error Calculations for 16-run Fractional Factorial Design

APPENDIX B. SECOND EXPERIMENT

EXPERIMENTAL DESIGN MODEL FOR SECOND EXPERIMENT

TREATMENT COMBINATION	FIBER WEIGHT	FOAM DENSITY	SATURATOR GAP
1	+	+	+
2	+	+	O
3	+	+	−
4	+	O	+
5	+	O	O
6	+	O	−
7	+	−	+
8	+	−	O
9	+	−	−
10	−	+	+
11	−	+	O
12	−	+	−
13	−	O	+
14	−	O	O
15	−	O	−
16	−	−	+
17	−	−	O
18	−	−	−

Figure B-1. 3x3x2 Factorial Design

VARIABLES ON LINE 13

SECOND EXPERIMENT

AREA	VARIABLE	CLASSIFICATION	VALUE	
Raw fiber	Fiber length	SETPOINT	1.5	1.5
	Fiber denier	SETPOINT	15	3
	Length of time bale sits after being opened	CONSTANT		
	Fiber blend percentage	SETPOINT	60%	40%
	Fiber type/finish	CONSTANT	Da T54	Borarr Ps
Hoppers	Speed of spiked apron	SETPOINT	–	
	Gap between apron and beater roll	CONSTANT	–	
Multimixer	Number of chambers used	CONSTANT	3	
Fine opener	Feedroll speeds	SETPOINT	–	
	One section / both sections/ by-pass	CONSTANT	both	
Vibrafeed	Frequency of vibration (3 gears available)	SETPOINT	middle	
	Width of vibrating box (6 settings)	SETPOINT	1/2 (lowest)	
	Intensity of vibration / stroke	SETPOINT	6 / 5 1/2	
	Apron speed	SETPOINT	–	
	Beater roll speed	SETPOINT	–	
	Feedroll speed	SETPOINT	–	
	Evener roll/doffer roll speed	SETPOINT	–	
	Gap between evener roll and spiked apron	CONSTANT	–	
Feedrolls	Calibrate density for the Servolap	CONSTANT	✓	
	Calibrate distance from Servolap measuring point to the feedrolls	CONSTANT	–	
	Desired fiber weight out of card (g/m^2)	IND. VARIABLE		
Card	Worker speed	SETPOINT	116	
	Stripper speed	SETPOINT	617	
	Doffer speed	SETPOINT	54.2	
	Main cylinder speed	SETPOINT	133	
	Doffing comb angle	CONSTANT	0	
	Comb frequency	CONSTANT	–	
	Gap between each nip point	CONSTANT	–	
	Clothing wire type	CONSTANT	–	
	(tooth configuration for each individual roll)	CONSTANT	–	
	Front angle of teeth	CONSTANT	–	
	Back angle of teeth	CONSTANT	–	
	Tooth height	CONSTANT	–	
	Overall wire height	CONSTANT	–	
Crosslapper	Pitch (web width/# of layers)	CONSTANT	–	
	Width of web	SETPOINT	.47 / .95	
	Axis (center point of web on belt)	SETPOINT	–	
	Delivery apron speed	SETPOINT	57.5	
	Outlet apron speed	SETPOINT	1.9	
	Up/down setting on outlet apron	CONSTANT	–	

Figure B-2. Values of Background Variables For Second Experiment

Fehrer	Transversal blower speed	SETPOINT	—
	Main cylinder speed	SETPOINT	—
	Worker/stripper speed	SETPOINT	1.5
	Inlet conveyor speed	SETPOINT	1.2
	Outlet conveyor speed	SETPOINT	4.5
	2-stage suction system (one/two stages)	CONSTANT	2 stages
	Wire on rolls (angle, teeth, etc. like card)	CONSTANT	—
Saturator	Saturator speed	SETPOINT	
	Triangle apron speed	SETPOINT	5.5
	Floor apron speed	SETPOINT	5.0
	Carrier roll speed	SETPOINT	6.0
	Transverse nozzle speed	SETPOINT	—
	Saturator gap	IND. VARIABLE	
	Compactor roll on carrier rolls (yes/no)	SETPOINT	yes
Less Foamer	Foam density setpoint	IND. VARIABLE	
	Output flow setpoint	IND. VARIABLE	
	Reservoir height	SETPOINT	High
	Humidity of air entering rotor	CONSTANT	—
Latex	Quantity of each ingredient	CONSTANT	—
	Mixing time	CONSTANT	—
	Quantity of water in latex (% solids)	CONSTANT	—
	Variation in individual ingredients	CONSTANT	—
Dry cans	Infrared heaters (on/off)	CONSTANT	
	Speed of cans (relative to saturator)	SETPOINT	
	Steam pressure on cans	SETPOINT	90/75/75
Calender	Calender speed	SETPOINT	—
	Calender pressure	SETPOINT	0
	Selection of calender (large/small/cooling rolls)	CONSTANT	none
Accumulator	Accumulator outfeed speed	SETPOINT	8.3
	Nip roll (open/closed)	CONSTANT	—
	Amount of counter weight on accumulator	CONSTANT	—
Winder	Tension during winding	AFTER	
	Winder speed	AFTER	
	A-frame/finished rolls	AFTER	
	Width on A-frame/finished rolls	AFTER	
Menzel slitter	Line speed	AFTER	
	Actual width	AFTER	
	Tension on finished roll	AFTER	
	Slitter blade speed	AFTER	

Figure B–2. Continued

RANDOM ORDER FOR SECOND EXPERIMENT

TREATMENT COMBINATION	FIBER WEIGHT	FOAM DENSITY	SATURATOR GAP
1	−	−	−
2	+	−	O
3	−	−	+
4	+	+	−
5	+	O	−
6	+	+	O
7	−	+	O
8	−	O	−
9	−	−	O
10	+	−	+
11	+	O	O
12	−	O	+
13	+	−	−
14	+	+	+
15	+	O	+
16	−	O	O
17	−	+	+
18	−	+	−

Figure B–3. Random Order of Treatment Combinations for Second Experiment

BASIS WEIGHT OF 7395 BLUE
SECOND DESIGNED EXPERIMENT

SAMPLE	A				B				C			
#	1	2	3	4	1	2	3	4	1	2	3	4
1	109.7	109.3	111.0	117.1	114.1	112.7	109.3	112.9	118.9	109.7	105.8	111.6
2	121.3	121.2	123.3	128.2	130.5	126.3	125.0	129.3	119.2	117.1	120.0	123.6
3	119.4	117.9	116.6	120.8	113.1	115.4	128.9	126.7	116.2	113.9	112.4	118.1 ~~[illegible]~~
4	135.3	129.4	120.6	127.1	135.1	132.6	129.0	134.0	145.3	143.6	134.0	135.3
5	122.5	124.6	123.5	131.9	131.1	128.6	120.8	131.5	131.1	122.1	124.2	134.6
6	136.1	131.7	133.8	139.5	140.5	133.4	133.8	139.7	135.5	130.9	129.8	138.4
7	129.2	127.7	126.3	134.7	124.6	127.5	130.2	134.9	123.6	118.0	120.2	132.4
8	120.2	115.4	110.8	121.7	112.7	112.9	113.5	123.6	115.0	114.5	112.5	117.7
9	114.1	113.9	110.1	114.6	119.8	111.4	107.2	114.1	110.4	108.5	107.6	115.2
10	125.4	126.1	129.0	131.9	135.9	130.7	130.8	135.7	127.1	126.3	130.3	141.1
11	135.9	133.8	131.7	137.2	136.3	131.7	133.8	141.8	142.6	142.4	131.1	135.9
12	129.0	125.9	125.0	135.1	131.9	131.5	130.3	136.1	136.1	137.4	139.0	137.2
13	129.6	128.0	126.3	139.9	135.7	133.4	124.8	129.2	126.5	127.7	126.9	137.8
14	144.3	140.7	132.8	145.3	146.0	139.7	140.5	147	146.8	142.4	138.4	149.3
15	124.0	123.8	111.4	115.6	113.3	116.8	116.6	126.3	122.1	115.0	111.0	119.6
16	121.7	117.7	108.5	118.3	118.7	117.1	115.2	124.4	121.7	119.8	118.7	124.6
17	135.1	135.5	124.4	134.4	128.2	134.0	125.7	131.9	131.7	133.0	121.7	128.4
18	123.8	122.7	120.8	133.2	126.3	124.4	125.7	128.0	125.9	125.2	122.3	134.7

Figure B–4. Results of Basis Wt. Testing
for Second Experiment

CALIPERS OF 7395 BLUE
SECOND DESIGNED EXPERIMENT

SAMPLE	A				B				C			
#	1	2	3	4	1	2	3	4	1	2	3	4
1	52	52	52	58	55	53	52	52	59	54	51	55
2	59	61	61	64	63	59	60	64	58	57	57	59
3	60	61	57	59	57	57	55	59	56	54	51	57
4	58	56	54	53	59	58	57	54	59	59	55	55
5	56	53	52	58	60	60	57	60	62	56	55	61
6	56	55	55	60	57	54	54	61	56	57	57	59
7	52	56	54	56	53	55	55	57	55	54	51	57
8	53	54	53	60	54	52	51	55	52	53	48	55
9	52	51	53	56	56	53	51	57	51	53	50	52
10	61	61	61	67	64	64	63	67	63	60	60	66
11	58	56	61	63	61	62	61	64	64	64	67	66
12	56	60	63	70	57	56	63	66	62	60	63	72
13	64	64	64	76	65	61	65	70	62	63	62	66
14	60	63	63	71	61	63	67	72	62	67	65	70
15	56	59	58	60	54	55	57	58	56	57	58	65
16	51	49	51	60	54	53	54	59	56	53	52	58
17	57	54	57	63	58	57	59	67	53	54	60	64
18	52	50	51	57	53	53	55	55	57	53	54	61

Figure B–5. Results of Caliper Testing for Second Experiment

AIR PERMEABILITY OF 7395 BLUE
SECOND DESIGNED EXPERIMENT

SAMPLE	A				B				C			
#	1	2	3	4	1	2	3	4	1	2	3	4
1	303	296	288	289	293	302	307	299	297	303	304	309
2	288	278	288	278	253	261	268	274	278	293	274	276
3	280	293	288	278	301	291	272	272	287	298	296	294
4	234	248	280	256	248	250	254	244	218	231	245	240
5	270	258	265	250	253	261	272	268	267	267	260	245
6	242	242	226	240	232	232	232	254	247	257	245	240
7	250	242	250	236	257	250	237	254	261	276	268	232
8	265	284	298	274	284	287	287	261	292	291	288	281
9	285	278	288	286	287	280	304	289	291	288	296	264
10	268	268	248	256	257	251	263	279	274	270	257	254
11	248	248	257	250	253	247	256	239	234	251	268	274
12	254	261	271	268	260	247	268	254	264	248	264	248
13	264	267	271	263	261	240	275	271	275	264	268	256
14	226	250	261	257	223	247	250	236	219	242	253	234
15	267	269	311	304	289	284	291	280	267	293	305	289
16	264	257	309	291	271	267	285	268	265	272	278	260
17	236	218	264	265	272	231	271	260	236	232	294	289
18	242	254	253	253	253	257	251	267	256	261	275	251

Figure B–6. Results of CFM Testing for
Second Experiment

	A	B	C
1.	6	6	7
2.	6	6	6
3.	3	3	3
4.	9	9	9
5.	8	8	8
6.	6	6	7
7.	6	6	6
8.	6	7	7
9.	5	5	5
10.	4	3	3
11.	2	2	2
12.	2	2	2
13.	1	1	2
14.	3	3	3
15.	1	1	1
16.	2	2	2
17.	2	2	2
18.	2	5	5

10 = Saturator marks;   0 = White, fuzzy

Figure B–7. Results of Appearance Testing for Second Experiment

FOAM DENSITY SAMPLES FOR SECOND DESIGNED EXPERIMENT

Grams

SAMPLE	A	B	C
1	21.15	24.31	29.10
2	21.03	21.77	21.19
3	20.85	22.36	23.29
4	27.65	30.23	29.98
5	21.39	24.25	27.19
6	30.02	30.71	31.32
7	30.53	32.10	34.21
8	28.16	28.43	28.24
9	23.20	26.06	20.93
10	26.30	26.36	20.53
11	25.90	25.65	26.03
12	26.08	26.59	28.16
13	26.51	24.95	25.17
14	33.65	38.17	34.29
15	26.36	24.90	26.20
16	26.76	24.28	26.15
17	31.88	32.02	30.78
18	33.46	30.43	33.95
Tare	2.75	2.75	2.75

CUP SIZE 260 ml

Figure B-8. Foam Density Measurements for Second Experiment

APPENDIX C. ANALYSIS OF CFM

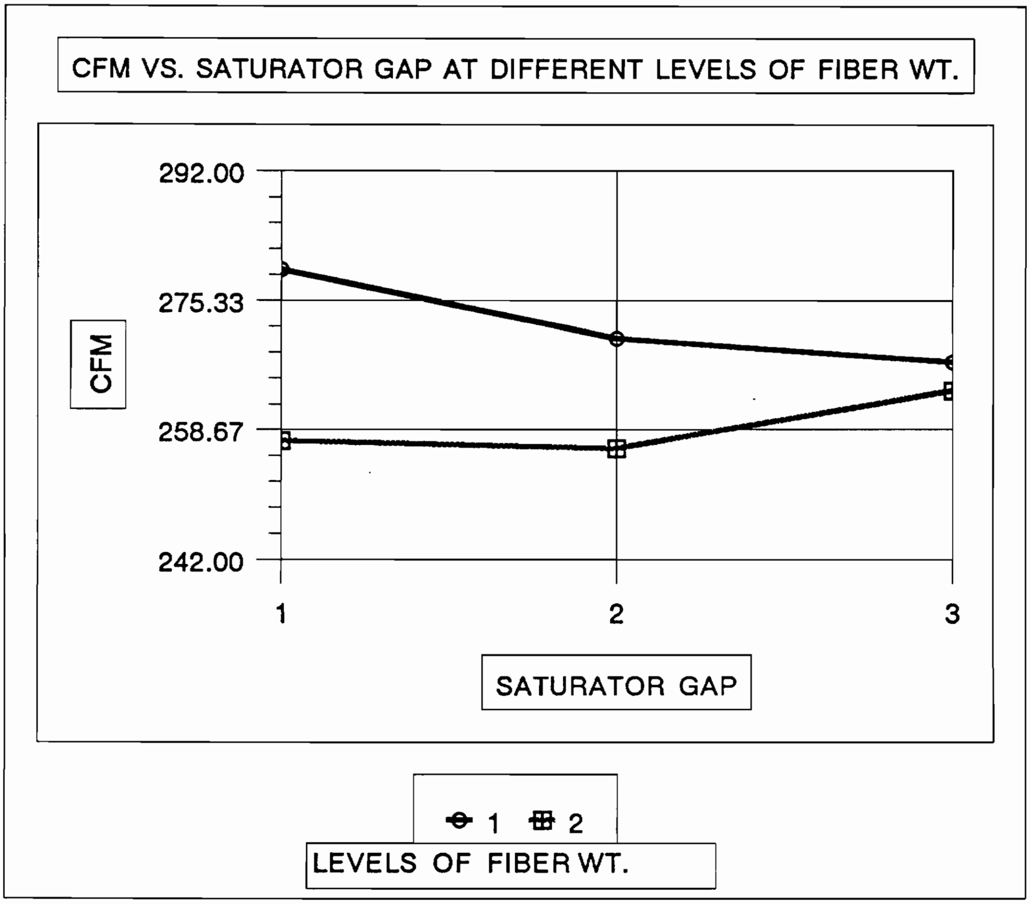

Figure C-1. CFM vs. Saturator Gap at Two Levels of Fiber Wt.

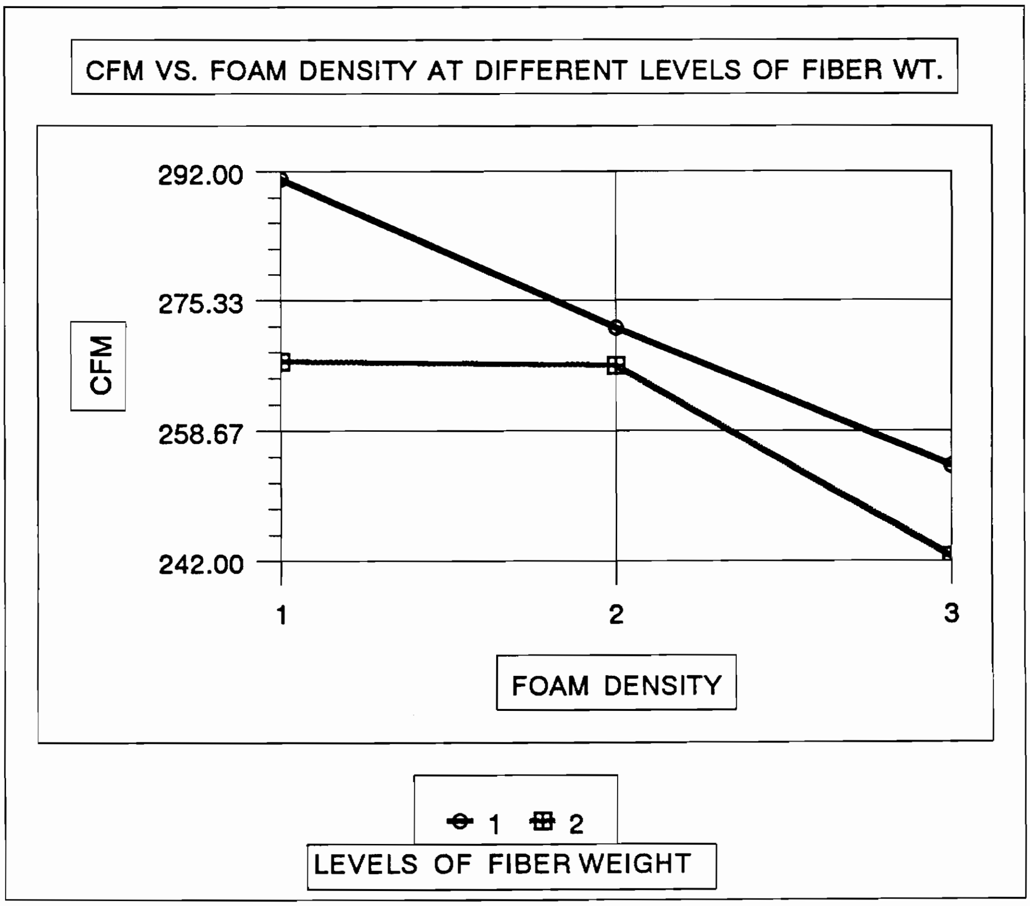

Figure C–2. CFM vs. Foam Density at Two Levels of Fiber Wt.

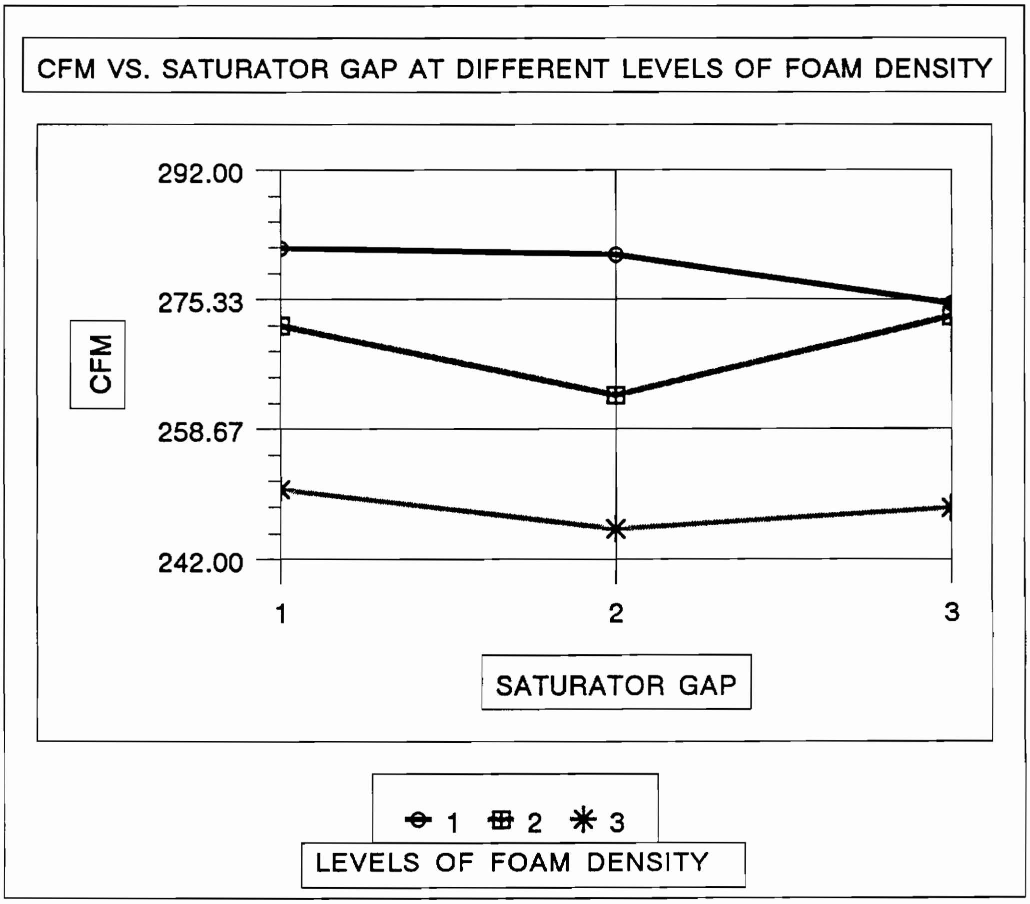

Figure C–3. CFM vs. Saturator Gap at Three Levels of Foam Density

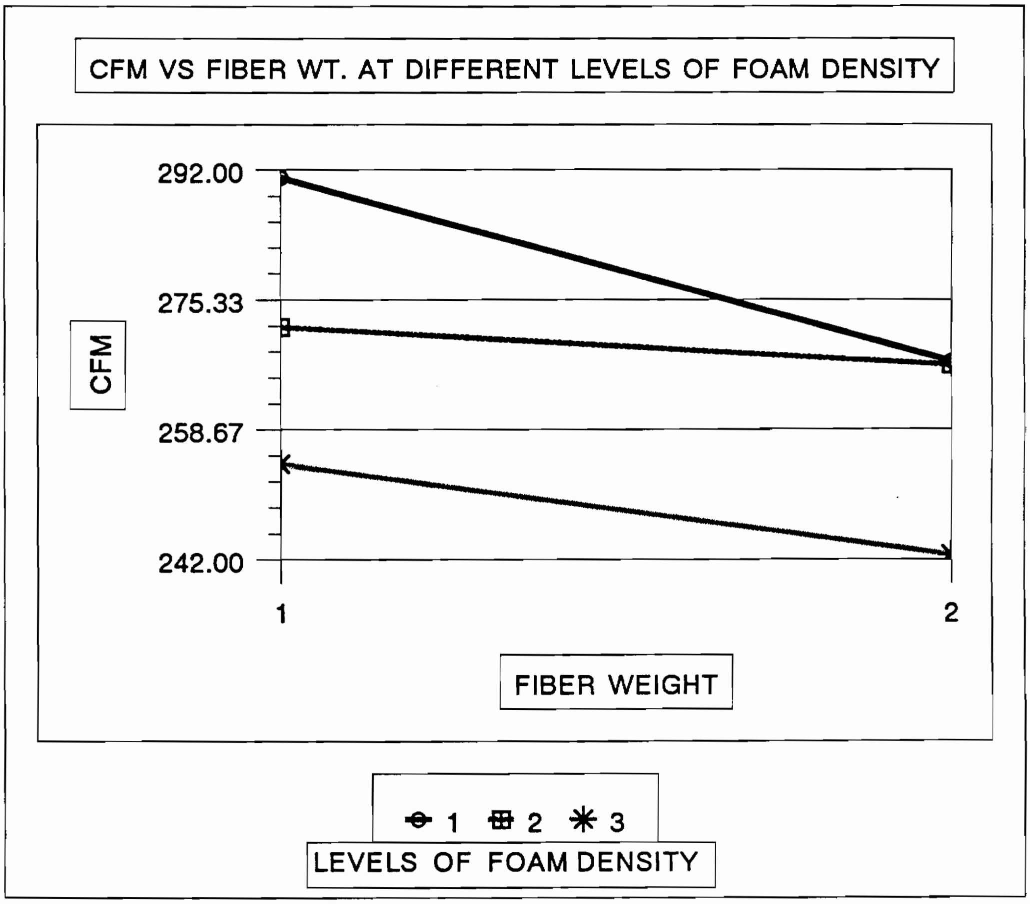

Figure C-4. CFM vs. Fiber Wt. at Three levels of Foam Density

Level of Foam Density	CFM
1	279.28
2	269.56
3	248.67

$CR_T = q(r_{max}, df_{S/A}) * SQRT(MS_{S/A}/s)$

$= 3.42 * SQRT(157/18)$

$= 10.1$

Foam(1) − Foam(2) = 279.28 − 269.56 = 9.72

Foam(1) − Foam(3) = 279.28 − 248.67 = 30.61 *

Foam(2) − Foam(3) = 269.56 − 248.67 = 20.89 *

Foam(1) and Foam(2) are significantly higher in CFM than Foam(3) at the 95% confidence level.

Figure C-5. Tukey Test for CFM at Three Levels of Foam Density

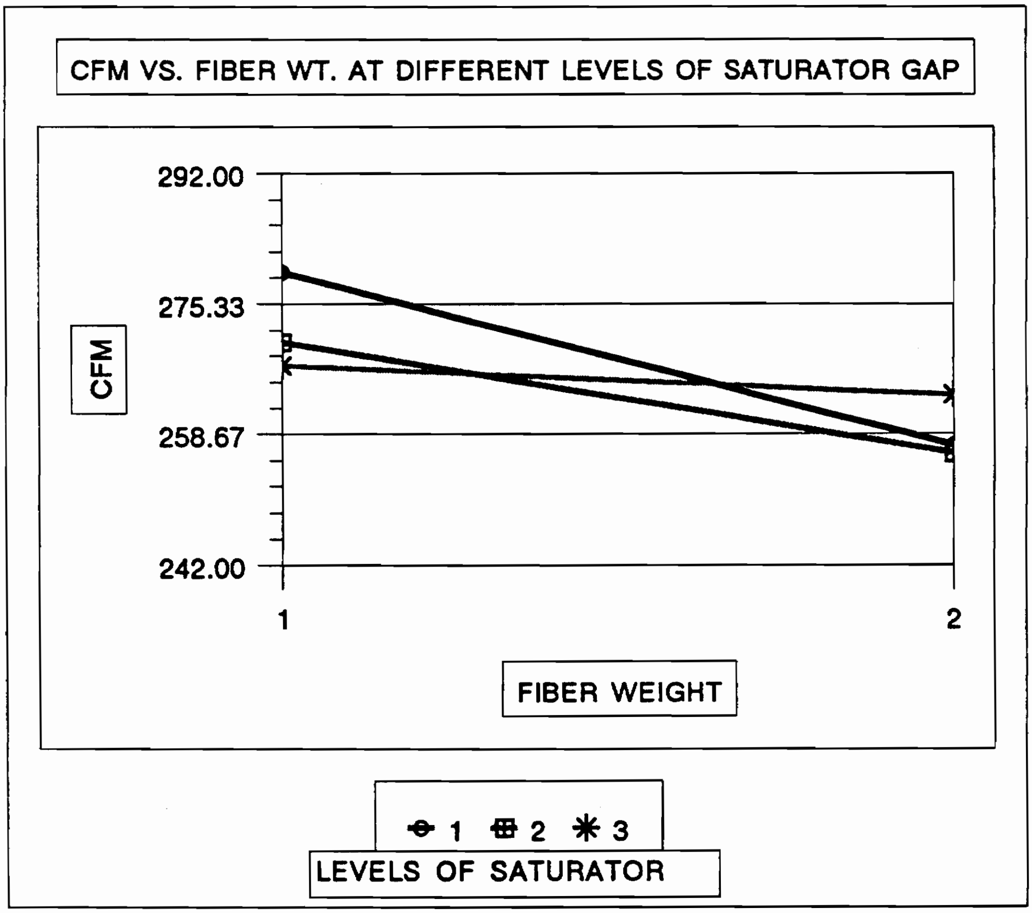

Figure C-6. CFM vs. Fiber Wt. at Three Levels of Saturator Gap

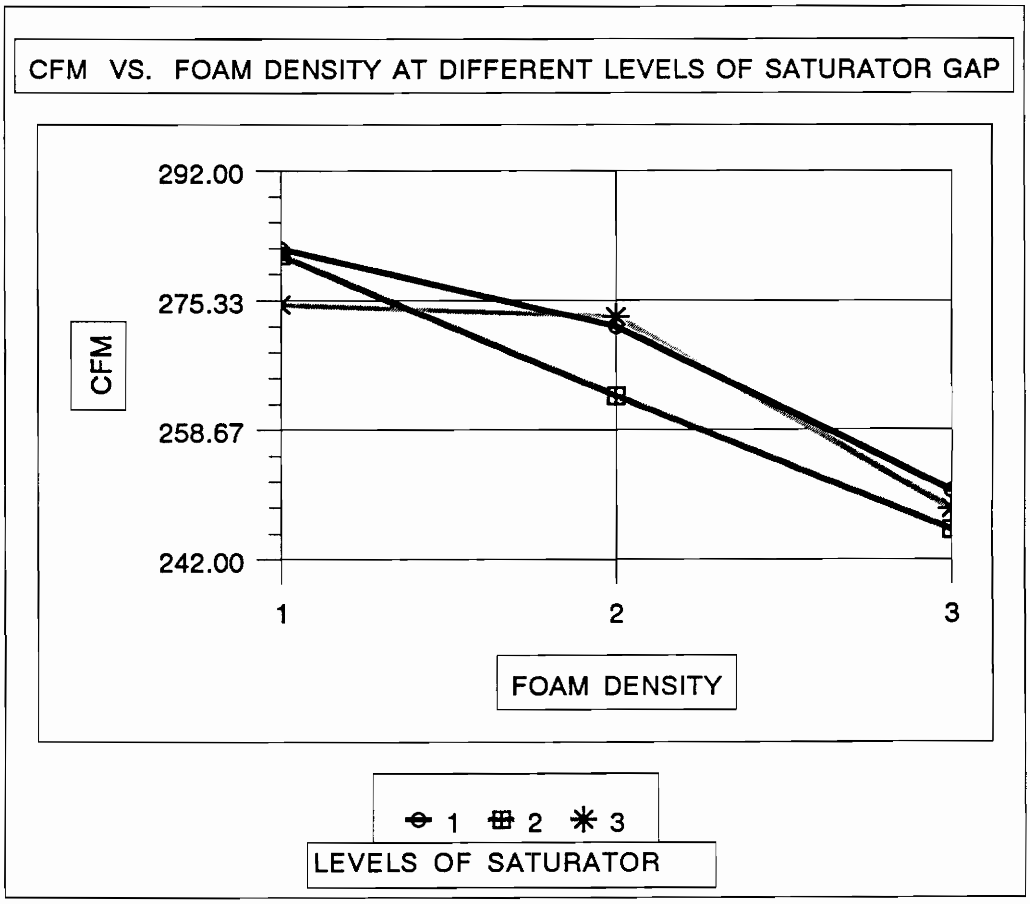

Figure C-7. CFM vs. Foam Density and Three Levels of Foam Density

```
Analysis of Variance for cfm(f-1)

Source               DF        SS         MS         F       P
den(f-1)              2      5981.6    2990.81    93.57   0.000
sat(f-1)              2       674.3     337.15    10.55   0.001
den(f-1)*sat(f-1)     4       523.5     130.87     4.09   0.016
Error                18       575.3      31.96
Total                26      7754.7     298.26


Analysis of Variance for cfm(f-2)

Source               DF        SS         MS         f        P
den(f-2)              2      3634.7    1817.37    50.07   0.000
sat(f-2)              2       305.4     152.70     4.21   0.032
den(f-2)*sat(f-2)     4      2058.6     514.65    14.18   0.000
Error                18       653.3      36.30
Total                26      6652.1     255.85
```

Figure C-8. ANOVA Tables for CFM at Two Levels of Fiber Wt.

```
Analysis of Variance for cfm(d-1)

Source             DF       SS         MS         F      P
fib(d-1)            1     2473.4    2473.39    84.48  0.000
sat(d-1)            2      166.8      83.39     2.85  0.097
fib(d-1)*sat(d-1)   2      428.1     214.06     7.31  0.008
Error              12      351.3      29.28
Total              17     3419.6     201.15


Analysis of Variance for cfm(d-2)

Source             DF       SS         MS         F      P
fib(d-2)            1      98.00      98.00     6.17  0.029
sat(d-2)            2     371.44     185.72    11.69  0.002
fib(d-2)*sat(d-2)   2    2500.33    1250.17    78.68  0.000
Error              12     190.67      15.89
Total              17    3160.44     185.91


Analysis of Variance for cfm(d-3)

Source             DF       SS        MS          F      P
fib(d-3)            1     624.22    624.222    10.91  0.006
sat(d-3)            2      80.33     40.167     0.70  0.515
fib(d-3)*sat(d-3)   2      14.78      7.389     0.13  0.880
Error              12     686.67     57.222
Total              17    1406.00     82.706
```

Figure C-9. ANOVA Tables for CFM at Three Levels of Foam Density

APPENDIX D. ANALYSIS OF BASIS WEIGHT

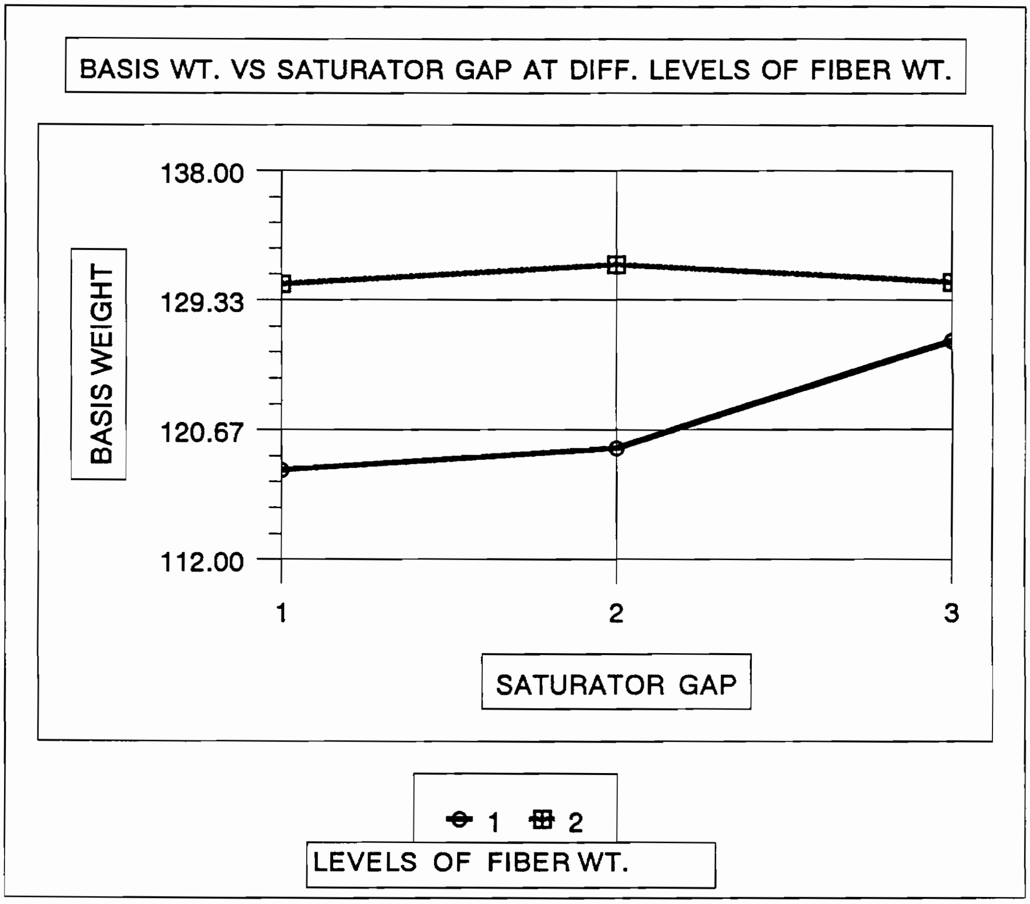

Figure D-1. Basis Wt. vs. Saturator Gap at Two Levels of Fiber Wt.

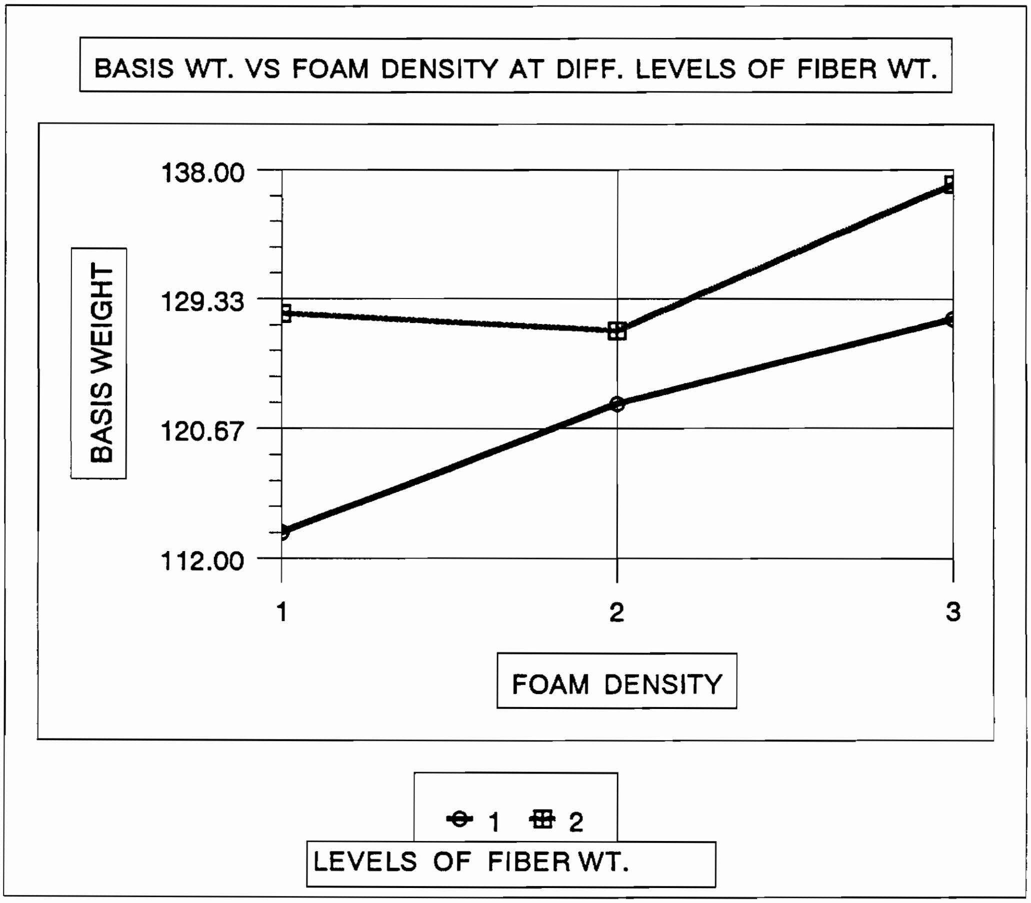

Figure D–2. Basis Wt. vs. Foam Density at Two Levels of Fiber Wt.

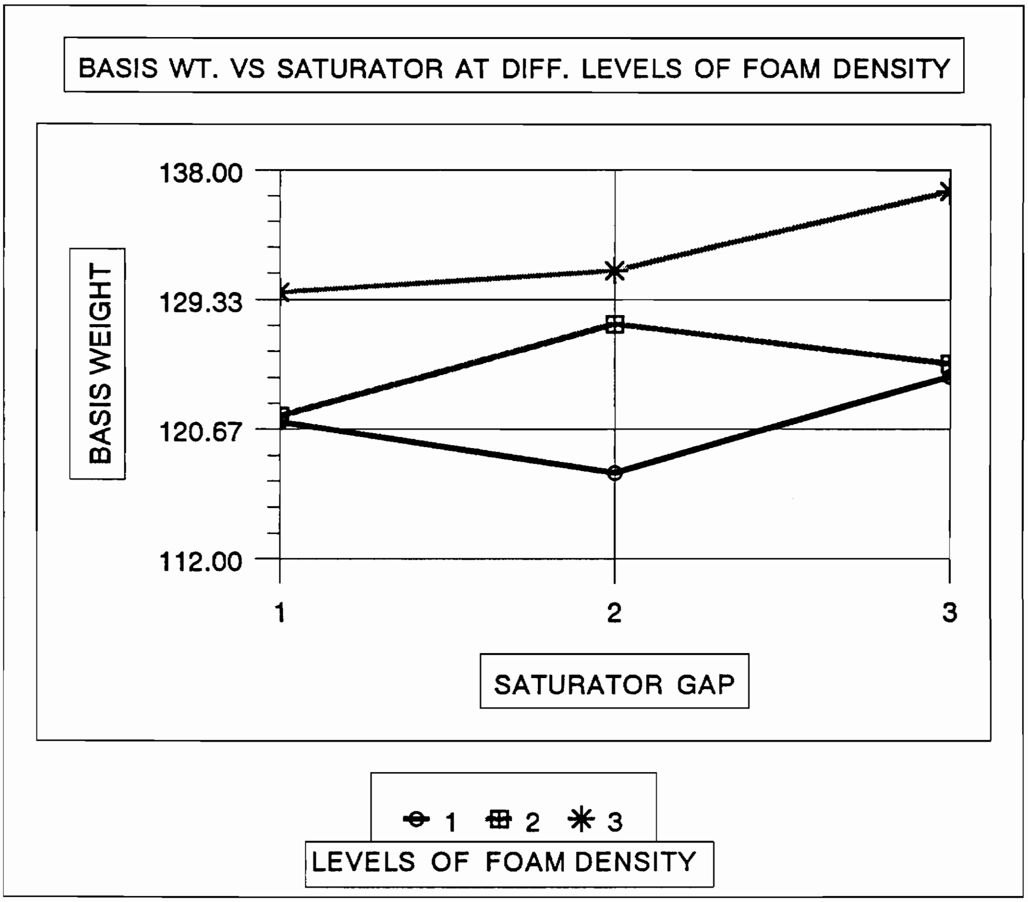

Figure D-3. Basis Wt. vs. Saturator Gap at Three Levels of Foam Density

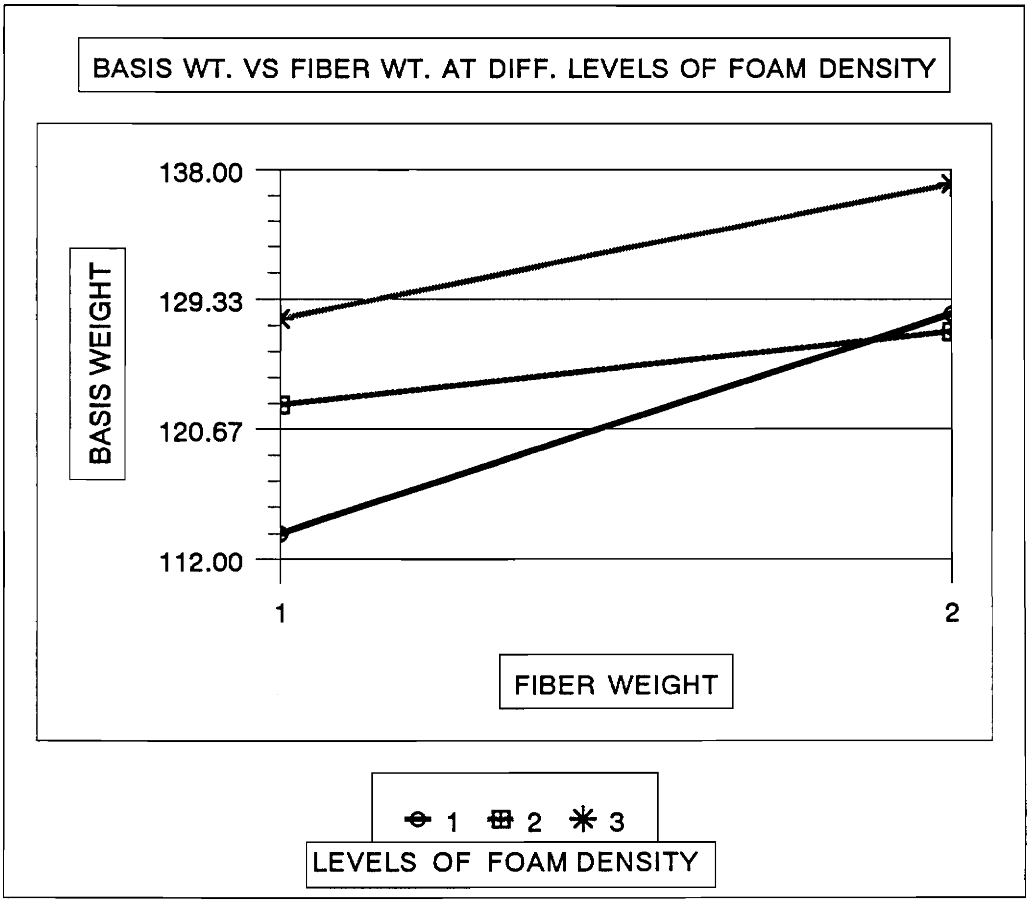

Figure D–4. Basis Wt. vs. Fiber Wt. at Three Levels of Foam Density

Level of Foam Density	Basis Wt.
1	121.03
2	124.75
3	132.52

$CR_T = q(r_{max}, df_{S/A})*SQRT(MS_{S/A}/s)$

$= 3.42*SQRT(57.8/18)$

$= 6.13$

Foam(3) − Foam(2) = 132.52 − 124.75 = 7.77 *

Foam(3) − Foam(1) = 132.52 − 121.03 = 11.49 *

Foam(2) − Foam(1) = 124.75 − 121.03 = 3.72

Foam(3) is significantly higher in Basis Wt. than Foam(1) and Foam(2) at the 95% Confidence Level.

Figure D–5. Tukey Test for Basis Wt. at Three Levels of Foam Density

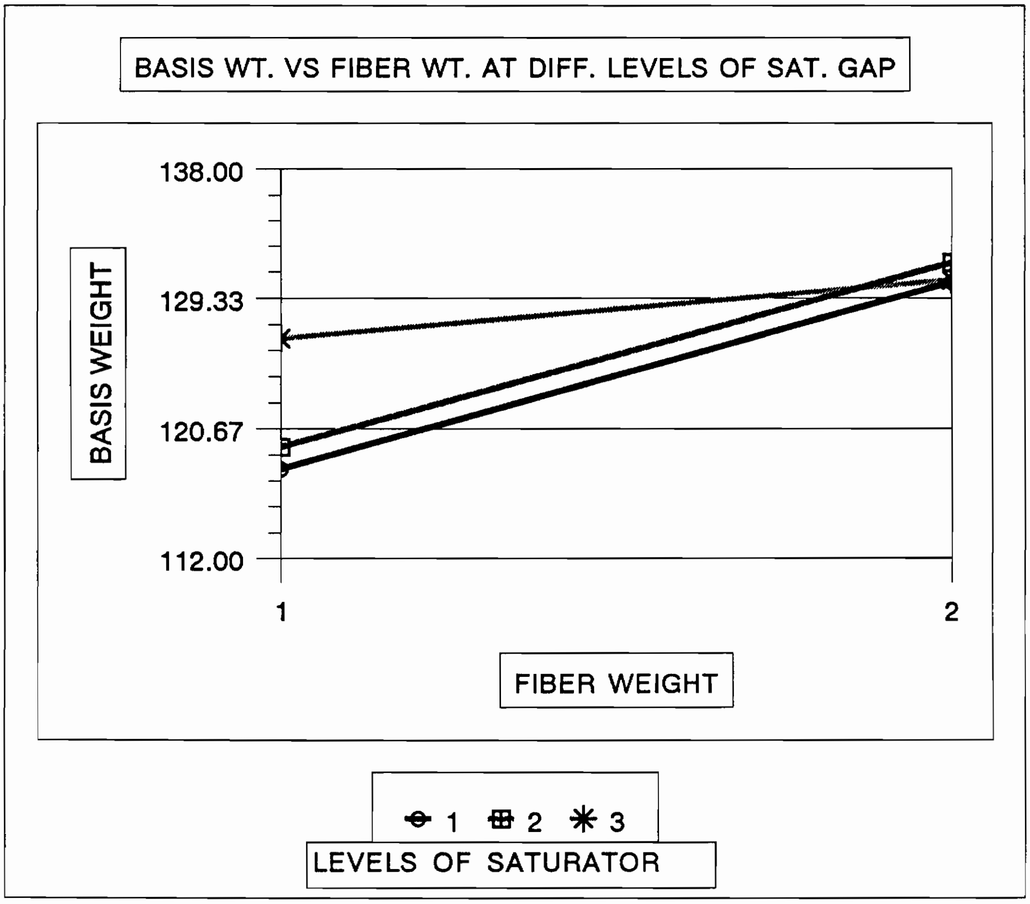

Figure D-6. Basis Wt. vs. Fiber Wt. at Three Levels of Saturator Gap

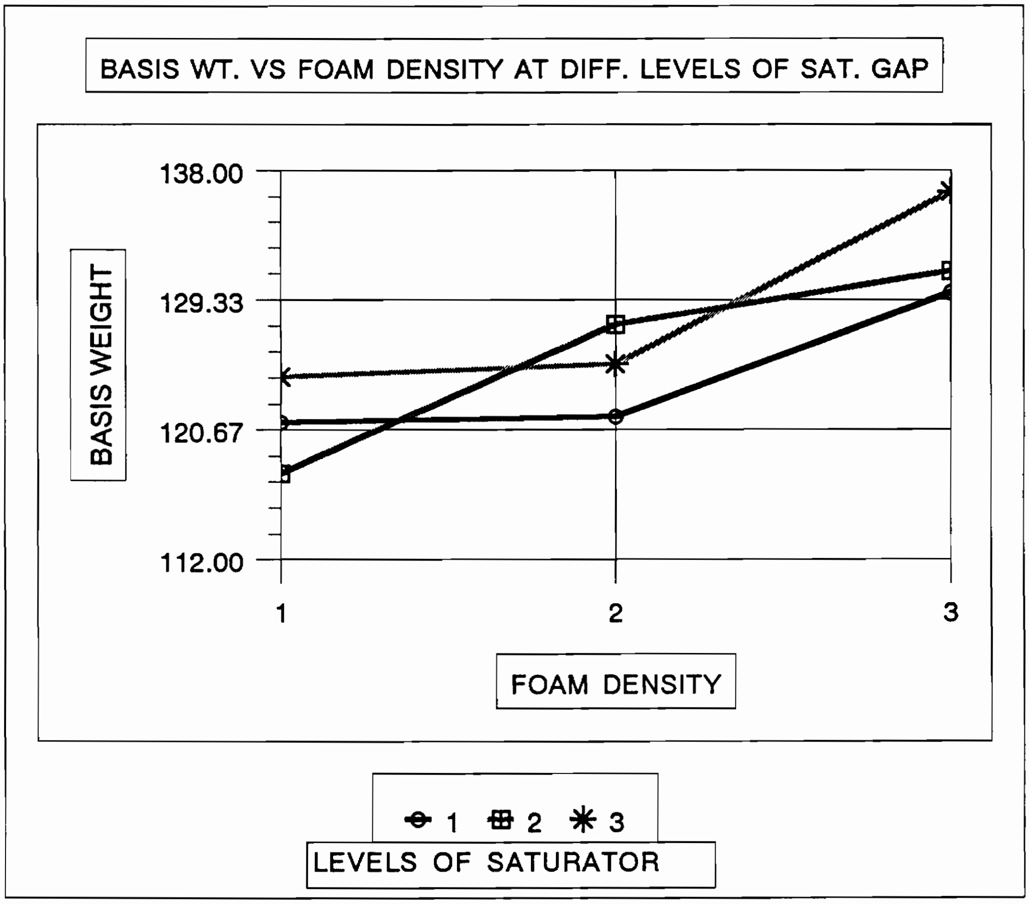

Figure D-7. Basis Wt. vs. Foam Density at Three Levels of Saturator Gap

```
Analysis of Variance for wt(d-1)

Source             DF        SS          MS        F      P
fib(d-1)            1    966.53     966.534   202.86  0.000
sat(d-1)            2    121.76      60.882    12.78  0.001
fib(d-1)*sat(d-1)   2     37.21      18.607     3.91  0.049
Error              12     57.17       4.764
Total              17   1182.69      69.570
```

```
Analysis of Variance for wt(d-2)

Source             DF        SS          MS        F      P
fib(d-2)            1    108.04     108.045    29.05  0.000
sat(d-2)            2    114.31      57.154    15.37  0.000
fib(d-2)*sat(d-2)   2    849.96     424.982   114.28  0.000
Error              12     44.63       3.719
Total              17   1116.94      65.703
```

```
Analysis of Variance for wt(d-3)

Source             DF        SS          MS        F      P
fib(d-3)            1    364.50     364.500    41.32  0.000
sat(d-3)            2    152.57      76.287     8.65  0.005
fib(d-3)*sat(d-3)   2     26.01      13.007     1.47  0.268
Error              12    105.85       8.821
Total              17    648.94      38.173
```

Figure D–8. ANOVA Tables for Basis Wt. at Three Levels of Foam Density

```
Analysis of Variance for wt(f-1)

Source             DF        SS         MS        F      P
den(f-1)            2     933.96    466.981   110.59  0.000
sat(f-1)            2     390.78    195.391    46.27  0.000
den(f-1)*sat(f-1)   4     150.94     37.734     8.94  0.000
Error              18      76.01      4.223
Total              26    1551.69     59.680


Analysis of Variance for wt(f-2)

Source             DF        SS         MS        F      P
den(f-2)            2     518.27    259.134    35.43  0.000
sat(f-2)            2       9.30      4.651     0.64  0.541
den(f-2)*sat(f-2)   4     750.81    187.704    25.66  0.000
Error              18     131.65      7.314
Total              26    1410.03     54.232
```

Figure D–9. ANOVA Tables for Basis Wt. at Two Levels of Fiber Wt.

APPENDIX E. ANALYSIS OF CALIPER

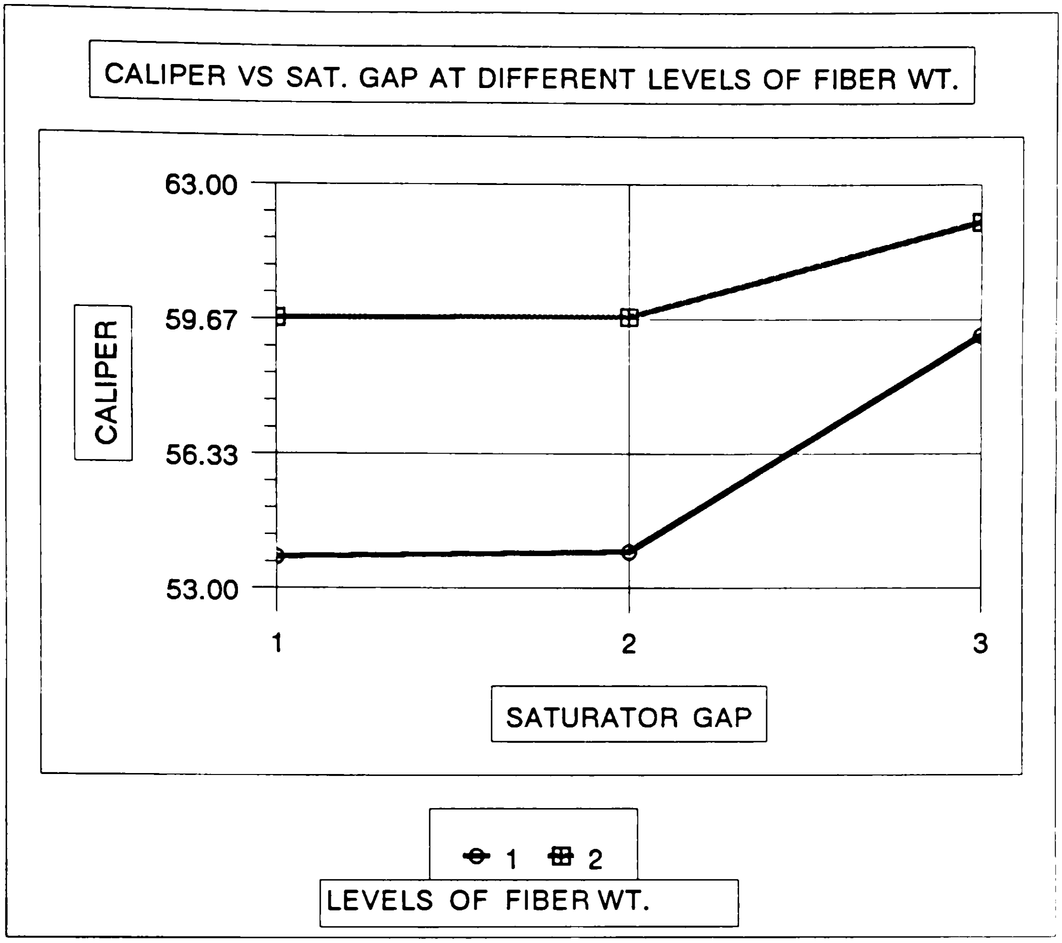

Figure E-1. Caliper vs. Saturator Gap at Two Levels of Fiber Wt.

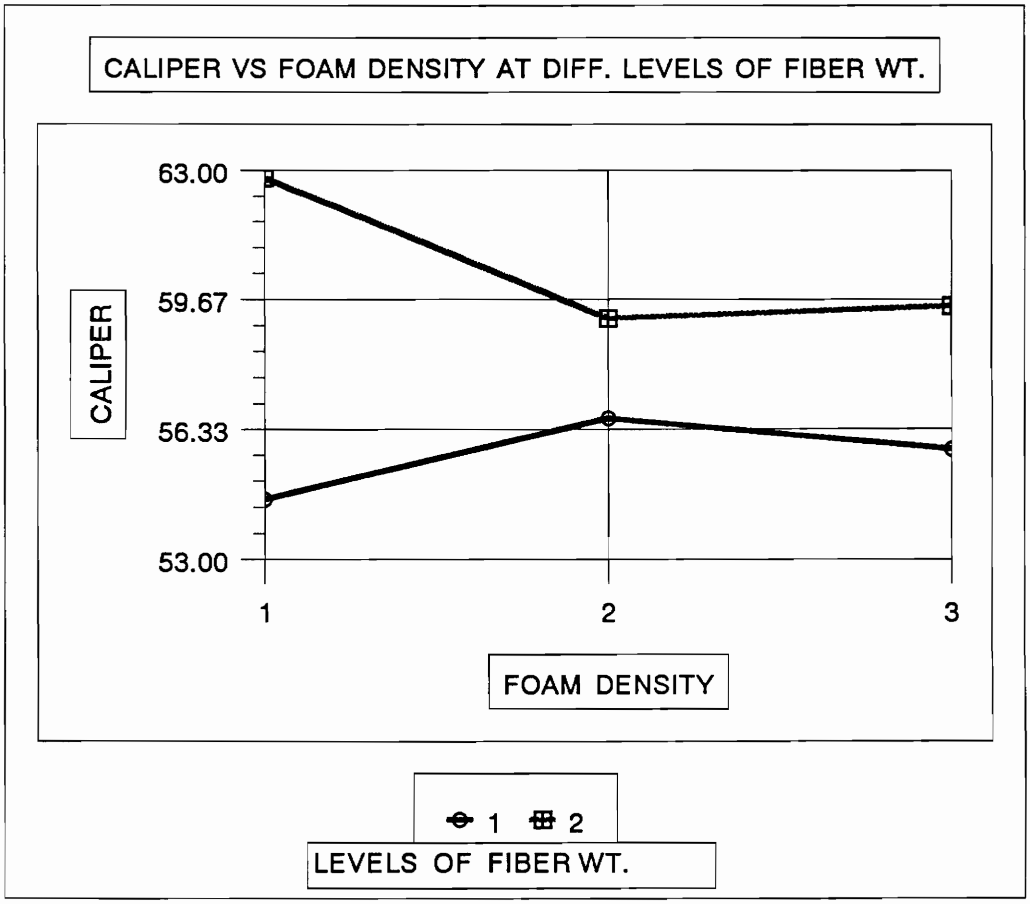

Figure E–2. Caliper vs. Foam Density at Two Levels of Fiber Wt.

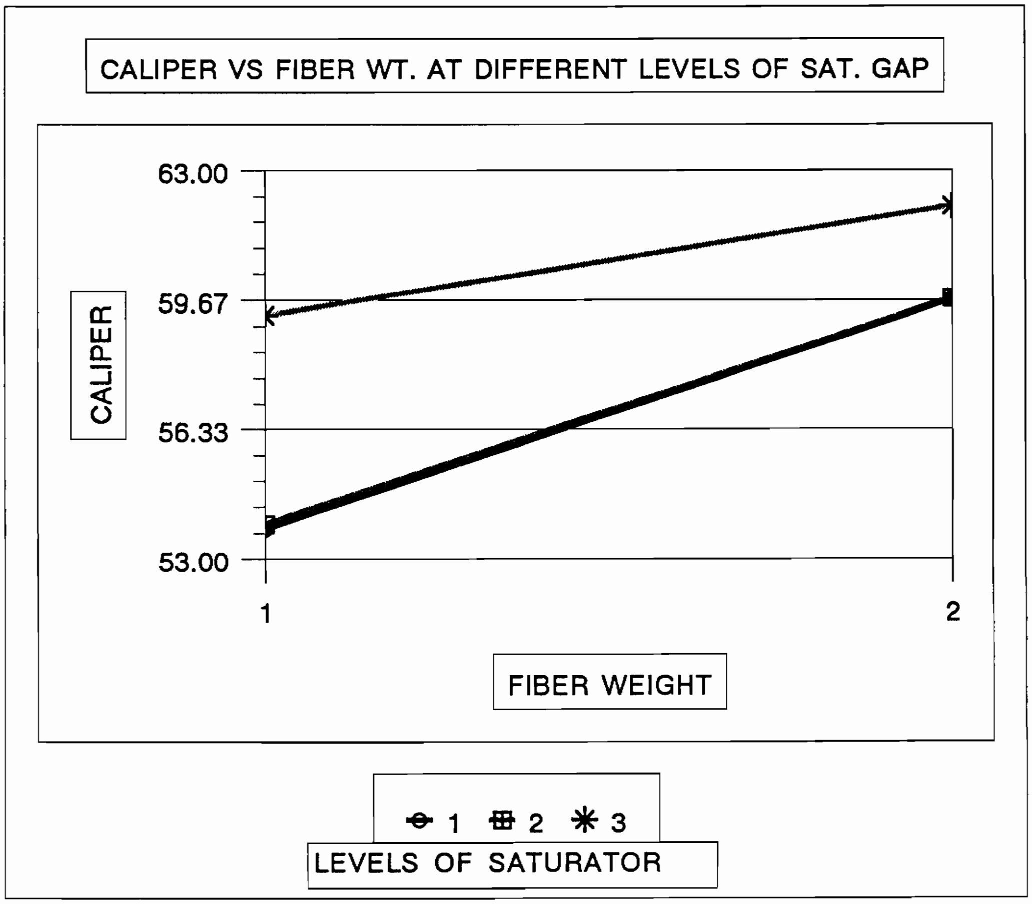

Figure E-3. Caliper vs. Fiber Wt. at Three Levels of Saturator Gap

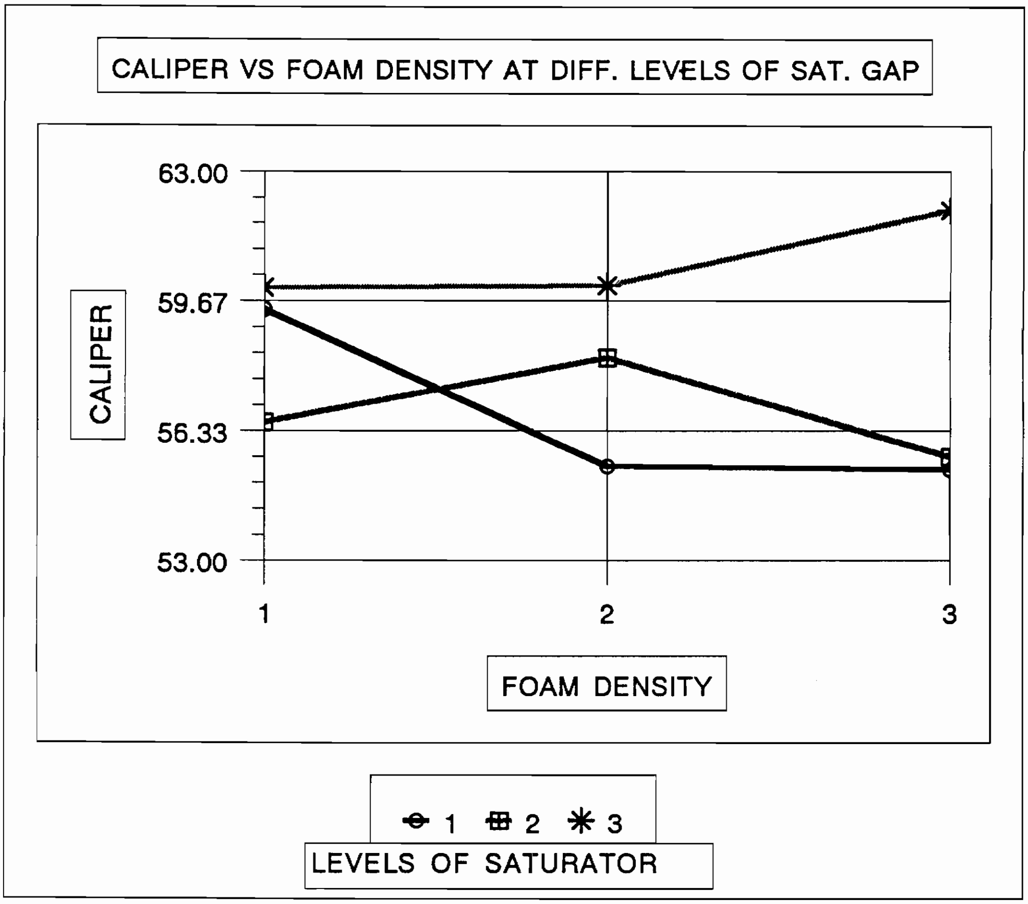

Figure E–4. Caliper vs. Foam Density at Three Levels of Saturator Gap

```
Analysis of Variance for cal(d-1)

Source              DF        SS         MS         F       P
fib(d-1)             1    304.22    304.222    109.52   0.000
sat(d-1)             2     41.44     20.722      7.46   0.008
fib(d-1)*sat(d-1)    2     18.11      9.056      3.26   0.074
Error               12     33.33      2.778
Total               17    397.11     23.359
```

```
Analysis of Variance for cal(d-2)

Source              DF        SS         MS         F       P
fib(d-2)             1     29.39     29.389      8.82   0.012
sat(d-2)             2     62.11     31.056      9.32   0.004
fib(d-2)*sat(d-2)    2    127.44     63.722     19.12   0.000
Error               12     40.00      3.333
Total               17    258.94     15.232
```

```
Analysis of Variance for cal(d-3)

Source              DF        SS         MS         F       P
fib(d-3)             1     60.50     60.500     54.45   0.000
sat(d-3)             2    165.44     82.722     74.45   0.000
fib(d-3)*sat(d-3)    2     20.33     10.167      9.15   0.004
Error               12     13.33      1.111
Total               17    259.61     15.271
```

Figure E-5. ANOVA Tables for Caliper at Three Levels of Foam Density

APPENDIX F. ANALYSIS OF APPEARANCE

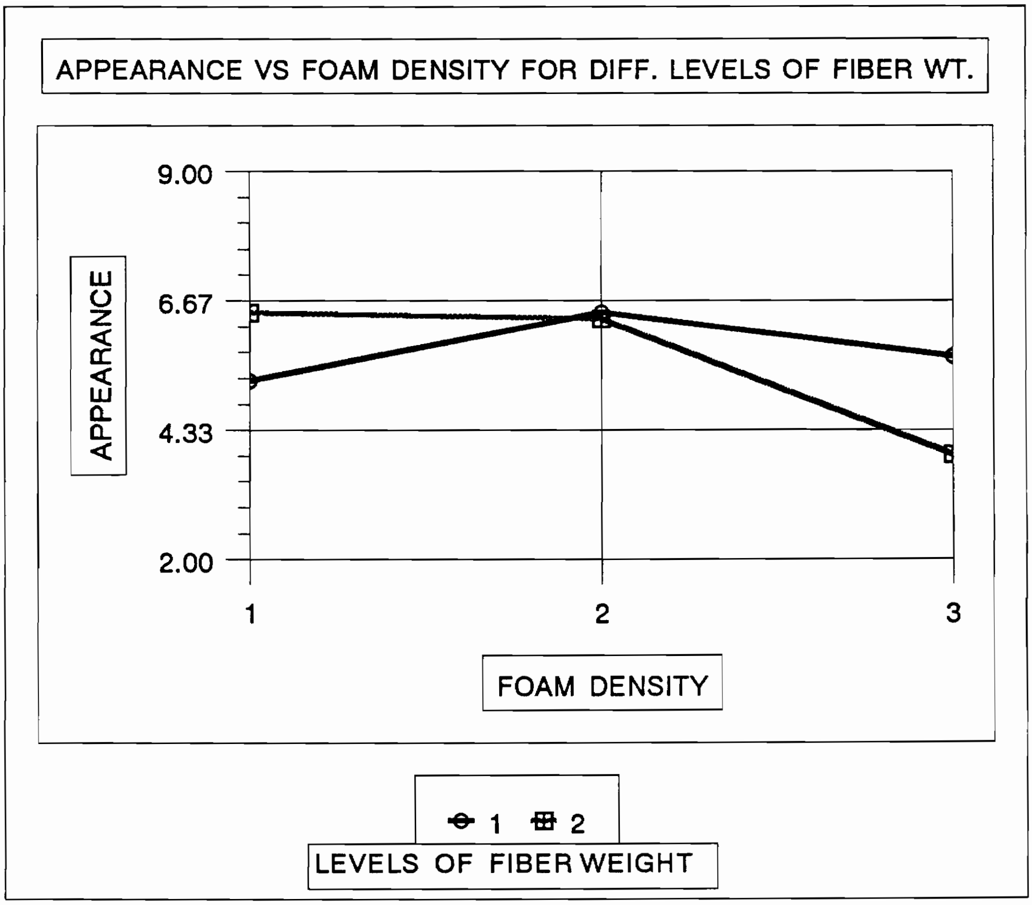

Figure F-1. Appearance vs. Foam Density at Two Levels of Fiber Wt.

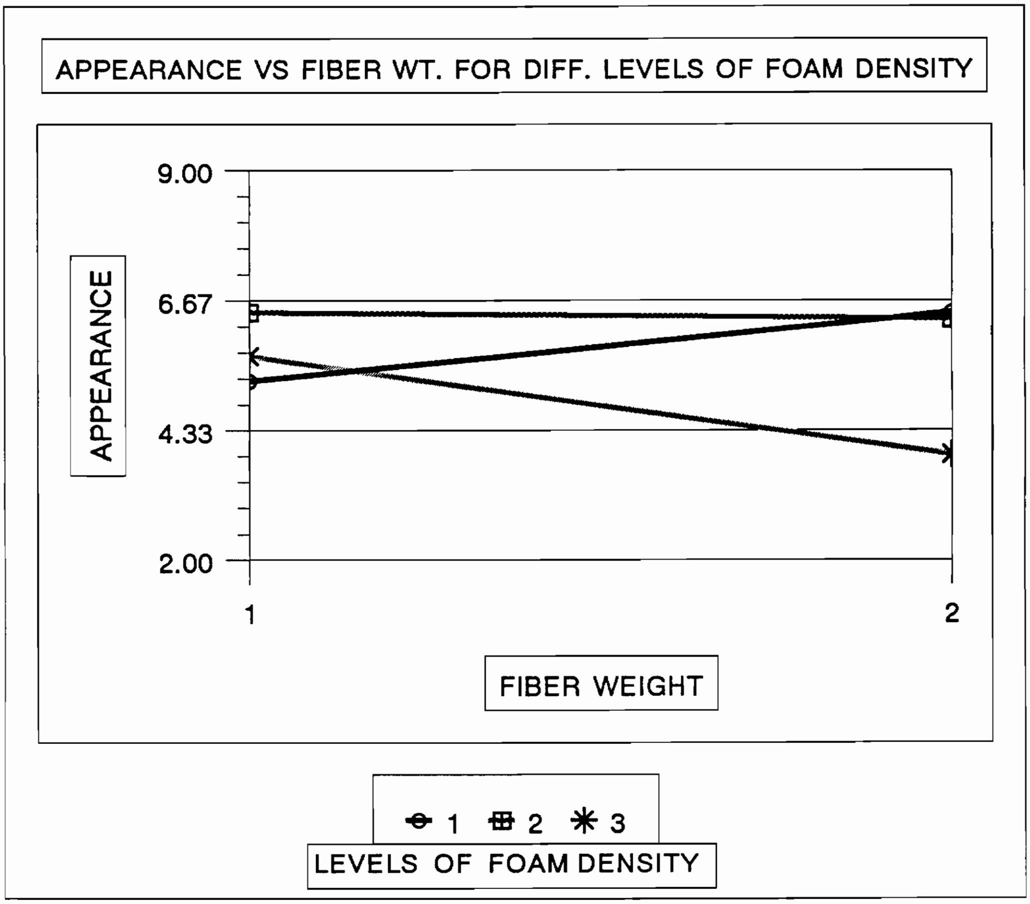

Figure F-2. Appearance vs. Fiber Wt. at Three Levels of Foam Density

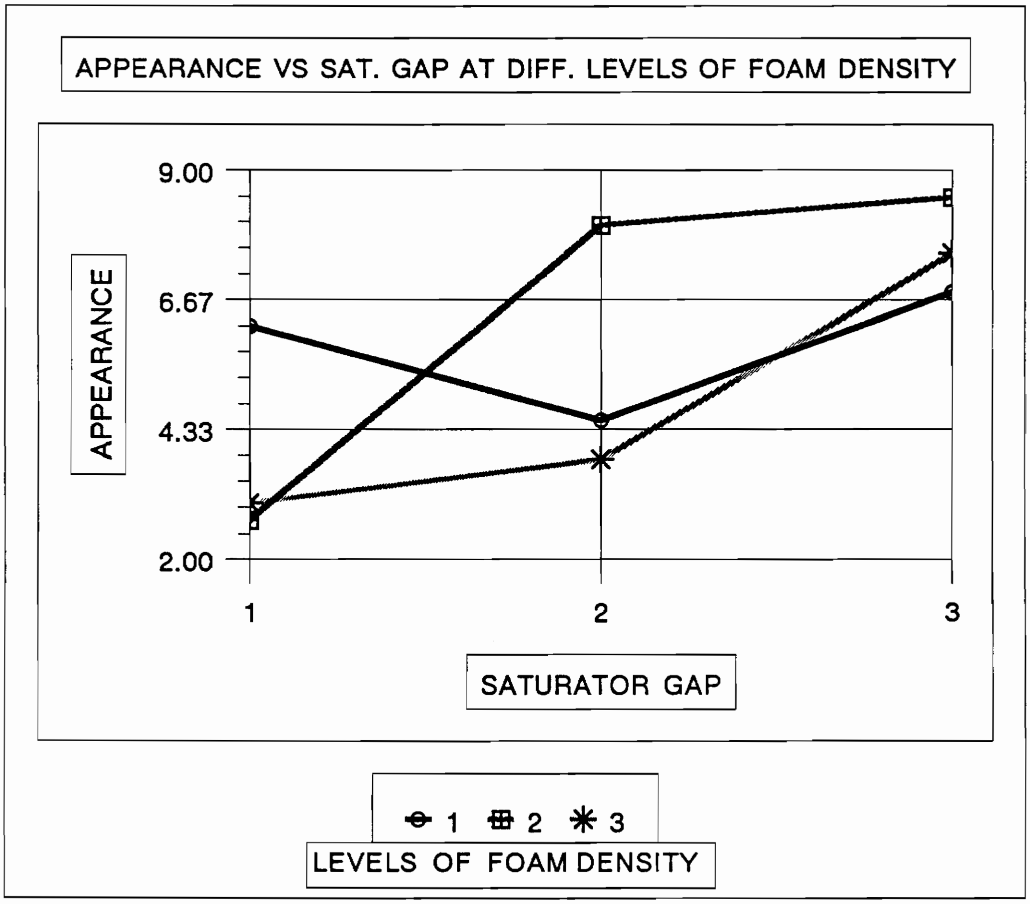

Figure F-3. Appearance vs. Saturator Gap at Three Levels of Foam Density

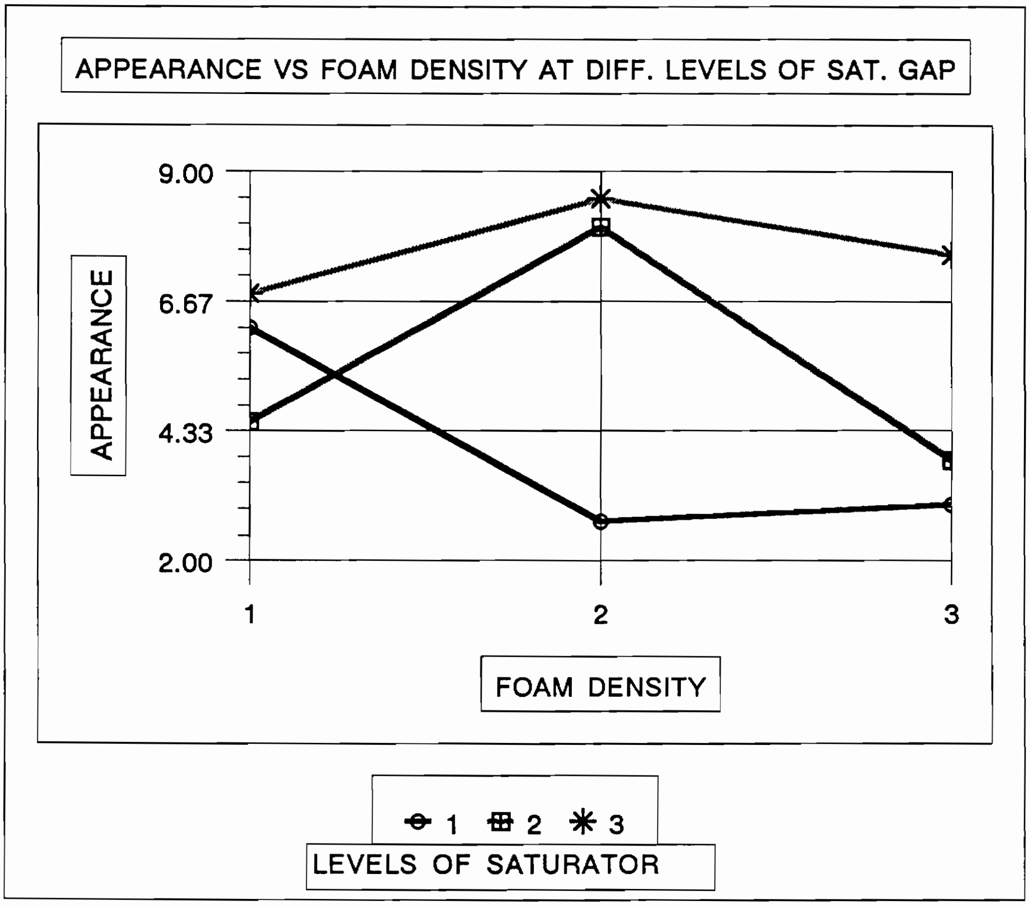

Figure F-4. Appearance vs. Foam Density at Three Levels of Saturator Gap

```
Analysis of Variance for app(f-1)

Source              DF        SS         MS        F      P
den(f-1)             2     6.889     3.4444    46.50  0.000
sat(f-1)             2    60.667    30.3333   409.50  0.000
den(f-1)*sat(f-1)    4    25.778     6.4444    87.00  0.000
Error               18     1.333     0.0741
Total               26    94.667     3.6410

Analysis of Variance for app(f-2)

Source              DF        SS         MS        F      P
den(f-2)             2    37.556    18.7778   169.00  0.000
sat(f-2)             2    62.000    31.0000   279.00  0.000
den(f-2)*sat(f-2)    4   111.111    27.7778   250.00  0.000
Error               18     2.000     0.1111
Total               26   212.667     8.1795
```

Figure F–5. ANOVA Tables for Appearance at Two Levels of Fiber Wt.

```
Analysis of Variance for app(s-1)

Source              DF        SS         MS        F      P
fib(s-1)             1     0.056     0.0556     0.33  0.574
den(s-1)             2    44.778    22.3889   134.33  0.000
fib(s-1)*den(s-1)    2    64.111    32.0556   192.33  0.000
Error               12     2.000     0.1667
Total               17   110.944     6.5261

Analysis of Variance for app(s-2)

Source              DF       SS         MS        F      P
fib(s-2)             1   0.8889     0.8889    16.00  0.002
den(s-2)             2  60.1111    30.0556   541.00  0.000
fib(s-2)*den(s-2)    2   0.7778     0.3889     7.00  0.010
Error               12   0.6667     0.0556
Total               17  62.4444     3.6732

Analysis of Variance for app(s-3)

Source              DF       SS        MS         F      P
fib(s-3)             1   0.0556   0.05556      1.00  0.337
den(s-3)             2   8.4444   4.22222     76.00  0.000
fib(s-3)*den(s-3)    2   3.1111   1.55556     28.00  0.000
Error               12   0.6667   0.05556
Total               17  12.2778   0.72222
```

Figure F–6. ANOVA Tables for Appearance at Three Levels of Saturator Gap

```
Analysis of Variance for app(d-1)

Source             DF         SS         MS        F       P
fib(d-1)            1      6.722     6.7222    40.33   0.000
sat(d-1)            2     17.333     8.6667    52.00   0.000
fib(d-1)*sat(d-1)   2     32.444    16.2222    97.33   0.000
Error              12      2.000     0.1667
Total              17     58.500     3.4412


Analysis of Variance for app(d-2)

Source             DF         SS         MS        F       P
fib(d-2)            1      0.056     0.0556     1.00   0.337
sat(d-2)            2    125.444    62.7222    1E+03   0.000
fib(d-2)*sat(d-2)   2      4.111     2.0556    37.00   0.000
Error              12      0.667     0.0556
Total              17    130.278     7.6634


Analysis of Variance for app(d-3)

Source             DF         SS         MS        F       P
fib(d-3)            1    14.2222    14.2222   256.00   0.000
sat(d-3)            2    68.7778    34.3889   619.00   0.000
fib(d-3)*sat(d-3)   2    11.4444     5.7222   103.00   0.000
Error              12     0.6667     0.0556
Total              17    95.1111     5.5948
```

Figure F-7. ANOVA Tables for Appearance at Three Levels of Foam Density

APPENDIX G. REGRESSION MODELS

```
The regression equation is

CFM = 416 - 1.80 fiber - 81 sat-gap - 737 density

Predictor       Coef       Stdev    t-ratio        p
Constant      415.61       22.20      18.72    0.000
fiber        -1.8033      0.4015      -4.49    0.000
sat-gap        -80.9       262.3      -0.31    0.759
density       -737.3       101.1      -7.30    0.000

s = 11.79       R-sq = 58.6%     R-sq(adj) = 56.1%

Analysis of Variance

SOURCE       DF          SS          MS         F        p
Regression    3      9846.3      3282.1     23.62    0.000
Error        50      6947.2       138.9
Total        53     16793.5


SOURCE       DF      SEQ SS
fiber         1      2386.7
sat-gap       1        64.0
density       1      7395.6
```

Figure G-1. Linear Regression Model for CFM

```
The regression equation is

CFM = 1051 - 12.5 fiber - 20697 sat-gap - 1115 density -
4447 foam*2 + 113055 sat*2 + 13.1 fib*foam + 250 fib*sat +
15106 foam*sat

Predictor       Coef        Stdev    t-ratio        p
Constant      1050.8        148.8       7.06    0.000
fiber        -12.461        2.977      -4.19    0.000
sat-gap       -20697         4938      -4.19    0.000
density        -1115         1229      -0.91    0.369
foam*2         -4447         4861      -0.91    0.365
sat*2         113055        51632       2.19    0.034
fib*foam       13.12        22.72       0.58    0.566
fib*sat       249.65        57.63       4.33    0.000
foam*sat       15106        15551       0.97    0.337

s = 9.983       R-sq = 73.3%     R-sq(adj) = 68.6%

Analysis of Variance

SOURCE       DF          SS          MS         F        p
Regression    8     12309.2      1538.6     15.44    0.000
Error        45      4484.3        99.7
Total        53     16793.5


SOURCE       DF      SEQ SS
fiber         1      2386.7
sat-gap       1        64.0
density       1      7395.6
foam*2        1         4.9
sat*2         1       472.8
fib*foam      1        88.2
fib*sat       1      1803.1
foam*sat      1        94.0
```

Figure G-2. Quadratic Regression Model for CFM

```
The regression equation is

WEIGHT = 33.8 + 1.25 fiber + 255 sat-gap + 309 density

Predictor        Coef       Stdev    t-ratio        p
Constant        33.82       10.26       3.30    0.002
fiber          1.2491      0.1855       6.73    0.000
sat-gap         254.6       121.2       2.10    0.041
density        309.37       46.69       6.63    0.000

s = 5.446       R-sq = 64.6%     R-sq(adj) = 62.4%

Analysis of Variance

SOURCE       DF          SS          MS         F        p
Regression    3     2701.70      900.57     30.36    0.000
Error        50     1483.15       29.66
Total        53     4184.85

SOURCE       DF      SEQ SS
fiber         1     1223.13
sat-gap       1      176.45
density       1     1302.12
```

Figure G–3. Linear Regression Model for Basis Wt.

```
The regression equation is

WEIGHT = - 160 + 5.90 fiber + 5321 sat-gap + 263 density +
1534 foam*2 - 5503 sat*2 - 5.7 fib*foam - 110 fib*sat + 645
foam*sat

 Predictor       Coef        Stdev    t-ratio        p
 Constant     -159.95        73.86      -2.17    0.036
 fiber          5.903        1.478       3.99    0.000
 sat-gap         5321         2452       2.17    0.035
 density        262.9        610.1       0.43    0.669
 foam*2          1534         2414       0.64    0.528
 sat*2          -5503        25638      -0.21    0.831
 fib*foam       -5.72        11.28      -0.51    0.614
 fib*sat      -109.85        28.62      -3.84    0.000
 foam*sat         645         7722       0.08    0.934

 s = 4.957       R-sq = 73.6%     R-sq(adj) = 68.9%

 Analysis of Variance

 SOURCE       DF          SS          MS         F        p
 Regression    8     3079.19      384.90     15.67    0.000
 Error        45     1105.65       24.57
 Total        53     4184.85

 SOURCE       DF      SEQ SS
 fiber         1     1223.13
 sat-gap       1      176.45
 density       1     1302.12
 foam*2        1        0.52
 sat*2         1        0.86
 fib*foam      1        8.26
 fib*sat       1      367.68
 foam*sat      1        0.17
```

Figure G-4. Quadratic Regression Model for Basis Wt.

```
The regression equation is

CALIPER = 20.1 + 0.606 fiber + 260 sat-gap + 23.7 density

Predictor       Coef       Stdev    t-ratio        p
Constant      20.107       5.751       3.50    0.001
fiber         0.6064      0.1040       5.83    0.000
sat-gap       259.85       67.94       3.82    0.000
density        23.67       26.18       0.90    0.370

s = 3.054       R-sq = 49.7%     R-sq(adj) = 46.7%

Analysis of Variance

SOURCE       DF          SS          MS         F        p
Regression    3      460.61      153.54     16.47    0.000
Error        50      466.20        9.32
Total        53      926.81

SOURCE       DF      SEQ SS
fiber         1      312.96
sat-gap       1      140.03
density       1        7.62
```

Figure G–5. Linear Regression Model for Caliper.

```
The regression equation is

CALIPER = 30.7 + 2.00 fiber - 1579 sat-gap - 105 density +
269 foam*2 + 30998 sat*2 - 4.50 fib*foam - 26.6 fib*sat +
6976 foam*sat


Predictor        Coef        Stdev     t-ratio        p
Constant        30.66        43.47        0.71    0.484
fiber          1.9952       0.8700        2.29    0.027
sat-gap         -1579         1443       -1.09    0.280
density        -105.3        359.0       -0.29    0.771
foam*2            269         1421        0.19    0.850
sat*2           30998        15088        2.05    0.046
fib*foam       -4.499        6.640       -0.68    0.502
fib*sat        -26.58        16.84       -1.58    0.121
foam*sat         6976         4544        1.54    0.132

s = 2.917       R-sq = 58.7%      R-sq(adj) = 51.3%

Analysis of Variance

SOURCE       DF          SS          MS         F        p
Regression    8     543.888      67.986      7.99    0.000
Error        45     382.926       8.509
Total        53     926.815

SOURCE       DF      SEQ SS
fiber         1     312.963
sat-gap       1     140.028
density       1       7.623
foam*2        1       0.245
sat*2         1      36.060
fib*foam      1       0.917
fib*sat       1      25.999
foam*sat      1      20.054
```

Figure G–6. Quadratic Regression Model for Caliper

```
The regression equation is

APP = 11.3 + 0.0298 fiber - 246 sat-gap + 10.6 density

Predictor        Coef        Stdev     t-ratio        p
Constant       11.275        3.621        3.11    0.003
fiber         0.02981      0.06548        0.46    0.651
sat-gap       -245.84        42.78       -5.75    0.000
density         10.60        16.48        0.64    0.523

s = 1.923        R-sq = 40.0%      R-sq(adj) = 36.4%

Analysis of Variance

SOURCE        DF          SS           MS           F         p
Regression     3     123.196       41.065       11.11     0.000
Error         50     184.804        3.696
Total         53     308.000


SOURCE        DF      SEQ SS
fiber          1       0.667
sat-gap        1     121.000
density        1       1.529
```

Figure G-7. Linear Regression Model for Appearance

```
The regression equation is

APP = 9.9 - 0.076 fiber + 811 sat-gap - 331 density + 1592
foam*2 - 7050 sat*2 + 3.61 fib*foam - 6.0 fib*sat - 3065
foam*sat

Predictor          Coef         Stdev      t-ratio         p
Constant           9.91         28.83         0.34     0.733
fiber           -0.0759        0.5771        -0.13     0.896
sat-gap           811.2         957.2         0.85     0.401
density          -330.7         238.1        -1.39     0.172
foam*2           1591.5         942.2         1.69     0.098
sat*2             -7050         10008        -0.70     0.485
fib*foam          3.615         4.404         0.82     0.416
fib*sat           -6.02         11.17        -0.54     0.593
foam*sat          -3065          3014        -1.02     0.315

s = 1.935          R-sq = 45.3%      R-sq(adj) = 35.6%

Analysis of Variance

SOURCE        DF          SS           MS          F         p
Regression     8     139.534       17.442       4.66     0.000
Error         45     168.466        3.744
Total         53     308.000


SOURCE        DF      SEQ SS
fiber          1       0.667
sat-gap        1     121.000
density        1       1.529
foam*2         1       8.936
sat*2          1       1.604
fib*foam       1       1.219
fib*sat        1       0.709
foam*sat       1       3.871
```

Figure G–8. Quadratic Regression Model for Appearance.

VITA

Brian S. Platnick was born on August 3, 1966 in Columbus, Ohio and raised in Bluefield, West Virginia. After earning his bachelor's degree in Industrial Engineering and Operations Research from Virginia Polytechnic Institute and State University, he began working at Hollingsworth and Vose Company in Floyd, Virginia while also pursuing his master's degress in Industrial and Systems Engineering. Upon graduation, Brian will began his studies at the Marshall Wythe School of Law at the College of William and Mary.