THE EFFECT OF CONTACT PRESSURE ON WEB PERMEABILITY

By

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NOMENCLATURE

q	Amount of Gases Diffusing through Unit Area of the Film in Unit Time (in/s)
D	Diffusion Constant
p	Pressure of the Gases (psi.)
p_c	Contact Pressure (psi.)
S	Solubility Coefficient of the Gases
c	Concentration of Gases (lb/in^3)
α	Permeability Coefficient of Gases (in^2/lbf-sec.)
L	Homogeneous Thickness of the Web Layer (in.)
h	The Air-Layer Thickness (in.)
P_a	The Ambient Air Pressure (psi)
R	The Wound Roll Radius (in.)
T	The Web Tension (lbf)
μ_a	The Viscosity of Air (in^2/lbf)
μ_f	The Viscosity of fluid (in^2/lbf)
ρ	The Air Density (lb/in^3)
V	The Sum of Web Velocity and Roller Velocity (in/sec)

CHAPTER I

INTRODUCTION

Winding webs into rolls is a popular method used by industries to store flexible sheet of materials such as those made of paper and plastic film. Winding is usually performed by automatic machines which can operate at high speeds. Over the past decade, many publications have dealt with the stress analysis of wound rolls and how to reduce winding defects.

There are many winding techniques used in web process industries, one of them is centerwinding. In centerwinding, a winding torque is provided to the core of the winding roll. During the winding process, air entrance, especially at high winding speed, can make the film buckle and slip in the wound roll. A nip roll is then used to reduce the entrance of air during the rolling process. However, the nip roll cannot completely remove the defects, because there is still some entrance of air.

To remove defects in the wound roll, the behavior of the entrance of air needs to be taken into consideration. Then, a suitable method can be found to eliminate the air in the wound roll in order to prevent it from buckling, sliding, etc. that would make the wound roll defective. The trapped air usually leaks laterally to the edges of impermeable films which have bean wound. However, the air wound in beneath permeable webs, such as bond paper and newsprint paper, can leak in both radial and tangential directions.

The behavior of the air in the interlayers of a wound roll is complex. In past years, several papers reported working on the behavior of air to try to find the factors that affect the permeability of air in the permeable webs [1][3][6]. In order to analyze the air in the wound roll, an important notation, permeability coefficient, is introduced. A higher permeability coefficient of the web corresponds to higher permeability. But, the permeability coefficient seems to change under different conditions. The purpose of this study is to investigate the transverse (perpendicular to the surface) permeability of paper, including measurements of transverse permeability as a function of sheet compression which has not been documented in the literature.

CHAPTER II

THEORY APPROACH

Permeability of films has been studied by researchers for a long time. The basic theory of permeability is established by Barrer [1]. Considering a paper with the thickness L, pressure difference p_1 - p_2 and the difference of gases concentration is c_1 - c_2, as figure 1.

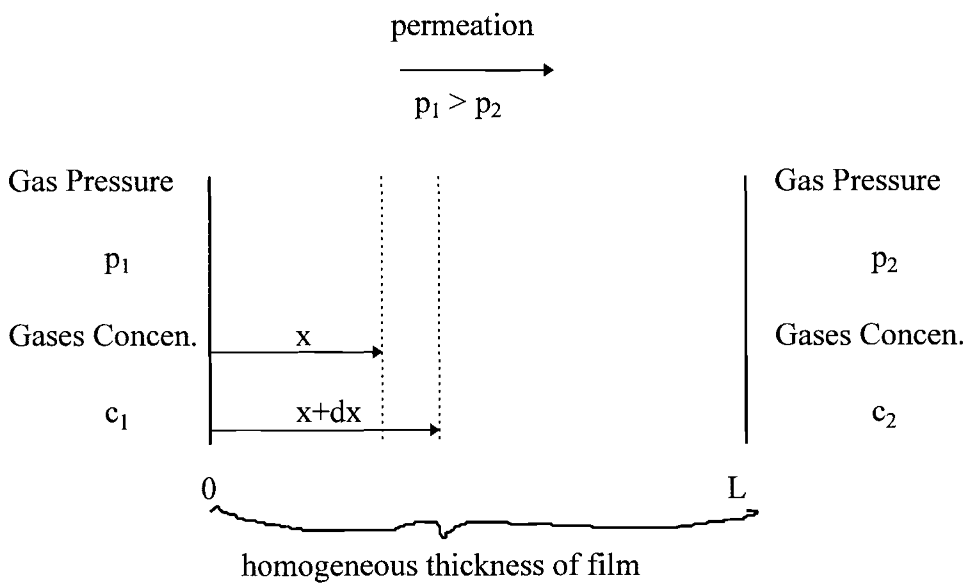

Figure 1 Gas Permeability in a Film

By the Fick's 1st Law, we have

$$q = -D\left(\frac{dc}{dx}\right) \tag{1}$$

where q is the amount of air diffusing through the unit area of the film in unit time and D the diffusion constant. The amount of gases retained in a unit volume of film is -(dq/dx). It is equal to the rate of change of concentration, c, with time, i.e.:

$$-\frac{dq}{dx} = \frac{dc}{dt} \tag{2}$$

Combining (1) and (2), the equation becomes

$$\frac{dc}{dt} = \frac{d}{dx}(D\frac{dc}{dx}) \tag{3}$$

Assume diffusion constant D is independent of concentration

$$\frac{dc}{dt} = D\frac{d^2c}{dx^2} \tag{4}$$

It is also assumed that the permeation in the paper is reached in a steady state. Then the equation (1) becomes

$$-\frac{dq}{dx} = \frac{dc}{dt} = 0 \qquad (5)$$

Combining equation (4) and equation (5), finally we can get

$$q = -D(\frac{dc}{dx}) = \text{constant} \qquad (6)$$

Solving equation (6)

$$q\int_0^L dx = -D\int_{c_1}^{c_2} dc$$
$$q = \frac{D(c_1 - c_2)}{L} \qquad (7)$$

By Henry's Law,

$$c = S \cdot p \qquad (8)$$

where S is the solubility coefficient of the gases. Substituting equation (8) into equation (7):

$$q = \frac{DS(p_1 - p_2)}{L} \qquad (9)$$

In equation (9), DS is called the permeability coefficient. If we let α = DS, the equation (9) becomes:

$$q = \frac{\alpha \cdot (p_1 - p_2)}{L} \tag{10}$$

Equation (10) is similar to the Darcy's law, which states that the fluid velocity through a porous medium is related to the pressure gradient:

$$q = \frac{K \cdot \Delta p}{\mu_f \cdot L} \tag{11}$$

where q is the superficial velocity (volumetric flow rate divided by cross-sectional area of the flow); K, the permeability; μ_f, the viscosity of the fluid; $\nabla p/L$, the pressure drop divided by distance.

Comparing equation (11) with equation (10), they are similar except those constants. The permeability coefficient includes the viscosity of the fluid (or air). The relation is:

$$\alpha = \frac{K}{\mu} \tag{12}$$

From equation (10), the permeability coefficient can also be expressed as

$$\alpha = \frac{qL}{p_1 - p_2} \tag{13}$$

This equation of permeability coefficient is valid for ideal gases such as oxygen, nitrogen and carbon dioxide [1]. The air with low humidity also acts like ideal gases. Therefore, it also obeys the equation (13).

When a web is wound, air must enter between the layers of the web. The volume of the air entered depends on the winding velocity, web tension and the permeability of the web. In general, the air thickness comes from two factors, inertial effect and viscous effect [2]. The inertial effect lets the web transform momentum to the air. The viscous effect is significant when a nip load is applied on the web, because the appearance of a converging wedge builds up a pressure between the web and the roll. Depending on the above two factors, an equation form can be established [2]:

$$h_0/R = \phi[(P_a\, R/T),(\mu V/T),(RV^2\rho/T)] \tag{14}$$

where h : represents the air-layer thickness

P_a : represents the ambient air pressure

R : represents the wound roll radius

T : represents the web tension

μ : represents the air viscosity

ρ : represents the air density

V : represents the sum of web velocity and roller velocity

In the equation P_aR/T is the pressure group; $\mu V/T$, the viscous effect; $RV^2\rho/T$, the inertial effect.

For an impermeable web, assuming no side leakage due to the large width of the web compared to the air-layer thickness and constant air pressure in the air-layer, an equation of air-layer thickness of entrance region is established [2].

$$h_0/R = 0.65[6\mu V/T]^{2/3} \tag{15}$$

But, the air-layer thickness would change in continuing rolling due to the air leakage, especially for a permeable web such as paper. The air usually leaks out in both radial and tangential directions on the wound roll.

Ducotey et al [3] use the theoretical the experimental approach to get a relation between the air-layer thickness and the angle the roller rotates in the constant pressure region for the permeable web. That is

$$\frac{h}{R} = 0.643\left(\frac{6\mu V}{T}\right)^{\frac{2}{3}} - 2\left(\frac{\alpha T}{V}\right)\theta \tag{16}$$

where θ is the angle that the wound roll rotates. This equation considers the transverse leakage of the air. The range of the angle, θ, is from 0° to 90°. In the equation, the pressure on the paper is due to the tension of the paper. Equation (16) is valid only for the condition of one paper sheet passing over a roller. Thus, contact pressure is not involved as is the case in winding. With continuing rolling of the wound roll, the layers of paper web continually accrete. The permeability coefficient will decrease, and it will decrease the rate at which the entrained air will escape from the wound roll.

There were several papers written in past years whose authors tried to find the permeability of air through the multiple permeable layers, although none study the effect of interlayer pressure on permeability. Bergmann et al [4] worked on leathers. When the leather membranes are placed in contact, and the permeability coefficients of the separate membranes are α_1 and α_2, it is found that the resultant permeability coefficient, α, is within 6% given by

$$\frac{1}{\alpha} = \frac{1}{\alpha_1} + \frac{1}{\alpha_2} \tag{17}$$

With the n layer of the leathers, equation (17) becomes

$$\frac{1}{\alpha} = \sum_{i=1}^{n} \frac{1}{\alpha_i} \tag{18}$$

The reciprocal of the permeability is called the impedance, so that the above expression means that the impedance is additive. The same property is also observed for gas/rubber diffusion systems [5]

For the multiple layers of membranes, the boundary resistance should be considered between the layers[6]. For one homogeneous membrane, there is no boundary resistance. Then, the permeability coefficient can be taken as a product of diffusivity and solubility (α = DS). Of course, the diffusivity is assumed as uniform throughout the entire membrane. However, when the membrane exhibits two or more layers with same or different permeability coefficients, and there are boundary resistances, the observed overall permeability becomes a function of membrane thickness and boundary resistances.

The overall permeability equation (13) can be written as

$$\frac{L}{\alpha} = \frac{p_1 - p_2}{q} \qquad (19)$$

The L/α can be defined as the overall resistance in the multilayer membrane [6]. Considering two layers of paper with boundary resistances r_1 and r_2 respectively as shown in figure 2.

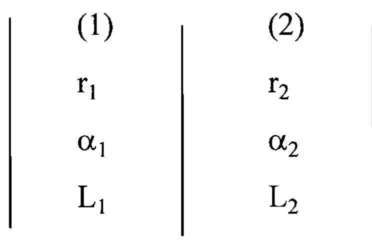

Fig. 2 Two-Layer Membrane

Then the total resistance to the permeation consists of resistances of different laminates and resistance of boundary layers or interfaces [6]

$$\frac{L'}{\alpha} = r_1 + r_2 + \frac{L_1}{\alpha_1} + \frac{L_2}{\alpha_2} \qquad \text{where } L' = L_1 + L_2 \qquad (20)$$

If each layer of the paper has the same thickness, L, the above equation becomes

$$\frac{1}{\alpha} = \frac{r_1 + r_2}{2L} + \frac{1}{2\alpha_1} + \frac{1}{2\alpha_2} \tag{21}$$

To modify the equation (21), it can be also written as

$$\frac{1}{\alpha} = (\frac{r_1}{2L} - \frac{1}{\alpha_1}) + (\frac{r_2}{2L} - \frac{1}{\alpha_2}) + \frac{1}{\alpha_1} + \frac{1}{\alpha_2} \tag{22}$$

With the n layers of paper, the equation (22) becomes

$$\frac{1}{\alpha} = \sum_{i=1}^{n} \left[(\frac{r_i}{2L} - \frac{1}{\alpha_i}) + \frac{1}{\alpha_i} \right] \tag{23}$$

Objective

Newsprint paper and bond paper compose a large portion of the paper wound by the paper industries. A volume of air is trapped between the layers of the paper when winding according to equation (15). When the wound roll continues its rolling, the layers of papers above the trapped air will increase and affect the permeation of the air radially through out the roll.

To study the permeation of the air through multiple layers of paper, two experiments were performed. One experiment was set up to find permeability coefficient of the air through multiple layers of paper without considering the contact pressure between the papers. As layers of paper are wound onto the winding roll, the paper inside the wound roll is subjected to radial pressure called contact pressure. It has long been known that the radial modulus of the wound roll is a function of interlayer pressure [7]. This is partially due to compression of asperities upon the mating paper surfaces and partially due to compression of the void volume within the sheet. Since permeability is often interrelated with the void volume, the permeability of paper sheets may be a function of interlayer pressure as well.

The objective of this research is to determine how permeability of paper sheets is affected by interlayer pressure. An apparatus will be designed and constructed to study permeability as a function of contact pressure since this measurement has not been previously performed. The results of this research will aid future research in winding permeable webs. So, the experiment was set up to discover the effect of the permeability coefficient of air under contact pressure.

CHAPTER III

EXPERIMENTAL APPROACH

The purpose of the experiment was to find the transverse permeability coefficients with multiple layers of paper without contact pressure and with contact pressure as a variable. Two different apparatuses were used, one for multiple layers of paper without contact pressure and the other with contact pressure. However, both setups employed the differential-pressure air permeability method.

An advantage of using the differential-pressure air permeability test is that it is inexpensive. Furthermore, the test is simple, accurate, repeatable, and reliable. Adjustment is usually not required for changes in atmospheric density. The major difficulties in using the test include sealing samples to prevent edge leakage and possible oil overflows when used carelessly. In the experiments, newsprint and bond paper were tested.

From equation (13) we know that the permeability coefficient is proportional to the thickness of the paper and rate of volume of the air passing through the paper, but is inversely related to the differential gauge pressure across the two surfaces of the paper. In the experiment, $100ml$ of the air was used to pass through the papers. In order to measure the time precisely, a timer was used to measure the time that the volume of air passing through.

Apparatus to Test Permeability without Contact Pressure

The apparatus was built and commercially manufactured by Teledyne Gurley (Teledyne Gurley, 514 Fulton St., Troy, NY 12181-0088) in accordance with TAPPI T 460. It is called densometer, model 4110. It consisted of an outer cylinder and an inner cylinder. The outer cylinder was filled with sealing fluid, a lubricating oil with a kinematic viscosity of $12 mm^2/s$ at $38°C$. The inner cylinder had an closed top, which could slide freely in the outer cylinder. The air pressure provided by the weight of the inner cylinder was applied on the testing paper which was held between the clamping plates in a circular orifice having an area of approximately $1 in^2$. The clamping plates were mounted in the base of the apparatus. An elastic gasket which was attached to the clamping plate prevented leakage of air between the surface of the paper and the clamping plate.

The gasket consisted of a thin, elastic, oil-resistant non-oxidizing material having a smooth surface. The inside diameter of the gasket was 1.13*in*, and the outside diameter 1.37*in*. The aperture in the gasket was aligned accurately with the aperture in the clamping plates. To align and protect the gasket in use, it was cemented in a groove machined in the clamping plate. The groove was concentric with the aperture in the opposing plate. Its internal diameter was 1.12*in* and it was 0.018*in* deep. Its outside diameter was 1.38*in,* for convenience in inserting and attaching the gasket.

The outer cylinder was 10*in* high with an internal diameter of 3.25*in*. It had four vertical bars, each 10*in* long, and 0.094*in* diameter, mounted equidistantly on the inner surface of the outer cylinder to serve as guides for the inner cylinder.

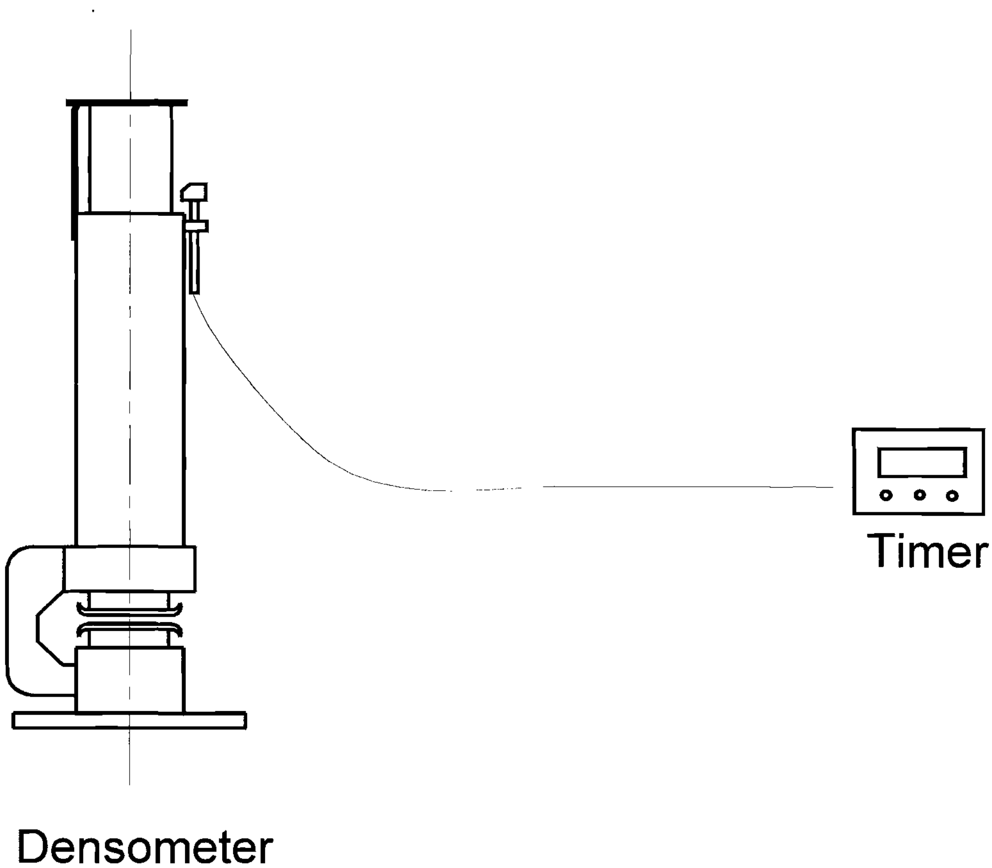

Figure 3. Permeability Testing Apparatus without Contact Pressure

The inner cylinder made of aluminum alloy and graduated in units of 50*ml* had a total ranged of 350*ml*. It was 10*in* high with an external diameter of 3*in* and internal diameter of 2.92*in*. It had a mass of 0.80*lb* so as to produce a pressure of 0.1769*psi*.

A digital timer (Gurley model 4320) was used to detect the precise time of the air passing through the papers. The resolution of the timer was $0.01 sec$.

The sealing oil inside the outer cylinder was preferred over light spindle oil. This kind of oil did not affect the moisture content of the specimen nor corrode the inner cylinder. The sealing fluid should not contain any easily volatile oil, and for that reason, a minimum flash point was specified. The flash point of the sealing oil used in the experiment was, at least, $135°C$.

Apparatus to Test Permeability with Contact Pressure

The purpose of the experiment was to find the relation between the permeability coefficient of the newsprint paper and the contact pressure on it. In the process of winding paper, the newsprint paper actually bears a contact pressure. The deeper the paper in the wound roll, the higher contact pressure it would bear. How fast the air can escape is dependent on the permeability coefficient of the paper. With the increase of the contact pressure, it may affect the permeability coefficient. A further experiment was set up to find any relationship.

The device could be divided into three parts, a main body, an air controller and a timer. The Teledyne Gurley air controller and timer, previously discussed, were used with this apparatus. I designed and constructed the main body of this apparatus since it was not commercially available. The testing specimen is clamped within the main body. The main body would bear thousands of pounds load. Therefore, it was made of solid steel. It consisted of an upper clamping ring and a lower support. The testing paper was held between the upper clamping ring and the lower supporter in a circular orifice having a diameter of 3*in*. An elastic gasket which was attached to the clamping ring and lower supporter respectively, prevented any possible leakage of air between the surface of the paper and the clamping plate. Several circular permeable metal disks, 3*in* in diameter, were put into the circular orifice. A load would be exerted on the permeable metal to give a contact pressure on the testing paper. A certain volume of air would pass through the testing paper from the lower supporter at a certain gauge pressure. The air was controlled by the air controller.

The controller was similar to the densometer in figure 3. It consisted of an outer cylinder and an inner cylinder. The outer cylinder was filled with sealing fluid. The inner cylinder had a closed top, which could slide freely in the outer cylinder. The air pressure provided by the weight of the inner cylinder was applied on the testing paper through a tube connected to the lower supporter of the main body. A timer was used to record the time when 100*ml* of air passed through the testing specimen.

In order to control the contact pressure as well as possible on the specimen, an instrument called 'Instron 8502' was used (Instron Cooperation, 100 Royall St., Canton, Massachusetts 02021). It was an automatic hydraulic fluid controlled device which could exert any load in the range of ±55,000*lb*. The whole setup is shown in figure 4.

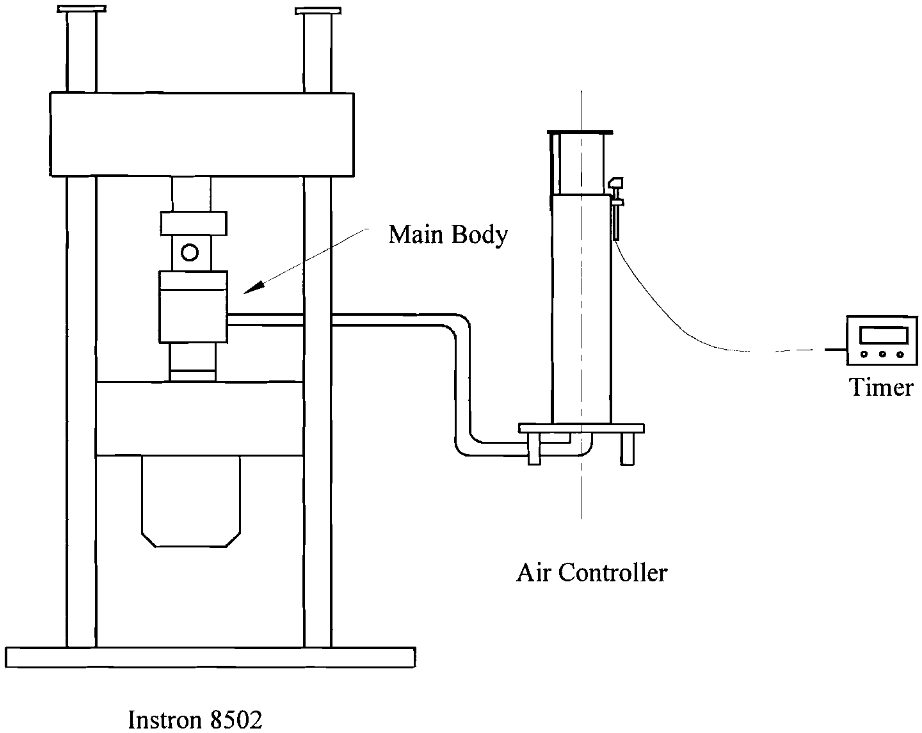

Figure 4. Test Unit for Air Permeability Measurements

The main body was made in precise dimensions to fit all its parts. To produce concise alignment, the main body directly screwed onto the 'Instron' hydraulic actuator. The main body consisted of ten parts. Figure 5 below shows all parts of the main body.

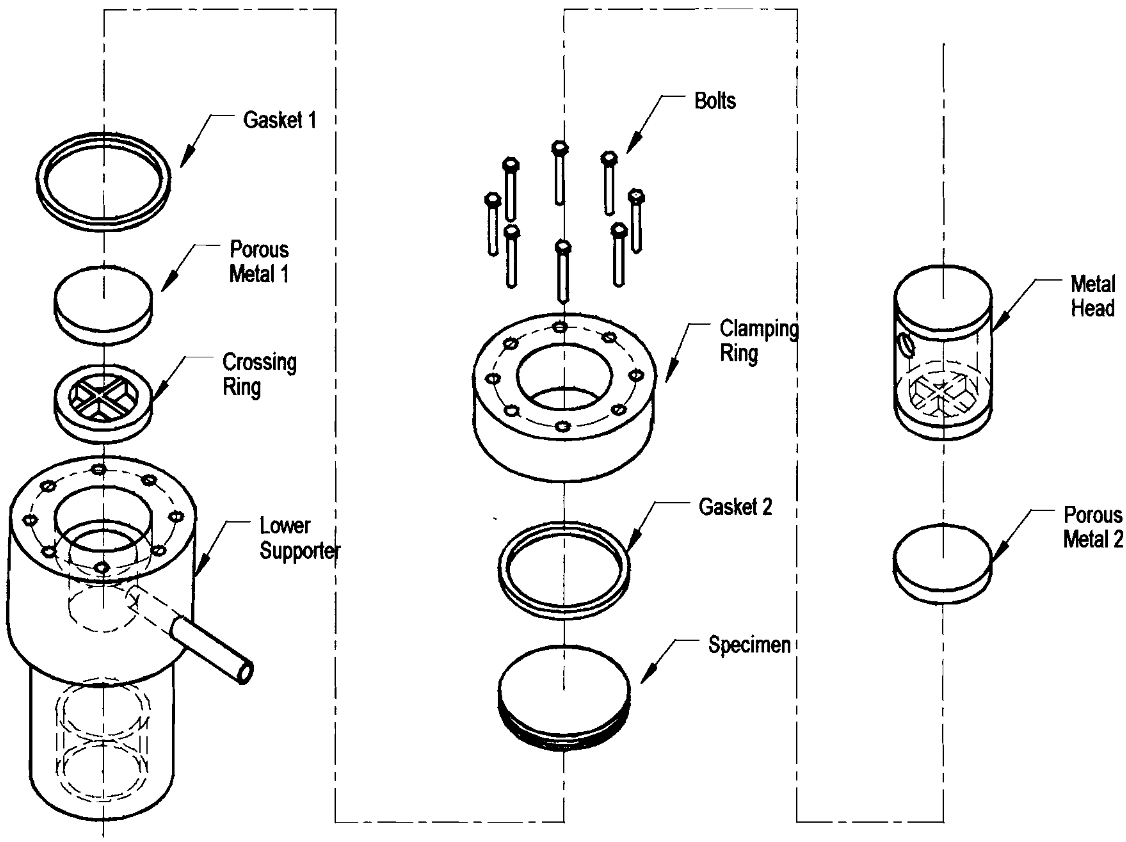

Figure 5. Detail Drawing of the Main Body

The supporter was machined of a solid round steel of 6*in* in diameter. The tube on the supporter was 0.5*in* in diameter, which connected to a small air chamber with 2*in* in diameter. A larger chamber above the smaller one had a 3*in* diameter, which was used to put the crossing ring and permeable metal plates. The crossing ring was used to support the permeable metal plates and prevent them from bending under high pressure. The permeable metal plates were formed by several permeable metal disks which were 3*in* in diameter and 1/8*in* in thickness. The disks were made of sintered bronze. Their properties and grades are shown in table I and table II.

Table I

The Properties of Materials

Material Properties	Sintered Bronze
Tensile Strength (psi)	3000-7000
Density (grams/cc)	4.5-5.6 (51-64%)
Oxidizing Temp. (°F)	+400
Max. Operating Temp. (°F)	+900
Min. Operating Temp. (°F)	-452
Chemical Composition	89-96% Copper, Bal. Tin

Table II

Standard Porosity Grades of the Porous Discs

Grade	Material	Particle Removal Size (Microns)	Bubble Point (in. H_2O)	Pressure Drop (PSI for 1 CFM/in^2 [AIR])	Maximum Pore Size (Microns)
F30	Bronze	65-110	1.1	0.04-0.07	200-330

Their permeabilities were very high compared to the testing paper; therefore, their permeability effect could be ignored in the experiment.

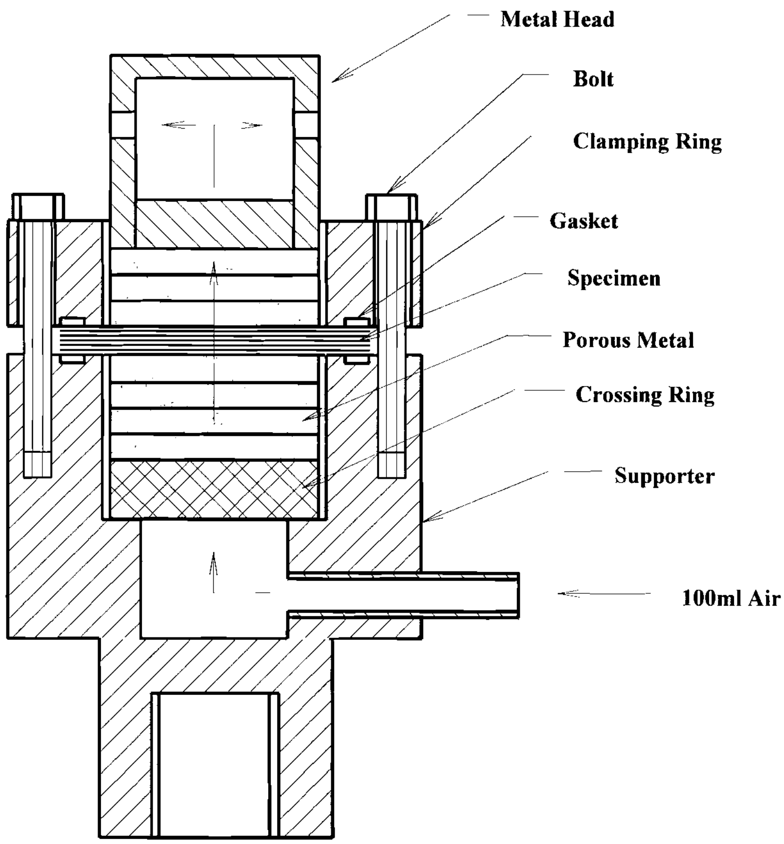

Figure 6 Assembly drawing of the Main Body

As shown in figure 6, the main body could be separated into two parts, the center part and surrounding part. The center part was used to test the paper with different load. The surrounding part was used to clamp the paper tightly and prevent any side leakage.

To eliminate the side leakage problem, two gaskets were used one on each side of the paper respectively. The inside diameter of the gaskets were 3.25*in*, and the outside diameter 4.1875*in*. The apertures in the gaskets were aligned accurately with each other. In order to align and protect the gaskets in use, they were cemented in grooves machined in the lower supporter and the clamping ring. The testing paper was placed between the gaskets, and its diameter was 4.2*in.* The clamping ring was aligned with the lower supporter. It was used to clamp the paper on the edge. The diameter of its aperture was also 3*in.* They were clamped tightly by using eight bolts. To make sure of the complete seal between the surfaces of the sheet and the plates, the clamping pressure exerted was over 300*psi*, which was much higher than the maximum pressure (about *150psi*) that would have been exerted on the center of the paper.

To avoid the error made by non-uniform compression, the uniformity of applied pressure was critical. To exert an uniform pressure on the paper, both the clamping ring and the supporter must be carefully machined to be parallel. On the other hand, several permeable disks were used so that a uniform contact pressure could be exerted on the testing paper. Four disks of permeable metal would be put under the specimen, and three of them on the top of the testing paper. The diameter of apertures of both the clamping ring and supporter were made 1/20*in* larger than 3*in* so that the permeable plates could move inside freely.

Another important consideration was the possibility of the tangential force on the testing paper. If the central part of the supporter could not be made in the same surface with the surrounding part, the paper would be damaged in that region as shown in figure 7.

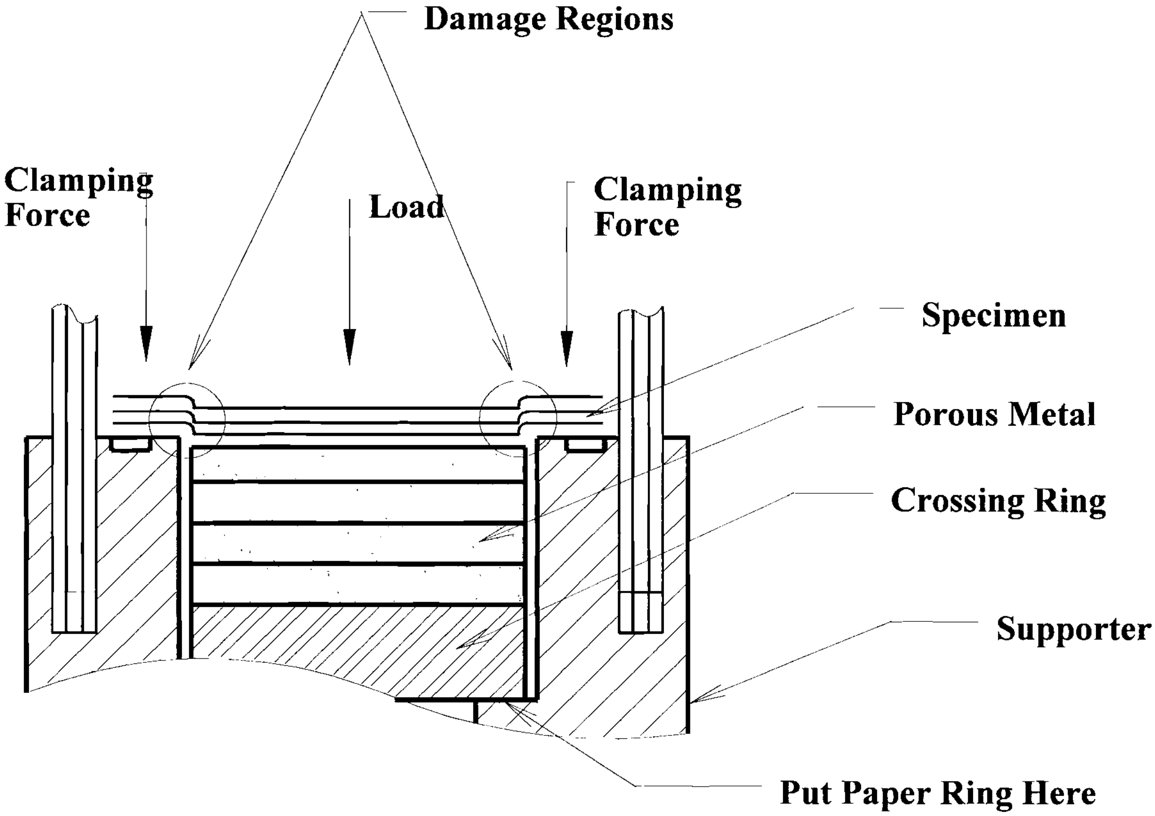

Figure 7. Illustration of a Paper Specimen in the Clamping Body

On the other hand, a tangential force would occur on the paper due to the different level gap. These forces could induce errors in the data. However, it was very difficult to make the same level between the central part and surrounding part. Several paper rings were used on the bottom of the crossing ring to raise the level of the central part. These paper rings were made of bond paper of thickness about *0.004in.* The problem could be reduced by using this method.

After a load was exerted on the permeable metal discs by the Instron, a certain volume of air would pass through the permeable metal and testing paper. The pressure and volume of air were determined by the air controller.

As for the previous tests, which did not impose an interlayer pressure, a new air controller was used. The outer cylinder of the air controller was 12*in* high with an internal diameter 3.08*in*. The inner cylinder, made of aluminum alloy, was graduated in units of 100*ml*. It was also 12*in* high with an external diameter of 2.867*in* and internal diameter of 2.462*in*. It had a mass of 1.20*lb*, so as to produce a pressure of 0.253*psi*. A Gurley automatic digital timer (model 4320) was used to measure the time for 100*ml* air to pass through the multilayer sample.

CHAPTER IV

EXPERIMENTAL RESULTS AND ANALYSIS

The purpose of the experiment was to determine the permeability of paper under different conditions. The experiment contained two parts; one was to test equation (18) to see if it was also true for the paper; the other was to find the relation between the permeability coefficient and contact pressure on the paper. In the experiments, bond paper and newsprint were employed to study the permeability. However, several restrictions had to be considered. Some assumptions were made in the experiment. The thickness of bond paper and newsprint were measured by using device called Schaevitz (the model is PPA-050, S/N 322) which was built by Schaevitz Engineering Company. This device could measure the paper thickness in $10^{-6} in$ accuracy. All the thickness measurements are listed in appendix A. Then the average thickness of the bond paper was found to be $4.75x10^{-3} in$ and newsprint, $2.81x10^{-3} in$. In the experiment, the load was assumed to be uniform on the paper.

The permeability coefficient has been derived in equation (13). If υ is the volume of the air that needs to pass through the paper, A is the cross-sectional area of the paper, and t is the time it needs to pass the air. Then the amount of air diffusing through an unit area of the film in unit time can be expressed as

$$q = \frac{\upsilon}{At} \tag{24}$$

Then the equation (13) can become

$$\alpha = (\frac{\upsilon L}{A})(\frac{1}{p_1 - p_2})(\frac{1}{t}) \tag{25}$$

From the equation (25), the permeability coefficient is in inverse proportion to the time. In the experiments, the time was recorded in keeping the other parameters constant.

Measurements of Permeability without The Contact Pressure

The air permeability was determined using the apparatus shown in figure 3. The volume of air $\upsilon = 100ml \cong 6.102\ in^3$, the cross-sectional area of the test chamber for the paper is $A = 1\ in^2$, the differential pressure of the air $p_1 - p_2 = 0.1769\ psi$, thickness of newsprint $L_n = 2.81x10^{-3}\ in$, thickness of bond paper $L_b = 4.75x10^{-3}\ in$. (Appendix A). Under this condition the permeability coefficient becomes

$\alpha = 0.09709\ (1/t)$ for newsprint

$\alpha = 0.16383\ (1/t)$ for bond paper (26) where t is the time measured in unit of seconds.

Figures 8 and 9 show the time for different number of layers without the contact pressure. In order to get a reliable result, the experimental procedure was repeated, at least, five times for each specimen. The data shown in the figures were the average values of those five times. All the experimental data are listed in Appendix B. Figure 8 shows the behavior for newsprint and figure 9 for bond paper. From the figures, it is obvious that more time is required for *100 ml* of air to pass through additional layers of paper. According to equation (26), the total permeability of the stack decreases with the increase of layers.

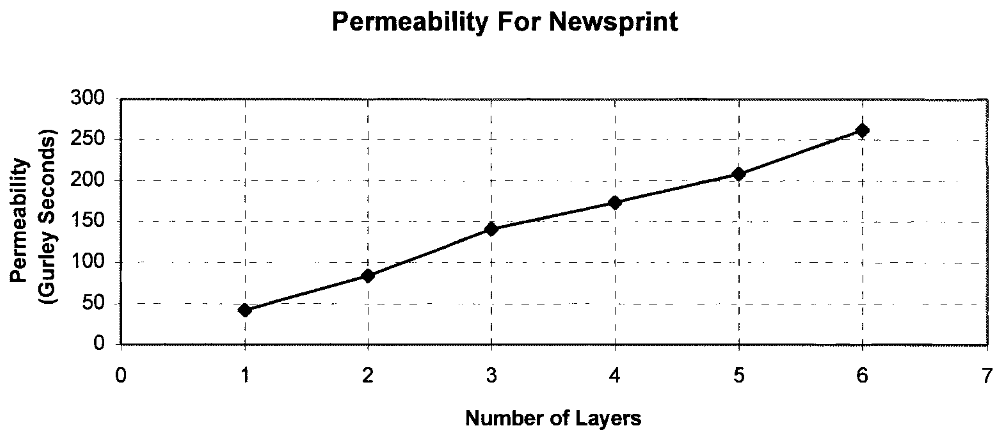

Fig. 8 Permeability Analysis for Newsprint

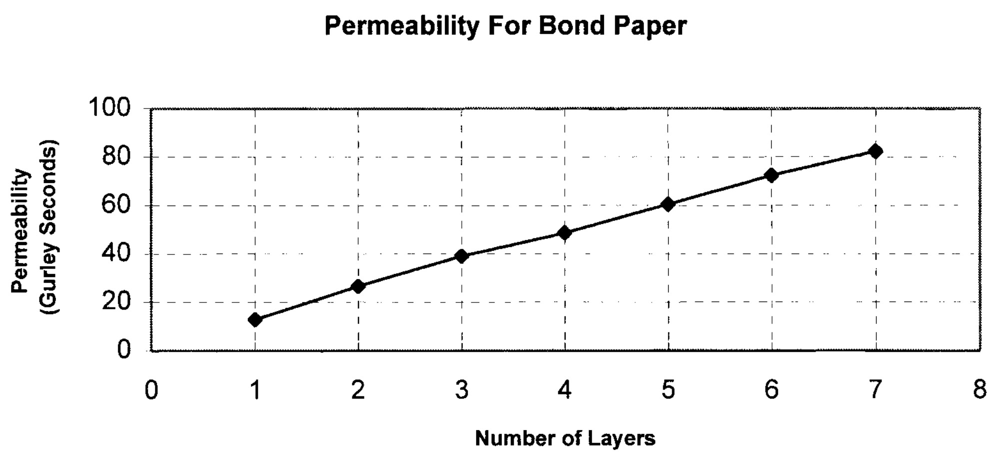

Fig. 9 Permeability Analysis for Bond Papers

As illustrated in figures 8 and 9, an almost linear time-layers behavior was observed for the air. If it is assumed that the times that a certain volume of air passes through each single sheet are t_1, t_2, t_3..., then if we treat the lines in figures 8 and 9 were straight line, they can be expressed as

$$t_{total} = t_1 + t_2 + t_3 + \ldots \tag{27}$$

where t_{total} is the overall time.

By using the equation (26), the equation (27) can be expressed as

$$\frac{1}{\alpha} = \frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \frac{1}{\alpha_3} \ldots \tag{28}$$

It is the same as the equation (18). Therefore, the newsprint and bond paper appear to be the same as the equation (18).

Measurements of Permeability with Contact Pressure

Transverse permeability measurements under the contact pressure were made with the apparatus shown in Figure 4. Newsprint paper was used as the specimen. Five test specimens were prepared. There was a one-sheet sample, two-sheet sample, three-sheet sample, four-sheet sample and five-sheet sample. In each sample experiment *100ml* of air was allowed to pass through the specimen. A relationship between the contact pressure and the time in passing a certain volume of air can be found from the graphs. In the experiment, volume of air $\upsilon = 100ml \cong 6.102\ in^3$, the crossing area of the testing part of the paper $A = 7.07\ in^2$, the differential pressure of the air $p_1 - p_2 = 0.253\ psi$, thickness of newsprint $L_n = 3.14x10^{-3}\ in.$ Under this condition, the relation between permeability coefficient and time can be found by using equation (25). It is

$$\alpha = 0.01070\ (1/t) \qquad (29)$$

where t is the time measured in unit of seconds

In the experiment, the contact pressure was given by the hydraulic device. It was an automatic control system. The experiment was done in the range of *0* to *1000lb* (about *0 - 150psi*). The data would be taken in a step of *20lb*. Because the Instron was automatic fluid controlled system , it could not exert the exact load as desired. In the experiment, the load tolerance was restricted to $\pm o.5lb$ when air was passing through the testing paper. Then an average value of the load was calculated.

In order to make sure that the volume of air was the same for each test, the starting mark and end mark on the air controller for time sensor were always kept in the same positions as they were in the other tests.

Before starting the experiment, an test was conducted to check if any leakage occurred. Several plastic films were used instead of the testing paper in the checking process. Under the higher clamping load (*2000lb*), no leakage was found in the leakage test.

The figures below show the experimental results of permeability for newsprint. Every experiment included an increasing load on paper from *0lb* to *1000lb* and then a decreasing load from *1000lb* to *0lb*. All the data are listed in Appendix B. Figure 10 below shows the plots between the time and contact pressure for one sheet of paper, figure 11 for two sheets of paper, figure 12 for three sheets of paper, figure 13 for four sheets of paper, and figure 14 for five sheets of paper.

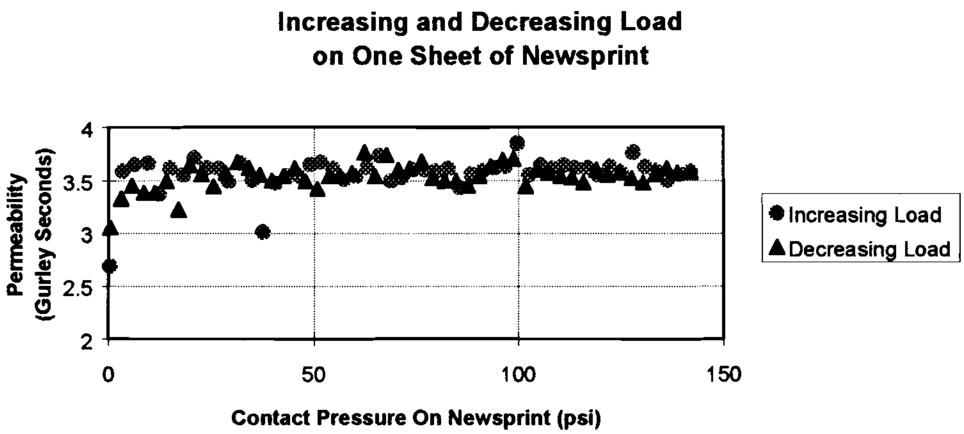

Figure 10 Permeability vs. Contact Pressure for One Sheet

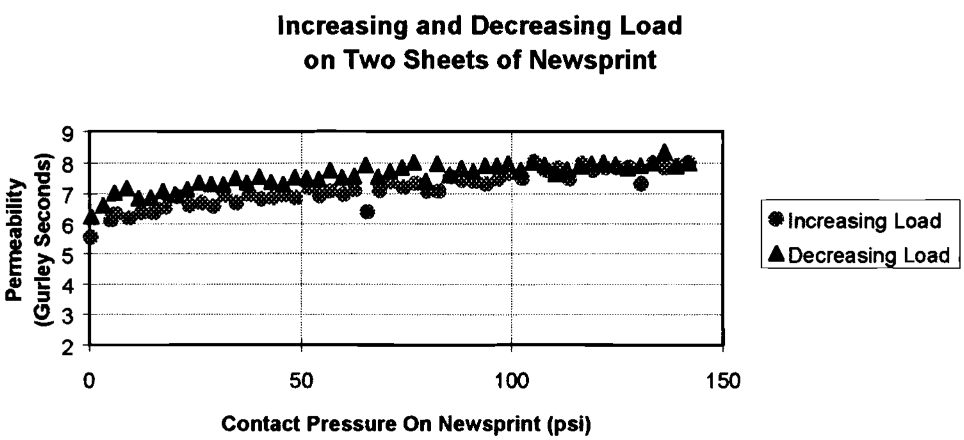

Figure 11 Permeability vs. Contact Pressure for Two Sheets

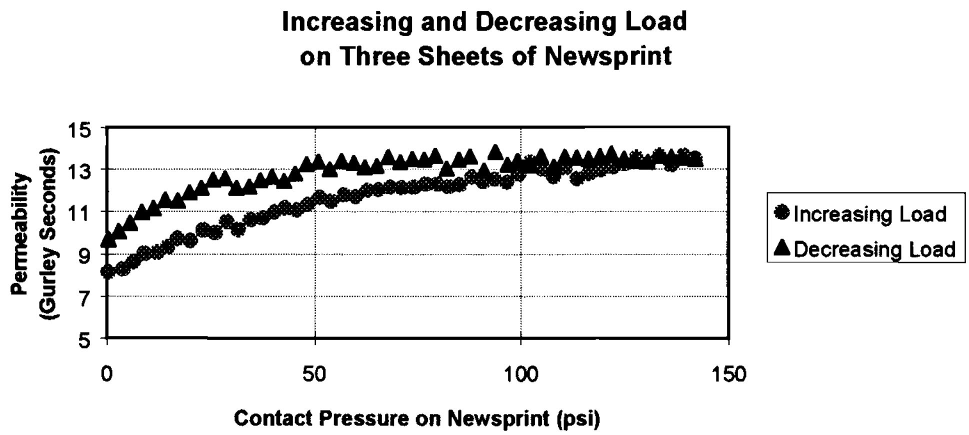

Figure 12 Permeability vs. Contact Pressure for Three Sheets

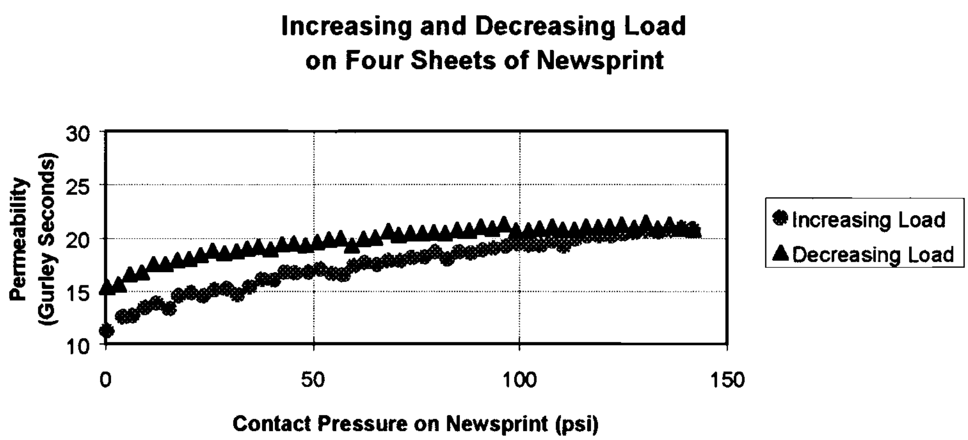

Figure 13 Permeability vs. Contact Pressure for Four Sheets

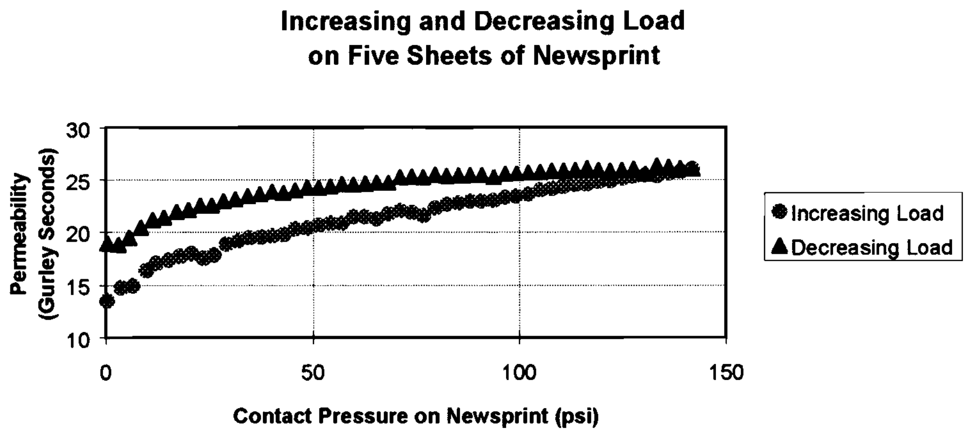

Figure 14 Permeability vs. Contact Pressure for Five Sheets

The five figures above show that the time for the passing air increases almost linearly with the increase of the contact pressure except the initial region. Based on the equation (29), we can find the relation between the permeability coefficient and contact pressure. Figures 15 through 19 show those relationships for different layers of paper.

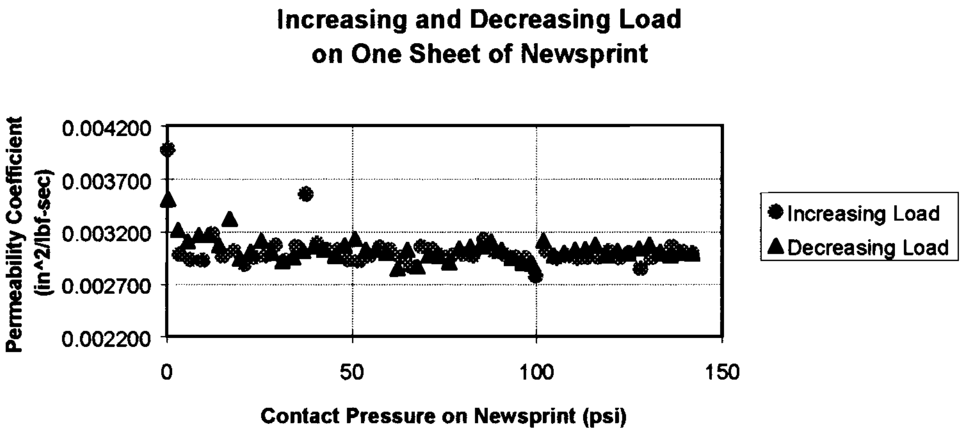

Figure 15. Permeability Coefficient vs. Contact Pressure for One Sheet

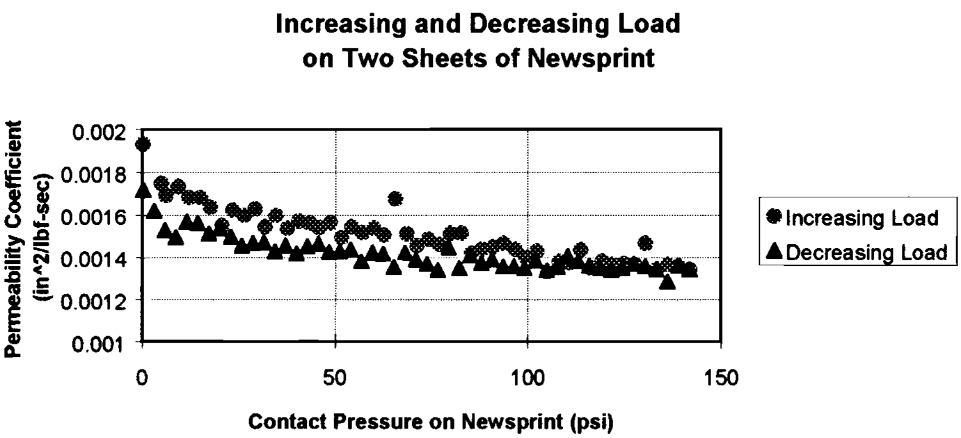

Figure 16. Permeability Coefficient vs. Contact Pressure for Two Sheets

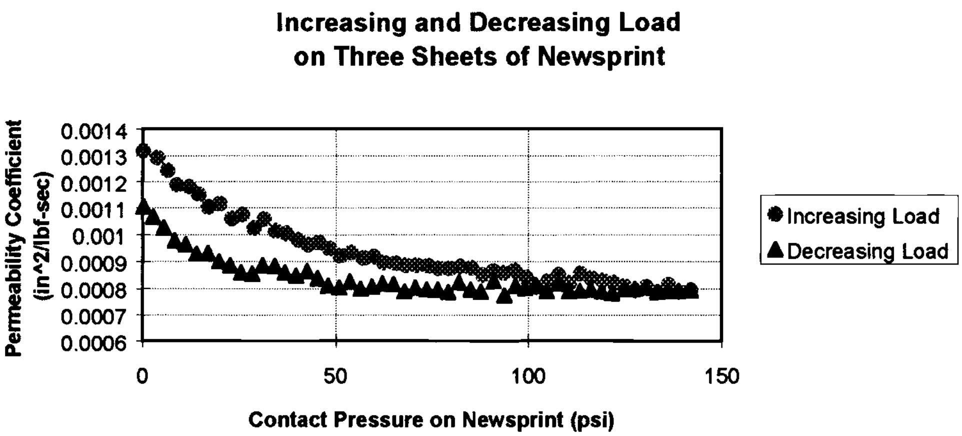

Figure 17. Permeability Coefficient vs. Contact Pressure for Three Sheets

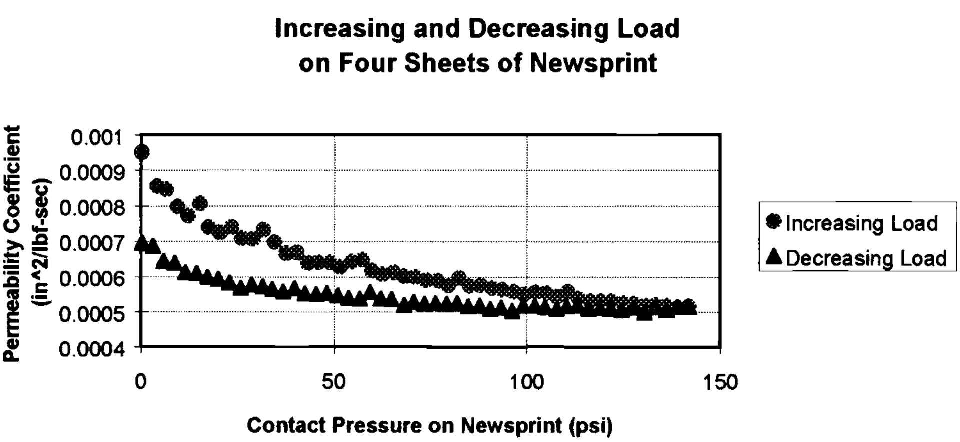

Figure 18. Permeability Coefficient vs. Contact Pressure for Four Sheets

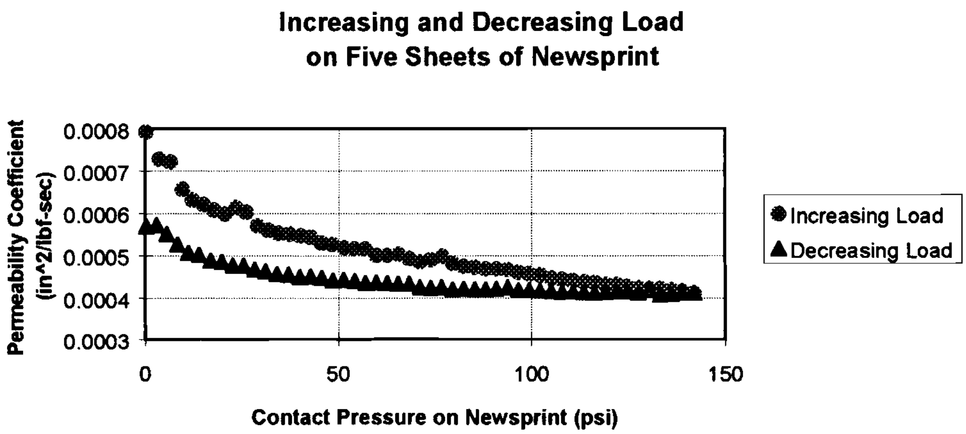

Figure 19. Permeability Coefficient vs. Contact Pressure for Five Sheets

In the figures the permeability coefficient would decrease almost linearly with the increase of the contact pressure. But when the contact pressure decreased, the permeability coefficient seemed to stay constant until the very low contact pressure. This trend could show clearly for more layers of papers. The increasing load line and decreasing load line could not be a coincidence. The reason is that contact pressure may change the paper's density permanently. The interesting point is that, with the increase of layers of paper, the separation between the increasing load line and decreasing load line became larger.

At this point in the research, it was obvious (fig. 10 - fig. 14) that permeability was affected by contact pressure which was a primary objective of this research. We then decided to apply simple theories to determine if multiple sheet behavior could possibly be determined from single sheet properties, an extension of the primary objective.

In order to realize the behavior of newsprint paper for different layers under the contact pressure, all the five groups of data were put in the same graph as shown in figures 20 and 21. Figure 20 shows all the effect of the permeability coefficients in different sheets of paper by increasing load and figure 21 shows that by decreasing load.

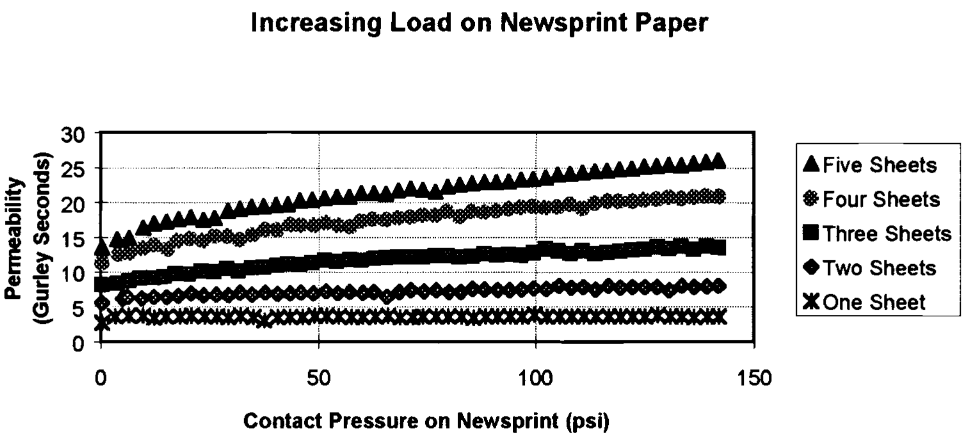

Figure 20. Permeability vs. Contact Pressure under Increasing Load

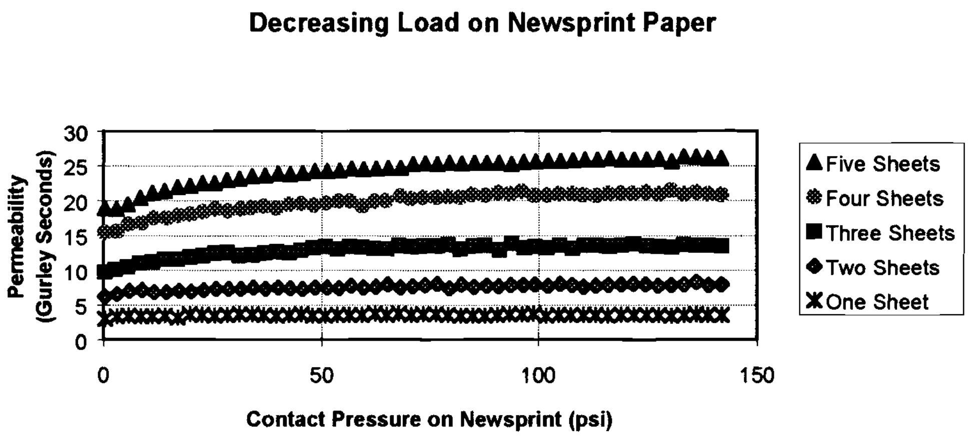

Figure 21. Permeability vs. Contact Pressure under Decreasing Load

Due to the different behavior of the permeability for increasing load and decreasing load, we must analyze them separately. In figure 20, under the increasing load, the slope of the line seems increasing with the increase of layers of paper. It shows that, with the contact pressure, the permeability coefficient can not completely obey the equation (18) which is also true for permeability without contact pressure. It becomes a function of contact pressure, and the equation (18) can be modified as

$$\frac{1}{\alpha(p_c)} = \frac{1}{\alpha_1(p_c)} + \frac{1}{\alpha_2(p_c)} + \frac{1}{\alpha_3(p_c)} \cdots \quad (30)$$

where α is the permeability coefficient, and p_c is the contact pressure. If the newsprint is uniform all over the wound roll, then the overall permeability coefficient can be expressed as

$$\frac{1}{\alpha(p_c)} = n \cdot \frac{1}{\alpha_1(p_c)} \tag{31}$$

where n is number of layers of the newsprint and $\alpha_1(p_c)$ is the permeability coefficient for one sheet of paper in the function of contact pressure. From equation (25), time for air passing through the paper is inverse to the permeability. Then an equation of time in the function of contact pressure can be found from the equation (32). That is

$$t(p_c) = n \cdot t_1(p_c) \tag{33}$$

where n is number of layers of the newsprint, and $t_1(p_c)$ is the permeability coefficient for one sheet of paper in the function of contact pressure.

At this point in the research the objectives had been fulfilled. Of additional interest is whether one multiple layer test can be used to determine the permeability of an n-layer stack. To this end a simple model was employed. From figure 20, the behavior for the time are almost straight lines for different layers of paper over a large domain of the tested contact pressure. Therefore, the time function can be assumed as

$$t(p_c) = n \cdot (a \cdot p_c + b) \tag{34}$$

where a and b are constants. In the experiment, as mention earlier, the data for five sheets of paper would be the least in error. A curve fitting was done as shown in figure 22.

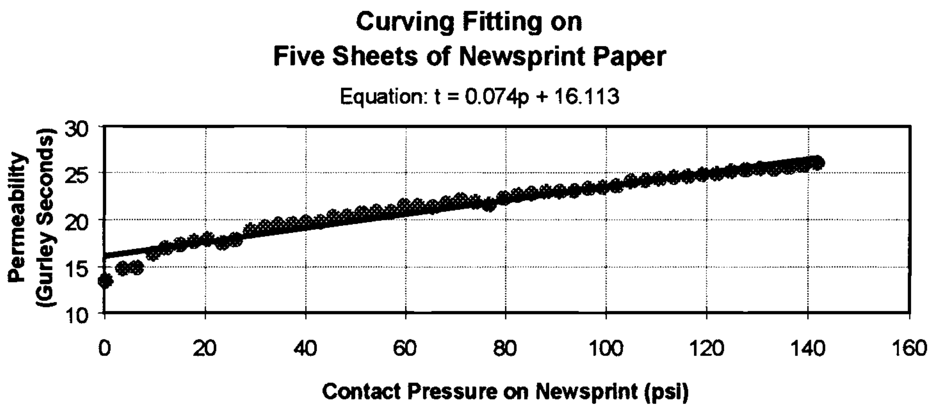

Fig. 22 Curve Fitting for Five-Sheet Paper

The straight line for five sheets of paper can be written as:

$$t(p_c) = 5\cdot(0.0148\cdot p_c + 3.223) \tag{35}$$

Then those constants a and b can be written as a = 0.0148, b = 3.223, and the function $t(p_c)$ can be expressed as:

$$t(p_c) = n\cdot(0.0148\cdot p_c + 3.223) \tag{36}$$

By using the equation (36), the straight lines for one-sheet paper, two-sheet paper, three-sheet paper, and four-sheet paper are:

$$t_1(p_c) = 0.0148 \cdot p_c + 3.223 \quad (37)$$

$$t_2(p_c) = 0.0296 \cdot p_c + 6.446 \quad (38)$$

$$t_3(p_c) = 0.0444 \cdot p_c + 9.669 \quad (39)$$

$$t_4(p_c) = 0.0592 \cdot p_c + 12.892 \quad (40)$$

Comparing the above straight lines with those by curve fitting as shown in figures 23 to 26, they are almost same except the straight line for one-sheet paper. That is reasonable because the experimental data for one-sheet paper may have a great error. These results are very encouraging though in that the curve fit values for a & b obtained for a 5-layer test produce acceptable results for 2, 3, & 4-layer tests. Thus equation (36) should be acceptable for 30 layers, 100 layers, or a 1000 layers which will be important in the development of a wound roll model.

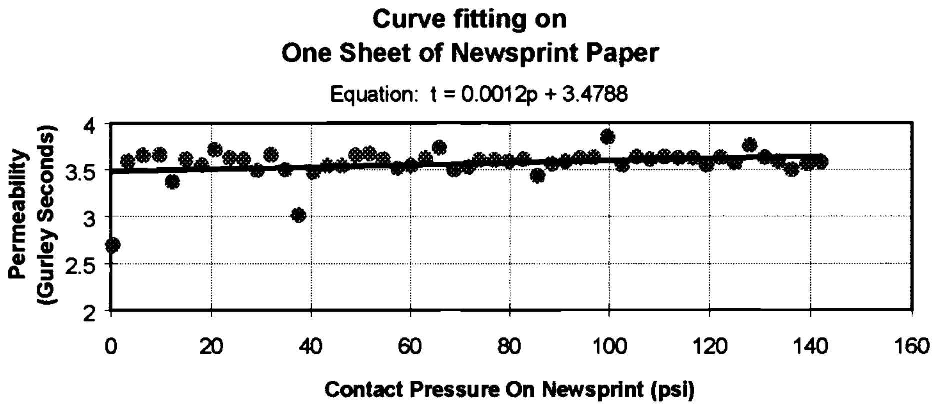

Fig. 23 Curve Fitting for One-Sheet Paper

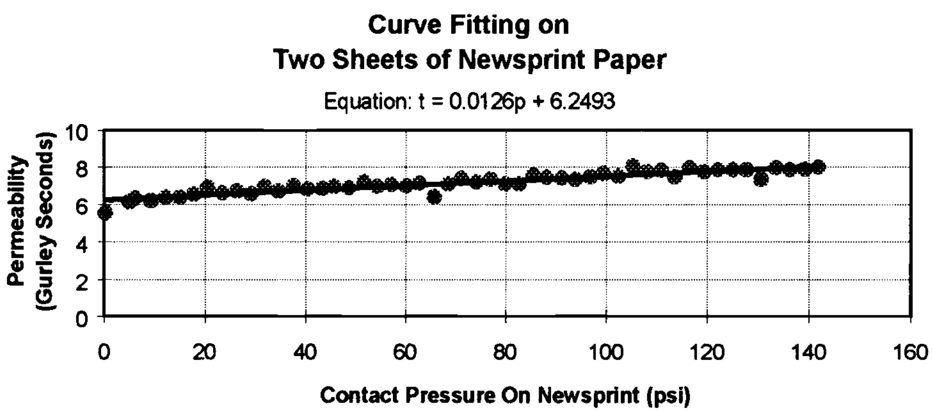

Fig. 24 Curve Fitting for Two-Sheet Paper

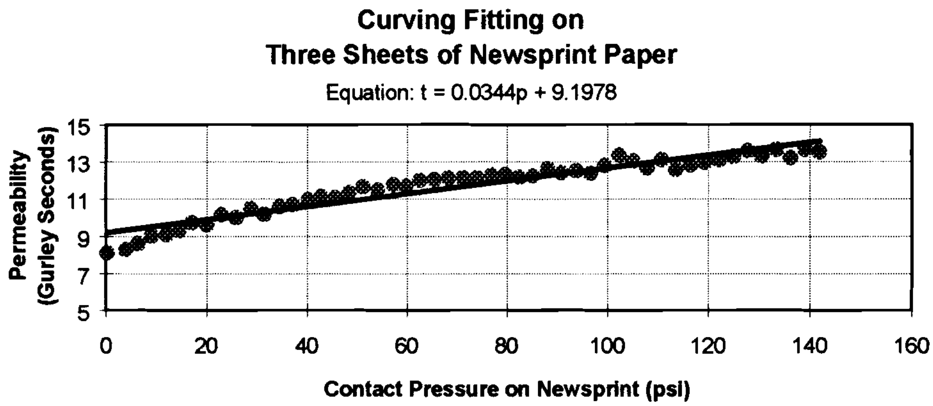

Fig. 25 Curve Fitting for Three-Sheet Paper

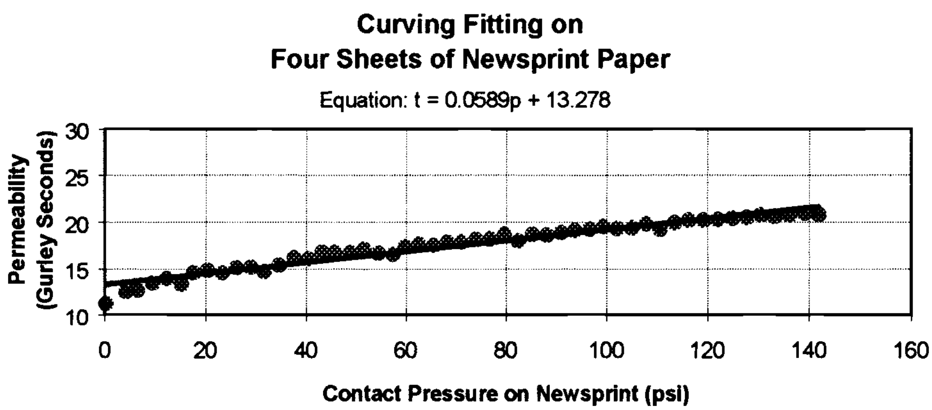

Fig. 26 Curve Fitting for Four-Sheet Paper

From equation (36), when contact pressure $p_c = 0$, the time is equal to constant b. That can be treated as the permeability without the contact pressure. Therefore, the value of constant b is dependent on the properties of the paper. The constant a is a slope of the straight line. It can only be determined in the experiment in the present research.

From figure 21, in the condition of decreasing contact pressure, the slope for every line appears the same (slope ≈ 0) over a large domain of pressure. The newsprint retained the permeability coefficient which was obtained in the maximum contact pressure as the contact pressure was decreased. This is reasonable, because the paper has some plastic deformation due to contact pressure. The effect is expected after studying Pfeiffer's data for pressure vs. strain in the stack [8]. These data indicates on download that a decrease in pressure is not necessarily accompanied by a proportionate decrease in strain(ε). Thus the sheets remain compacted with decreased void volume.

Discussion

In the experiment, the effect of air humidity was neglected. All the measurements were taken at room temperature. In the measurement of permeability without contact pressure, a straight line was formed, especially for the bond paper (Figure 8 and figure 9). The bond paper seemed to have a better quality for the test. Its standard deviation of thickness was smaller than that of newsprint (Appendix A), and its surface was smoother than the newsprint. Therefore, bond paper is better in meeting the assumptions made earlier. In the measurements the weight of the paper was neglected because only a few layers of paper were used. The effect of contact pressure by the weight of paper can be neglected. That is reasonable and could be proved by the second experiment.

In the measurements of permeability with contact pressure, fewer layers of paper may cause more errors, because recording time varied a little in the whole process, especially for the measurement of one sheet of paper. The time only varied within one second in the whole measurement. Any reading error, detecting error of the sensor, or loading error may cause a significant effect in the one-sheet or two-sheet measurements. On the other hand, under the high loading, the porous plates might damage the outermost layer of testing paper. An error could be made while collecting the data. In addition, more layers of paper would improve the contact condition. More uniform contact would appear for more layers of paper. The experiment indicated that, in from one to five layers, as shown in figure 10 to figure 15, the curves appeared smoother with more layers.

It is the first time to model the permeability coefficient with contact pressure. A straight line curve fitting method was used. Although the curves shown in figure 10 to figure 15 are not actually the straight lines, especially in the initial part, most of data behaves like the straight lines. That is why the straight line curve fitting method was used in analysis.

CHAPTER V

CONCLUSIONS

The conclusions of this research are:

(1). In the absence of contact pressure, the paper stacks have been proved to behave as same as the other multilayer stack in the first set of experiment. The expression is

$$\frac{1}{\alpha} = \sum_{i=1}^{n} \frac{1}{\alpha_i}$$

(2). Permeability of multilayer stacks is affected by contact pressure. The behavior of the permeability coefficient under the contact pressure is difficult to express as an exact equation. However this research has proved that contact pressure does affect the permeability of a multilayer paper stack which was henceforth unknown. A general equation can be expressed as

$$\frac{1}{\alpha(p_c)} = \sum_{i=1}^{n} \frac{1}{\alpha_i(p_c)}$$

or

$$\frac{1}{\alpha(p_c)} = \frac{n}{\alpha_1(p_c)} \qquad \text{If all the paper have same properties}$$

The function $\alpha_1(p_c)$ was obtained by the experiment. However it is very difficult to explain the function. There are many factors would affect the permeability function. Under the contact pressure, some deformations occur, which includes the change of its thickness, density, internal structure, etc. All these changes may affect its value of permeability coefficient. The measurements of permeability coefficient (α) under the contact pressure showed that $1/\alpha$ almost increased linearly when the contact pressure increased. However, the slope of the line increased with the increase of paper layers. This means that, more layers of paper, $1/\alpha$ would increase faster when the contact pressure increases. It is a very interesting point. It may show that boundary resistances of the paper become important under the contact pressure, because the overall boundary resistance would increase with the increase of the layers (Chapter II).

(3). The simple model shows great promise for testing a fixed number of sheets subject to contact pressure and extrapolating that data for various numbers development of wound roll models.

CHAPTER VI

SUGGESTIONS FOR FURTHER RESEARCH

The success of this experiment makes one wonder about future experiments that may expand the realm of further permeability analysis. The structure chosen for the current analysis was only transverse permeability on the homogeneous and isotropic bond paper and newsprint. According to Lindsay [9], most paper should not be considered isotropic and a lateral permeability may need to be considered.

In the experiment the contact pressure ranged from 0 to 150*psi*. The inverse of permeability coefficient went higher with the higher contact pressure. If the contact pressure keeps going higher, a critical value of the permeability coefficient may be found. That may help us understand the whole behavior of the permeability coefficient in the paper.

In the experiment with contact pressure, a general equation has been found. However, the function $\alpha(p_c)$ still remain unknown theoretically. In the experiment, this function was almost a straight line at higher contact pressures, and the constants a and b were found by using curve fitting. At lower contact pressures the behavior has definitely nonlinear and wound roll models will have to treat this as a nonlinear relationship since contact pressures vary from *0 to 50 psi* commonly in wound rolls of paper.

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APPENDIX

APPENDIX A

Measurements of Single Paper Thickness

1) Newsprint Paper

	Experiment without contact pressure	Experiment with contact pressure
Single paper thickness	$L(x10^{-3}$ in)	$L(x10^{-3}$ in)
	2.73	3.271
	2.8	3.226
	2.79	3.389
	2.8	3.00
	2.87	3.215
	2.72	3.2
	2.89	3.069
	2.85	2.93
	2.83	3.243
	3.02	3.350
	2.75	3.313
	2.81	2.663
	2.8	3.079
	2.74	3.210
	2.82	3.083
	2.82	3.040
	2.8	3.070
	2.83	3.226
	2.81	3.036
Mean	2.81	3.14

2) Bond Paper

	Experiment without contact pressure
Single Paper thickness	L($\times 10^{-3}$ in)
	4.74
	4.68
	4.61
	4.98
	4.78
	4.85
	4.71
	4.66
	4.61
	4.76
	4.9
	4.63
	4.86
	4.89
	4.55
	4.68
	4.85
mean	4.75

APPENDIX B

Experimental Data for Permeability without Contact Pressure

1) Newsprint Paper

L=2.8x10^{-3} in						
			Time (sec)			
	1 sheet	2 sheets	3 sheets	4 sheets	5 sheets	6 sheets
1st	41.94	74.58	141.65	184.83	199.91	249.97
2nd	36.13	85.56	142.99	169.13	197	242.21
3rd	44.19	82.33	139.22	168.02	195.75	236.62
4th	39.44	87.16	141.12	172.41	204.82	272.13
5th	47.34	88.39	139.58	181.49	225.66	284.85
mean	41.81	83.60	140.91	173.11	208.64	262.01

2) Bond Paper

L = 4.749x10^{-3} in							
				time (sec)			
	1 sheet	2 sheets	3 sheets	4 sheets	5 sheets	6 sheets	7 sheets
1st	13.49	28.23	40.18	50.66	63.31	74.29	85.36
2nd	12.19	26.97	37.99	47.94	61.1	71.76	83.12
3rd	13.25	27.06	38.8	47.12	59.62	71.24	82.27
4th	12.3	26.95	40.32	50.84	62.12	74.8	80.9
5th	12.59	25.26	39.44	48.44	58.7	71.84	81.2
6th	12.4	25.18	37.92	47.21	58.37	70.83	81.3
mean	12.703	26.61	39.11	48.70	60.54	72.46	82.36

APPENDIX C

Experimental Data for Permeability with Contact Pressure

1). Experimental Data for One Sheet

Pre.Load	Load (1)*	Load (2)*	[(1)+(2)]/2	Total Load	Press(psi)	Time(sec)	Perm.Coeff.
A (lbf)	B (lbf)	C (lbf)	(B+C)/2	A+(B+C)/2	T.L / Area	Measured	equa. (29)
2.6	0	0	0	2.6	0.368	2.69	0.003979
2.6	21.3	21.3	21.3	23.9	3.383	3.59	0.002981
2.6	42.6	42.9	42.75	45.35	6.419	3.65	0.002932
2.6	66	65.9	65.95	68.55	9.703	3.66	0.002924
2.6	84.1	84	84.05	86.65	12.265	3.37	0.003176
2.6	103.3	103.3	103.3	105.9	14.989	3.61	0.002965
2.6	125.9	125.8	125.85	128.45	18.181	3.55	0.003015
2.6	144.4	144.1	144.25	146.85	20.786	3.71	0.002885
2.6	165.4	165.3	165.35	167.95	23.772	3.62	0.002957
2.6	185.5	185.4	185.45	188.05	26.617	3.61	0.002965
2.6	203.7	203.5	203.6	206.2	29.186	3.49	0.003067
2.6	224	223.8	223.9	226.5	32.059	3.66	0.002924
2.6	244.4	244.5	244.45	247.05	34.968	3.5	0.003058
2.6	262.3	262.2	262.25	264.85	37.488	3.01	0.003556
2.6	284.5	284.1	284.3	286.9	40.609	3.47	0.003084
2.6	304.5	304.1	304.3	306.9	43.439	3.54	0.003023
2.6	325	324.7	324.85	327.45	46.348	3.54	0.003023
2.6	344.5	344.3	344.4	347	49.115	3.65	0.002932
2.6	363.5	363.8	363.65	366.25	51.840	3.67	0.002916
2.6	383.8	383.5	383.65	386.25	54.671	3.61	0.002965
2.6	404.5	404.1	404.3	406.9	57.594	3.51	0.003049
2.6	423.3	422.9	423.1	425.7	60.255	3.54	0.003023
2.6	443.8	443.3	443.55	446.15	63.149	3.62	0.002957
2.6	463.8	464	463.9	466.5	66.030	3.73	0.002869
2.6	484	483.7	483.85	486.45	68.854	3.5	0.003058
2.6	504.1	503.8	503.95	506.55	71.699	3.53	0.003032
2.6	520.5	520.5	520.5	523.1	74.041	3.6	0.002973
2.6	542.1	541.7	541.9	544.5	77.070	3.6	0.002973
2.6	562.3	561.7	562	564.6	79.915	3.59	0.002981

Pre.Load	Load (1)*	Load (2)*	[(1)+(2)]/2	Total Load	Press(psi)	Time(sec)	Perm.Coeff.
A (lbf)	B (lbf)	C (lbf)	(B+C)/2	A+(B+C)/2	T.L / Area	Measured	equa. (29)
2.6	583.1	583	583.05	585.65	82.895	3.61	0.002965
2.6	603.1	602.8	602.95	605.55	85.711	3.43	0.003120
2.6	623	622.4	622.7	625.3	88.507	3.56	0.003006
2.6	642.7	642.3	642.5	645.1	91.309	3.59	0.002981
2.6	663	662.7	662.85	665.45	94.190	3.62	0.002957
2.6	682.5	682.4	682.45	685.05	96.964	3.63	0.002948
2.6	702.7	702.5	702.6	705.2	99.816	3.85	0.002780
2.6	722.7	722.6	722.65	725.25	102.654	3.55	0.003015
2.6	743.3	742.5	742.9	745.5	105.520	3.64	0.002940
2.6	763.1	763	763.05	765.65	108.372	3.61	0.002965
2.6	782.7	782.4	782.55	785.15	111.132	3.64	0.002940
2.6	802.6	802.5	802.55	805.15	113.963	3.62	0.002957
2.6	823.1	822.5	822.8	825.4	116.829	3.62	0.002957
2.6	842.2	842.1	842.15	844.75	119.568	3.55	0.003015
2.6	862	862.3	862.15	864.75	122.399	3.63	0.002948
2.6	881.9	881.7	881.8	884.4	125.180	3.57	0.002998
2.6	903	902	902.5	905.1	128.110	3.76	0.002847
2.6	923.2	922.6	922.9	925.5	130.998	3.63	0.002948
2.6	942.1	941.5	941.8	944.4	133.673	3.59	0.002981
2.6	961.5	961.1	961.3	963.9	136.433	3.5	0.003058
2.6	982.2	982.3	982.25	984.85	139.398	3.56	0.003006
2.6	1001	1001	1001	1003.6	142.052	3.58	0.002990
2.6							
2.6	1001	1001	1001	1003.6	142.052	3.58	0.002990
2.6	978.1	977.9	978	980.6	138.797	3.57	0.002998
2.6	959.8	959.5	959.65	962.25	136.200	3.61	0.002965
2.6	940.1	939.8	939.95	942.55	133.411	3.56	0.003006
2.6	919.5	919.3	919.4	922	130.502	3.48	0.003076
2.6	899.4	899.3	899.35	901.95	127.665	3.52	0.003041
2.6	879.1	879.2	879.15	881.75	124.805	3.58	0.002990
2.6	858.7	858.6	858.65	861.25	121.904	3.55	0.003015
2.6	838.6	838.4	838.5	841.1	119.052	3.6	0.002973
2.6	816.3	816.6	816.45	819.05	115.931	3.48	0.003076
2.6	796.6	797.1	796.85	799.45	113.156	3.53	0.003032
2.6	777.6	777.7	777.65	780.25	110.439	3.54	0.003023
2.6	756.4	756.7	756.55	759.15	107.452	3.57	0.002998
2.6	736.5	736.9	736.7	739.3	104.643	3.6	0.002973
2.6	717	717.1	717.05	719.65	101.861	3.44	0.003111
2.6	696	696.2	696.1	698.7	98.896	3.7	0.002893
2.6	676.9	677.1	677	679.6	96.192	3.69	0.002901
2.6	656.7	656.4	656.55	659.15	93.298	3.63	0.002948
2.6	637.1	637.1	637.1	639.7	90.545	3.54	0.003023
2.6	616.9	617	616.95	619.55	87.693	3.45	0.003102
2.6	596.8	596.9	596.85	599.45	84.848	3.5	0.003058

Pre.Load	Load (1)*	Load (2)*	[(1)+(2)]/2	Total Load	Press(psi)	Time(sec)	Perm.Coeff.
A (lbf)	B (lbf)	C (lbf)	(B+C)/2	A+(B+C)/2	T.L / Area	Measured	equa. (29)
2.6	577.1	577.3	577.2	579.8	82.067	3.5	0.003058
2.6	556.2	556.4	556.3	558.9	79.108	3.52	0.003041
2.6	536.8	537	536.9	539.5	76.362	3.68	0.002908
2.6	516	516.4	516.2	518.8	73.432	3.61	0.002965
2.6	496.7	496.8	496.75	499.35	70.679	3.6	0.002973
2.6	476.4	476.3	476.35	478.95	67.792	3.74	0.002862
2.6	457	456.7	456.85	459.45	65.032	3.54	0.003023
2.6	438	438	438	440.6	62.364	3.76	0.002847
2.6	416.2	416.1	416.15	418.75	59.271	3.57	0.002998
2.6	395.9	396	395.95	398.55	56.412	3.54	0.003023
2.6	376.7	376.5	376.6	379.2	53.673	3.54	0.003023
2.6	356.7	356.4	356.55	359.15	50.835	3.42	0.003130
2.6	336.3	336.5	336.4	339	47.983	3.49	0.003067
2.6	317.7	317.4	317.55	320.15	45.315	3.61	0.002965
2.6	297.8	297.5	297.65	300.25	42.498	3.54	0.003023
2.6	277.7	277.3	277.5	280.1	39.646	3.5	0.003058
2.6	256.9	256.7	256.8	259.4	36.716	3.55	0.003015
2.6	237.8	237.6	237.7	240.3	34.013	3.62	0.002957
2.6	217.9	217.6	217.75	220.35	31.189	3.67	0.002916
2.6	197.6	197.4	197.5	200.1	28.323	3.57	0.002998
2.6	177.2	176.9	177.05	179.65	25.428	3.44	0.003111
2.6	156.9	156.7	156.8	159.4	22.562	3.56	0.003006
2.6	136.6	136.6	136.6	139.2	19.703	3.64	0.002940
2.6	116.7	116.9	116.8	119.4	16.900	3.22	0.003324
2.6	96.6	96.4	96.5	99.1	14.027	3.49	0.003067
2.6	76.4	76.3	76.35	78.95	11.175	3.38	0.003167
2.6	57.8	57.5	57.65	60.25	8.528	3.38	0.003167
2.6	37.6	37.5	37.55	40.15	5.683	3.45	0.003102
2.6	18.9	18.8	18.85	21.45	3.036	3.33	0.003214
	0	0	0	2.6	0.368	3.05	0.003509

* Load (1): Load at Start of Test
Load (2): Load at End of Test

2). Experimental Data for Two Sheets

Pre. Load	Load (1)*	Load (2)*	[(1)+(2)]/2	Total Load	Press(psi)	Time(sec)	Perm.Coeff.
A (lbf)	B (lbf)	C (lbf)	(B+C)/2	A+(B+C)/2	T.L / Area	Measured	equa. (29)
2.6	0	0	0	2.6	0.368	5.54	0.001932
2.6	33.1	32.9	33	35.6	5.039	6.12	0.001749
2.6	40.8	41	40.9	43.5	6.157	6.33	0.001691
2.6	63.7	63.7	63.7	66.3	9.384	6.18	0.001732
2.6	83.6	83.5	83.55	86.15	12.194	6.36	0.001683
2.6	104.3	103.5	103.9	106.5	15.074	6.36	0.001683
2.6	123	122.7	122.85	125.45	17.757	6.54	0.001637
2.6	143.5	143.1	143.3	145.9	20.651	6.91	0.001549
2.6	163.5	163.3	163.4	166	23.496	6.6	0.001622
2.6	183.8	184.3	184.05	186.65	26.419	6.7	0.001597
2.6	204	203.5	203.75	206.35	29.207	6.58	0.001627
2.6	222.9	222.2	222.55	225.15	31.868	6.94	0.001542
2.6	243.1	242.1	242.6	245.2	34.706	6.7	0.001597
2.6	263.7	262.9	263.3	265.9	37.636	6.97	0.001536
2.6	283.8	283.1	283.45	286.05	40.488	6.81	0.001572
2.6	303.8	303.3	303.55	306.15	43.333	6.85	0.001562
2.6	321.3	320.8	321.05	323.65	45.810	6.95	0.00154
2.6	341.9	341.4	341.65	344.25	48.726	6.86	0.00156
2.6	362.8	362.3	362.55	365.15	51.684	7.17	0.001493
2.6	382	381.2	381.6	384.2	54.381	6.93	0.001544
2.6	401.5	400.5	401	403.6	57.127	7.06	0.001516
2.6	422.1	423.1	422.6	425.2	60.184	6.97	0.001536
2.6	441.1	440.1	440.6	443.2	62.732	7.12	0.001503
2.6	462.2	461.4	461.8	464.4	65.732	6.39	0.001675
2.6	482.3	481.7	482	484.6	68.592	7.09	0.00151
2.6	501.2	500.8	501	503.6	71.281	7.36	0.001454
2.6	522.6	521.8	522.2	524.8	74.282	7.2	0.001487
2.6	542.6	541.6	542.1	544.7	77.098	7.33	0.00146
2.6	562.8	562.2	562.5	565.1	79.986	7.08	0.001512
2.6	582.4	581.8	582.1	584.7	82.760	7.08	0.001512
2.6	601.9	601	601.45	604.05	85.499	7.54	0.001419
2.6	621.3	620.5	620.9	623.5	88.252	7.44	0.001439
2.6	642	641.6	641.8	644.4	91.210	7.39	0.001448
2.6	662	661.3	661.65	664.25	94.020	7.31	0.001464
2.6	682.3	681.5	681.9	684.5	96.886	7.45	0.001437
2.6	701.3	700.9	701.1	703.7	99.604	7.64	0.001401
2.6	722.3	721.5	721.9	724.5	102.548	7.5	0.001427
2.6	742.3	741.8	742.05	744.65	105.400	8.03	0.001333
2.6	762.3	761.7	762	764.6	108.224	7.75	0.001381
2.6	782	781.6	781.8	784.4	111.026	7.81	0.00137
2.6	801.9	801.1	801.5	804.1	113.815	7.47	0.001433

Pre. Load	Load (1)*	Load (2)*	[(1)+(2)]/2	Total Load	Press(psi)	Time(sec)	Perm.Coeff.
A (lbf)	B (lbf)	C (lbf)	(B+C)/2	A+(B+C)/2	T.L / Area	Measured	equa. (29)
2.6	822.3	821.4	821.85	824.45	116.695	7.95	0.001346
2.6	842	841.5	841.75	844.35	119.512	7.75	0.001381
2.6	861.5	860.5	861	863.6	122.236	7.84	0.001365
2.6	881.6	881.1	881.35	883.95	125.117	7.83	0.001367
2.6	900.9	900.7	900.8	903.4	127.870	7.84	0.001365
2.6	921.3	920.6	920.95	923.55	130.722	7.31	0.001464
2.6	941.5	941	941.25	943.85	133.595	7.96	0.001345
2.6	961.5	960.5	961	963.6	136.391	7.84	0.001365
2.6	982.1	981.3	981.7	984.3	139.321	7.89	0.001357
2.6	1001	1000	1000.5	1003.1	141.982	7.99	0.00134
2.6	1001	1000	1000.5	1003.1	141.982	7.99	0.00134
2.6	979.9	979.6	979.75	982.35	139.045	7.88	0.001358
2.6	959.8	960.3	960.05	962.65	136.256	8.34	0.001283
2.6	940.3	939.8	940.05	942.65	133.425	7.99	0.00134
2.6	919.8	919.5	919.65	922.25	130.538	7.9	0.001355
2.6	898.8	898.2	898.5	901.1	127.544	7.82	0.001369
2.6	877.8	877.5	877.65	880.25	124.593	7.94	0.001348
2.6	857.6	857.8	857.7	860.3	121.769	8.01	0.001336
2.6	837.8	838	837.9	840.5	118.967	7.95	0.001346
2.6	817.5	817.2	817.35	819.95	116.058	7.87	0.00136
2.6	797.3	797.1	797.2	799.8	113.206	7.76	0.001379
2.6	777.4	778.4	777.9	780.5	110.474	7.62	0.001405
2.6	759	759.5	759.25	761.85	107.834	7.91	0.001353
2.6	739	739.5	739.25	741.85	105.004	8.01	0.001336
2.6	719.1	719.3	719.2	721.8	102.166	7.74	0.001383
2.6	698	698.5	698.25	700.85	99.200	7.95	0.001346
2.6	678.9	679.2	679.05	681.65	96.483	7.9	0.001355
2.6	659.1	659.4	659.25	661.85	93.680	7.9	0.001355
2.6	638.9	638.8	638.85	641.45	90.793	7.71	0.001388
2.6	619	619.5	619.25	621.85	88.018	7.81	0.00137
2.6	599	598.9	598.95	601.55	85.145	7.6	0.001408
2.6	578.2	578.6	578.4	581	82.236	7.95	0.001346
2.6	558.9	559.3	559.1	561.7	79.505	7.4	0.001446
2.6	539.1	539	539.05	541.65	76.667	8.01	0.001336
2.6	519.3	519.5	519.4	522	73.885	7.83	0.001367
2.6	499.2	499	499.1	501.7	71.012	7.71	0.001388
2.6	478.9	479	478.95	481.55	68.160	7.53	0.001421
2.6	458.5	458.2	458.35	460.95	65.244	7.92	0.001351
2.6	438.6	438.8	438.7	441.3	62.463	7.56	0.001416
2.6	418.7	418.9	418.8	421.4	59.646	7.52	0.001423
2.6	398.6	398.7	398.65	401.25	56.794	7.75	0.001381
2.6	379.2	379.2	379.2	381.8	54.041	7.45	0.001437
2.6	359.5	359.2	359.35	361.95	51.231	7.5	0.001427

Pre. Load	Load (1)*	Load (2)*	[(1)+(2)]/2	Total Load	Press(psi)	Time(sec)	Perm.Coeff.
A (lbf)	B (lbf)	C (lbf)	(B+C)/2	A+(B+C)/2	T.L / Area	Measured	equa. (29)
2.6	339.8	339.6	339.7	342.3	48.450	7.51	0.001425
2.6	320	319.7	319.85	322.45	45.640	7.31	0.001464
2.6	299.7	299.3	299.5	302.1	42.760	7.37	0.001452
2.6	280.1	279.6	279.85	282.45	39.979	7.54	0.001419
2.6	259.4	258.9	259.15	261.75	37.049	7.35	0.001456
2.6	240.1	239.6	239.85	242.45	34.317	7.5	0.001427
2.6	220	219.5	219.75	222.35	31.472	7.28	0.00147
2.6	200	199.4	199.7	202.3	28.634	7.3	0.001466
2.6	179.7	178.9	179.3	181.9	25.747	7.35	0.001456
2.6	159.7	159.1	159.4	162	22.930	7.14	0.001499
2.6	139.6	138.8	139.2	141.8	20.071	6.96	0.001538
2.6	119.4	118.8	119.1	121.7	17.226	7.08	0.001512
2.6	99	98.5	98.75	101.35	14.345	6.85	0.001562
2.6	79.2	78.7	78.95	81.55	11.543	6.83	0.001567
2.6	59.5	58.9	59.2	61.8	8.747	7.16	0.001495
2.6	39.3	39	39.15	41.75	5.909	7.01	0.001527
2.6	19.6	19.8	19.7	22.3	3.156	6.61	0.001619
2.6	0	0	0	2.6	0.368	6.23	0.001718

* Load (1): Load at Start of test
Load (2): Load at End of test

3). Experimental Data for Three Sheets

Pre. Load	Load (1)*	Load (2)*	[(1)+(2)]/2	Total Load	Press(psi)	Time(sec)	Perm.Coeff.
A (lbf)	B (lbf)	C (lbf)	(B+C)/2	A+(B+C)/2	T.L / Area	Measured	equa. (29)
2.6	0	0	0	2.6	0.368	8.12	0.001318
2.6	25.7	25	25.35	27.95	3.956	8.3	0.00129
2.6	43.3	42.9	43.1	45.7	6.469	8.61	0.001243
2.6	61.7	61.4	61.55	64.15	9.080	9.01	0.001188
2.6	83.4	83	83.2	85.8	12.144	9.08	0.001179
2.6	100.7	100.1	100.4	103	14.579	9.3	0.001151
2.6	117.4	117.7	117.55	120.15	17.006	9.72	0.001101
2.6	139.4	139.1	139.25	141.85	20.078	9.6	0.001115
2.6	160.6	160	160.3	162.9	23.057	10.11	0.001059
2.6	181.3	180.5	180.9	183.5	25.973	9.97	0.001074
2.6	201.6	201.2	201.4	204	28.875	10.48	0.001021
2.6	220.7	219.7	220.2	222.8	31.536	10.14	0.001056
2.6	241.5	241.3	241.4	244	34.536	10.58	0.001012
2.6	261.8	260.8	261.3	263.9	37.353	10.67	0.001003
2.6	282.8	282.4	282.6	285.2	40.368	10.94	0.000978
2.6	300.7	300.2	300.45	303.05	42.895	11.13	0.000962
2.6	320.5	319.9	320.2	322.8	45.690	11.04	0.000969
2.6	340.1	339.2	339.65	342.25	48.443	11.31	0.000946
2.6	360.3	359.1	359.7	362.3	51.281	11.63	0.00092
2.6	379.9	379.3	379.6	382.2	54.098	11.46	0.000934
2.6	402.6	401.1	401.85	404.45	57.247	11.75	0.000911
2.6	420.6	420.4	420.5	423.1	59.887	11.67	0.000917
2.6	440.3	440	440.15	442.75	62.668	11.97	0.000894
2.6	460.3	460.4	460.35	462.95	65.527	12.01	0.000891
2.6	480	480.2	480.1	482.7	68.323	12.11	0.000884
2.6	500.5	500	500.25	502.85	71.175	12.1	0.000885
2.6	520.6	520.2	520.4	523	74.027	12.13	0.000882
2.6	541.3	541	541.15	543.75	76.964	12.26	0.000873
2.6	561	560.4	560.7	563.3	79.731	12.28	0.000872
2.6	580.4	580	580.2	582.8	82.491	12.16	0.00088
2.6	600.9	599.7	600.3	602.9	85.336	12.23	0.000875
2.6	620.9	620	620.45	623.05	88.188	12.61	0.000849
2.6	640.2	640.6	640.4	643	91.012	12.4	0.000863
2.6	660.2	660.5	660.35	662.95	93.836	12.51	0.000856
2.6	680.3	680.1	680.2	682.8	96.645	12.37	0.000865
2.6	701	700.2	700.6	703.2	99.533	12.77	0.000838
2.6	720.5	720.1	720.3	722.9	102.321	13.33	0.000803
2.6	740.6	740.3	740.45	743.05	105.173	13	0.000823
2.6	760.3	760	760.15	762.75	107.962	12.63	0.000847
2.6	780.9	779.9	780.4	783	110.828	13.07	0.000819
2.6	800.3	800.6	800.45	803.05	113.666	12.56	0.000852

Pre. Load	Load (1)*	Load (2)*	[(1)+(2)]/2	Total Load	Press(psi)	Time(sec)	Perm.Coeff.
A (lbf)	B (lbf)	C (lbf)	(B+C)/2	A+(B+C)/2	T.L / Area	Measured	equa. (29)
2.6	820.8	820.2	820.5	823.1	116.504	12.8	0.000836
2.6	841.4	840.8	841.1	843.7	119.420	12.93	0.000828
2.6	861.1	860.7	860.9	863.5	122.222	13.08	0.000818
2.6	880.7	880.3	880.5	883.1	124.996	13.25	0.000808
2.6	903.1	900	901.55	904.15	127.976	13.55	0.00079
2.6	920.7	920.3	920.5	923.1	130.658	13.29	0.000805
2.6	940.6	940	940.3	942.9	133.461	13.64	0.000785
2.6	961	960.5	960.75	963.35	136.355	13.19	0.000811
2.6	981.3	980.7	981	983.6	139.222	13.63	0.000785
2.6	1001	1001	1001	1003.6	142.052	13.49	0.000793
2.6	1001	1001	1001	1003.6	142.052	13.49	0.000793
2.6	978.7	978.8	978.75	981.35	138.903	13.55	0.00079
2.6	960.3	959.6	959.95	962.55	136.242	13.56	0.000789
2.6	939.9	940.3	940.1	942.7	133.432	13.63	0.000785
2.6	919.7	920	919.85	922.45	130.566	13.32	0.000804
2.6	899	899.3	899.15	901.75	127.636	13.4	0.000799
2.6	879.9	879.7	879.8	882.4	124.897	13.47	0.000795
2.6	857.8	858.4	858.1	860.7	121.826	13.72	0.00078
2.6	838.3	838.9	838.6	841.2	119.066	13.59	0.000788
2.6	818.9	819.8	819.35	821.95	116.341	13.47	0.000795
2.6	798.6	799.4	799	801.6	113.461	13.55	0.00079
2.6	778.6	779.6	779.1	781.7	110.644	13.58	0.000788
2.6	759.6	760.1	759.85	762.45	107.919	13.11	0.000816
2.6	738	738.7	738.35	740.95	104.876	13.59	0.000788
2.6	717.7	718.9	718.3	720.9	102.038	13.17	0.000813
2.6	697.8	698.9	698.35	700.95	99.214	13.39	0.000799
2.6	680.7	680.9	680.8	683.4	96.730	13.22	0.00081
2.6	660	660.6	660.3	662.9	93.829	13.82	0.000774
2.6	640.7	640.9	640.8	643.4	91.069	12.95	0.000826
2.6	616.8	617.7	617.25	619.85	87.735	13.59	0.000788
2.6	597.9	598.5	598.2	600.8	85.039	13.46	0.000795
2.6	576.8	577.4	577.1	579.7	82.052	13.02	0.000822
2.6	557.1	557.6	557.35	559.95	79.257	13.63	0.000785
2.6	538.6	537.9	538.25	540.85	76.553	13.45	0.000796
2.6	517.5	517.9	517.7	520.3	73.645	13.47	0.000795
2.6	496.7	497.3	497	499.6	70.715	13.33	0.000803
2.6	476.6	477	476.8	479.4	67.856	13.58	0.000788
2.6	457.2	456.8	457	459.6	65.053	13.14	0.000815
2.6	436.7	436.2	436.45	439.05	62.144	13.1	0.000817
2.6	417	417.8	417.4	420	59.448	13.29	0.000805
2.6	396.5	396	396.25	398.85	56.454	13.4	0.000799
2.6	376.8	376.2	376.5	379.1	53.659	12.99	0.000824
2.6	357	356.5	356.75	359.35	50.863	13.35	0.000802

Pre. Load	Load (1)*	Load (2)*	[(1)+(2)]/2	Total Load	Press(psi)	Time(sec)	Perm.Coeff.
A (lbf)	B (lbf)	C (lbf)	(B+C)/2	A+(B+C)/2	T.L / Area	Measured	equa. (29)
2.6	337	336.6	336.8	339.4	48.040	13.23	0.000809
2.6	317.4	316.9	317.15	319.75	45.258	12.8	0.000836
2.6	298.6	297.6	298.1	300.7	42.562	12.42	0.000862
2.6	278.1	277.3	277.7	280.3	39.674	12.65	0.000846
2.6	257.7	257.6	257.65	260.25	36.837	12.46	0.000859
2.6	239.1	238.4	238.75	241.35	34.161	12.14	0.000882
2.6	217.5	216.6	217.05	219.65	31.090	12.09	0.000885
2.6	198	196.9	197.45	200.05	28.316	12.55	0.000853
2.6	178	177	177.5	180.1	25.492	12.47	0.000858
2.6	157.8	157.3	157.55	160.15	22.668	12.1	0.000885
2.6	137.8	136.8	137.3	139.9	19.802	11.89	0.0009
2.6	117.4	116.8	117.1	119.7	16.943	11.5	0.000931
2.6	96.9	95.4	96.15	98.75	13.977	11.53	0.000928
2.6	76.4	75.9	76.15	78.75	11.146	11.13	0.000962
2.6	56.5	56	56.25	58.85	8.330	10.95	0.000977
2.6	36.7	36.3	36.5	39.1	5.534	10.44	0.001025
2.6	17.5	17	17.25	19.85	2.810	10.04	0.001066
2.6	0	0	0	2.6	0.368	9.69	0.001105

* Load (1): Load at Start of Test
Load (2): Load at End of Test

4). Experimental Data for Four Sheets

Pre. Load	Load (1)*	Load (2)*	[(1)+(2)]/2	Total Load	Press(psi)	Time(sec)	Perm.Coeff.
A (lbf)	B (lbf)	C (lbf)	(B+C)/2	A+(B+C)/2	T.L / Area	Measured	equa. (29)
2.6	0	0	0	2.6	0.368	11.25	0.000951
2.6	27.5	27	27.25	29.85	4.225	12.52	0.000855
2.6	43.8	43.6	43.7	46.3	6.553	12.67	0.000845
2.6	64.9	64.6	64.75	67.35	9.533	13.43	0.000797
2.6	85	84	84.5	87.1	12.328	13.88	0.000771
2.6	105.2	105.2	105.2	107.8	15.258	13.29	0.000805
2.6	122.3	121.6	121.95	124.55	17.629	14.5	0.000738
2.6	143	142	142.5	145.1	20.538	14.79	0.000724
2.6	163.4	162.4	162.9	165.5	23.425	14.5	0.000738
2.6	182.7	181.7	182.2	184.8	26.157	15.11	0.000708
2.6	203	202.2	202.6	205.2	29.045	15.17	0.000706
2.6	222	221.4	221.7	224.3	31.748	14.63	0.000732
2.6	242.9	241.9	242.4	245	34.678	15.35	0.000697
2.6	263.5	263.5	263.5	266.1	37.665	16.08	0.000666
2.6	283.7	282.7	283.2	285.8	40.453	16.04	0.000667
2.6	303.6	302.3	302.95	305.55	43.248	16.76	0.000639
2.6	321	320.2	320.6	323.2	45.747	16.7	0.000641
2.6	343.2	342.6	342.9	345.5	48.903	16.73	0.00064
2.6	363	361.7	362.35	364.95	51.656	17.06	0.000627
2.6	382.9	382.2	382.55	385.15	54.515	16.65	0.000643
2.6	403.7	402	402.85	405.45	57.389	16.53	0.000647
2.6	420.6	420	420.3	422.9	59.858	17.35	0.000617
2.6	440.3	439.3	439.8	442.4	62.619	17.65	0.000606
2.6	461	459.7	460.35	462.95	65.527	17.5	0.000612
2.6	480.5	479.1	479.8	482.4	68.280	17.83	0.0006
2.6	500.5	499.5	500	502.6	71.139	17.85	0.0006
2.6	520.4	520	520.2	522.8	73.999	18.13	0.00059
2.6	540.6	539.9	540.25	542.85	76.837	18.2	0.000588
2.6	560.4	560	560.2	562.8	79.660	18.69	0.000573
2.6	580.3	579.7	580	582.6	82.463	18	0.000595
2.6	600.6	599.9	600.25	602.85	85.329	18.69	0.000573
2.6	620.3	620	620.15	622.75	88.146	18.59	0.000576
2.6	640.1	639.9	640	642.6	90.955	18.84	0.000568
2.6	660.5	659.6	660.05	662.65	93.793	19.04	0.000562
2.6	680.4	679.8	680.1	682.7	96.631	19.22	0.000557
2.6	700.5	700.1	700.3	702.9	99.490	19.46	0.00055
2.6	720.4	720	720.2	722.8	102.307	19.27	0.000555
2.6	740.1	739.8	739.95	742.55	105.103	19.32	0.000554
2.6	760.3	759.8	760.05	762.65	107.948	19.74	0.000542
2.6	780.1	779.7	779.9	782.5	110.757	19.21	0.000557
2.6	800.4	799.7	800.05	802.65	113.609	19.9	0.000538

Pre. Load	Load (1)*	Load (2)*	[(1)+(2)]/2	Total Load	Press(psi)	Time(sec)	Perm.Coeff.
A (lbf)	B (lbf)	C (lbf)	(B+C)/2	A+(B+C)/2	T.L / Area	Measured	equa. (29)
2.6	820.2	820.1	820.15	822.75	116.454	20.19	0.00053
2.6	840	840.3	840.15	842.75	119.285	20.17	0.000531
2.6	860.3	859.9	860.1	862.7	122.109	20.22	0.000529
2.6	880.7	880.1	880.4	883	124.982	20.39	0.000525
2.6	900	900.4	900.2	902.8	127.785	20.47	0.000523
2.6	920.3	920.1	920.2	922.8	130.616	20.7	0.000517
2.6	940.3	940	940.15	942.75	133.439	20.58	0.00052
2.6	960.2	959.8	960	962.6	136.249	20.71	0.000517
2.6	981.4	979.9	980.65	983.25	139.172	20.92	0.000512
2.6	1000	1001	1000.5	1003.1	141.982	20.79	0.000515
2.6	1000	1001	1000.5	1003.1	141.982	20.79	0.000515
2.6	978.7	979.2	978.95	981.55	138.931	20.87	0.000513
2.6	959.9	959.2	959.55	962.15	136.185	21.21	0.000505
2.6	939.4	939.3	939.35	941.95	133.326	20.86	0.000513
2.6	919.2	919.5	919.35	921.95	130.495	21.4	0.0005
2.6	899.4	899.6	899.5	902.1	127.686	20.9	0.000512
2.6	877.6	878.4	878	880.6	124.643	21.21	0.000505
2.6	857.4	858.2	857.8	860.4	121.783	21.03	0.000509
2.6	837.7	838.5	838.1	840.7	118.995	20.98	0.00051
2.6	817.1	818.1	817.6	820.2	116.093	21.02	0.000509
2.6	797	798.1	797.55	800.15	113.255	20.72	0.000517
2.6	776.7	778.3	777.5	780.1	110.418	20.77	0.000515
2.6	759	759.7	759.35	761.95	107.849	21.03	0.000509
2.6	737	738.9	737.95	740.55	104.820	20.85	0.000513
2.6	718.8	719.3	719.05	721.65	102.144	20.69	0.000517
2.6	698.1	697.3	697.7	700.3	99.122	20.67	0.000518
2.6	676.9	677.6	677.25	679.85	96.228	21.26	0.000503
2.6	656.5	657.4	656.95	659.55	93.355	20.89	0.000512
2.6	636.9	637.9	637.4	640	90.587	21.07	0.000508
2.6	616.6	618.2	617.4	620	87.757	20.67	0.000518
2.6	596.4	597.2	596.8	599.4	84.841	20.77	0.000515
2.6	576.1	577.1	576.6	579.2	81.982	20.43	0.000524
2.6	556	557.8	556.9	559.5	79.193	20.5	0.000522
2.6	536.6	537.6	537.1	539.7	76.391	20.41	0.000524
2.6	516.2	517.1	516.65	519.25	73.496	20.44	0.000524
2.6	496	497.5	496.75	499.35	70.679	20.27	0.000528
2.6	479	479.7	479.35	481.95	68.217	20.61	0.000519
2.6	456	456.7	456.35	458.95	64.961	20.01	0.000535
2.6	436.3	437	436.65	439.25	62.173	19.91	0.000538
2.6	416.5	417.3	416.9	419.5	59.377	19.28	0.000555
2.6	396.8	397.8	397.3	399.9	56.603	19.93	0.000537
2.6	376.9	377.6	377.25	379.85	53.765	19.84	0.000539
2.6	357	358	357.5	360.1	50.970	19.6	0.000546

Pre. Load	Load (1)*	Load (2)*	[(1)+(2)]/2	Total Load	Press(psi)	Time(sec)	Perm.Coeff.
A (lbf)	B (lbf)	C (lbf)	(B+C)/2	A+(B+C)/2	T.L / Area	Measured	equa. (29)
2.6	336.8	337.6	337.2	339.8	48.096	19.32	0.000554
2.6	317.6	317.1	317.35	319.95	45.287	19.48	0.000549
2.6	297	297.3	297.15	299.75	42.427	19.39	0.000552
2.6	277.3	278.1	277.7	280.3	39.674	18.9	0.000566
2.6	256.4	258.1	257.25	259.85	36.780	19.19	0.000558
2.6	237	238	237.5	240.1	33.984	18.99	0.000564
2.6	220.4	219.1	219.75	222.35	31.472	18.74	0.000571
2.6	198.8	199.7	199.25	201.85	28.570	18.54	0.000577
2.6	178.6	179.2	178.9	181.5	25.690	18.83	0.000568
2.6	158.3	158.9	158.6	161.2	22.817	18.39	0.000582
2.6	138.3	139.2	138.75	141.35	20.007	18.02	0.000594
2.6	118.5	119.1	118.8	121.4	17.183	17.88	0.000599
2.6	98.7	99.2	98.95	101.55	14.374	17.54	0.00061
2.6	78.4	79.2	78.8	81.4	11.522	17.51	0.000611
2.6	58.6	59.2	58.9	61.5	8.705	16.76	0.000639
2.6	38.5	39.2	38.85	41.45	5.867	16.6	0.000645
2.6	20	19.3	19.65	22.25	3.149	15.59	0.000687
2.6	0	0	0	2.6	0.368	15.39	0.000695

* Load (1): Load at Start of Test
Load (2): Load at End of Test

5). Experimental Data for Five Sheets

Pre. Load	Load (1)*	Load (2)*	[(1)+(2)]/2	Total Load	Press(psi)	Time(sec)	Perm.Coeff.
A (lbf)	B (lbf)	C (lbf)	(B+C)/2	A+(B+C)/2	T.L / Area	Measured	equa. (29)
2.6	0	0	0	2.6	0.368	13.51	0.000792
2.6	24.4	24	24.2	26.8	3.793	14.72	0.000727
2.6	43.2	43.2	43.2	45.8	6.483	14.85	0.000721
2.6	66	66.4	66.2	68.8	9.738	16.31	0.000656
2.6	83.9	83.4	83.65	86.25	12.208	16.97	0.000631
2.6	103.2	104.2	103.7	106.3	15.046	17.28	0.000619
2.6	124	122.8	123.4	126	17.834	17.65	0.000606
2.6	143.7	142.4	143.05	145.65	20.616	17.9	0.000598
2.6	163.7	162.7	163.2	165.8	23.468	17.49	0.000612
2.6	181.6	181	181.3	183.9	26.030	17.8	0.000601
2.6	203.6	202.4	203	205.6	29.101	18.8	0.000569
2.6	222.6	221.6	222.1	224.7	31.805	19.12	0.00056
2.6	241.8	241	241.4	244	34.536	19.39	0.000552
2.6	261	260.5	260.75	263.35	37.275	19.45	0.00055
2.6	281.7	280.5	281.1	283.7	40.156	19.6	0.000546
2.6	300.4	299.7	300.05	302.65	42.838	19.72	0.000543
2.6	320.5	319.2	319.85	322.45	45.640	20.24	0.000529
2.6	339.9	340.2	340.05	342.65	48.500	20.33	0.000526
2.6	360.4	359.8	360.1	362.7	51.338	20.63	0.000519
2.6	380.5	379.8	380.15	382.75	54.176	20.78	0.000515
2.6	400.3	400	400.15	402.75	57.006	20.78	0.000515
2.6	420.5	419.3	419.9	422.5	59.802	21.41	0.0005
2.6	440.3	440	440.15	442.75	62.668	21.38	0.000501
2.6	460.4	459.7	460.05	462.65	65.485	21.24	0.000504
2.6	480.3	479.9	480.1	482.7	68.323	21.7	0.000493
2.6	500.3	500	500.15	502.75	71.161	22.02	0.000486
2.6	520.2	519.9	520.05	522.65	73.977	21.84	0.00049
2.6	540.9	540	540.45	543.05	76.865	21.53	0.000497
2.6	560.5	560.2	560.35	562.95	79.682	22.26	0.000481
2.6	580.3	579.7	580	582.6	82.463	22.6	0.000474
2.6	600.1	599.9	600	602.6	85.294	22.72	0.000471
2.6	620.3	620.1	620.2	622.8	88.153	22.92	0.000467
2.6	640.3	639.9	640.1	642.7	90.970	22.94	0.000467
2.6	660.1	659.8	659.95	662.55	93.779	22.99	0.000466
2.6	680.2	680.2	680.2	682.8	96.645	23.27	0.00046
2.6	700.1	699.8	699.95	702.55	99.441	23.42	0.000457
2.6	720.4	720	720.2	722.8	102.307	23.56	0.000454
2.6	740	740.3	740.15	742.75	105.131	24	0.000446
2.6	760	760.3	760.15	762.75	107.962	24.12	0.000444
2.6	780.2	779.8	780	782.6	110.771	24.29	0.000441
2.6	800.4	800	800.2	802.8	113.631	24.49	0.000437

Pre. Load	Load (1)*	Load (2)*	[(1)+(2)]/2	Total Load	Press(psi)	Time(sec)	Perm.Coeff.
A (lbf)	B (lbf)	C (lbf)	(B+C)/2	A+(B+C)/2	T.L / Area	Measured	equa. (29)
2.6	820.3	819.9	820.1	822.7	116.447	24.55	0.000436
2.6	840.4	839.9	840.15	842.75	119.285	24.79	0.000432
2.6	860.5	859.9	860.2	862.8	122.123	24.82	0.000431
2.6	880.3	880	880.15	882.75	124.947	25.11	0.000426
2.6	900.4	900	900.2	902.8	127.785	25.25	0.000424
2.6	920.4	919.9	920.15	922.75	130.609	25.39	0.000422
2.6	940.3	939.9	940.1	942.7	133.432	25.32	0.000423
2.6	960.4	960	960.2	962.8	136.277	25.57	0.000419
2.6	980.3	980.1	980.2	982.8	139.108	25.77	0.000415
2.6	1000	1000	1000	1002.6	141.911	26	0.000412
2.6	1000	1000	1000	1002.6	141.911	26	0.000412
2.6	978.7	979	978.85	981.45	138.917	26.03	0.000411
2.6	959.7	959.4	959.55	962.15	136.185	26.2	0.000409
2.6	939.7	939.4	939.55	942.15	133.355	26.31	0.000407
2.6	919.6	919.9	919.75	922.35	130.552	25.54	0.000419
2.6	899.6	899.9	899.75	902.35	127.721	25.98	0.000412
2.6	879.5	879.8	879.65	882.25	124.876	25.87	0.000414
2.6	860	859.6	859.8	862.4	122.067	25.82	0.000415
2.6	839.4	839.8	839.6	842.2	119.207	25.88	0.000414
2.6	820.1	819.7	819.9	822.5	116.419	26.03	0.000411
2.6	800.1	799.7	799.9	802.5	113.588	25.88	0.000414
2.6	780	779.8	779.9	782.5	110.757	25.81	0.000415
2.6	760.1	760.3	760.2	762.8	107.969	25.8	0.000415
2.6	740.2	739.7	739.95	742.55	105.103	25.71	0.000416
2.6	720.2	719.7	719.95	722.55	102.272	25.64	0.000417
2.6	700.1	699.7	699.9	702.5	99.434	25.58	0.000418
2.6	680	680.2	680.1	682.7	96.631	25.52	0.000419
2.6	660.3	660.6	660.45	663.05	93.850	25.22	0.000424
2.6	640	639.8	639.9	642.5	90.941	25.37	0.000422
2.6	620	620.2	620.1	622.7	88.139	25.41	0.000421
2.6	600.4	599.8	600.1	602.7	85.308	25.41	0.000421
2.6	579.3	579.9	579.6	582.2	82.406	25.34	0.000422
2.6	559.4	559.8	559.6	562.2	79.575	25.43	0.000421
2.6	539	539.3	539.15	541.75	76.681	25.2	0.000425
2.6	519.9	519.3	519.6	522.2	73.914	25.27	0.000424
2.6	499.9	499.1	499.5	502.1	71.069	25.19	0.000425
2.6	479.9	479.5	479.7	482.3	68.266	24.69	0.000433
2.6	459.9	459.3	459.6	462.2	65.421	24.64	0.000434
2.6	440	439.5	439.75	442.35	62.611	24.61	0.000435
2.6	419.5	419.1	419.3	421.9	59.717	24.49	0.000437
2.6	399.8	399.4	399.6	402.2	56.929	24.53	0.000436
2.6	380.1	379.6	379.85	382.45	54.133	24.33	0.00044
2.6	359.5	360	359.75	362.35	51.288	24.17	0.000443

Pre. Load	Load (1)*	Load (2)*	[(1)+(2)]/2	Total Load	Press(psi)	Time(sec)	Perm.Coeff.
A (lbf)	B (lbf)	C (lbf)	(B+C)/2	A+(B+C)/2	T.L / Area	Measured	equa. (29)
2.6	340.3	339.7	340	342.6	48.493	24.22	0.000442
2.6	320	319	319.5	322.1	45.591	23.92	0.000447
2.6	299	299.8	299.4	302	42.746	23.71	0.000451
2.6	280	279.6	279.8	282.4	39.972	23.84	0.000449
2.6	258.9	258.3	258.6	261.2	36.971	23.55	0.000454
2.6	238.4	237.5	237.95	240.55	34.048	23.42	0.000457
2.6	217.4	216.7	217.05	219.65	31.090	23.1	0.000463
2.6	197.3	196.6	196.95	199.55	28.245	22.93	0.000467
2.6	177.4	176.6	177	179.6	25.421	22.49	0.000476
2.6	157.5	156.9	157.2	159.8	22.619	22.5	0.000476
2.6	137.3	136.9	137.1	139.7	19.774	22.08	0.000485
2.6	117.7	116.7	117.2	119.8	16.957	21.89	0.000489
2.6	96.2	95.2	95.7	98.3	13.914	21.33	0.000502
2.6	76.7	76	76.35	78.95	11.175	21.12	0.000507
2.6	56.8	56.1	56.45	59.05	8.358	20.35	0.000526
2.6	37.1	36.2	36.65	39.25	5.556	19.42	0.000551
2.6	18.7	18.2	18.45	21.05	2.979	18.75	0.000571
2.6	0	0	0	2.6	0.368	18.85	0.000568

* Load (1): Load at Start of Test
Load (2): Load at End of Test

VITA

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Master of Science

Thesis: THE EFFECT OF CONTACT PRESSURE ON WEB PERMEABILITY

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