USING FSRs TO MEASURE RADIAL PRESSURE IN WOUND ROLLS

J.K. Good and M.W.R. Fikes

School of Mechanical and Aerospace Engineering

Oklahoma State University

Stillwater, OK USA

ABSTRACT

The Force Sensing Resistor (FSR^{TM})[1] is a device which changes resistance in a predictable manner with the application of force on its surface.[1] The FSR has been used in a variety of applications since its invention in 1986, including position sensing, traffic counting, pressure sensing in wind tunnels and sensing in numerous security devices. This publication presents the results of a study in which the FSR was implemented as a tool for measuring the radial interlayer pressures in wound rolls.

The FSR exists in two primary forms: the shunt mode FSR, and the through-conduction mode FSR. The focus of this study is concentrated entirely upon the shunt mode form of the device. The term "FSR" will refer to this form of the device throughout this publication.

The FSR consists of two polyester sheets sandwiched together. One sheet contains a screen printed pattern of discontinuous conductive fingers. The other sheet contains a sensing film consisting of a number of organic and inorganic ingredients suspended in a polymer matrix. The sensing film acts as a shunt resistance to the printed conductor on the opposing polyester sheet. The shunt resistance of the sensing film decreases proportionately with the applied normal force by means of microscopic contact mechanisms in the sensing film. Very small conductors and semiconductors, ranging from fractions of microns to microns in size, are present in the sensing film. The intimate contact of these particles with other particles and with the conductive fingers on the opposite sheet produces a relatively uniform resistance that changes as a function of pressure. In Figure 1, the mechanical form of the FSR is illustrated.

Since the FSR is manufactured by a screen printing process, any size or shape of FSR can be manufactured. The FSR used for all of the work in this study is shown in Figure 2. This pattern can be used not only to measure interlayer pressures at various radii in the wound roll, but it can also be used to measure the

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[1] Force Sensitive Resistors(FSRs^{TM}), Interlink Electronics, P.O.Box 40760, Santa Barbara, CA 93103.

pressure variations across the width of the web in the cross machine direction.

This publication will first present a technique by which the FSR can be calibrated for experimental studies of the radial pressure profile in wound rolls. The results of wound roll studies which have led to the discovery of a new boundary condition for wound roll stress models are also presented. The development of this boundary condition allows models previously constrained to center-winding to be applied to center-winding with an undriven nip roll pressed against the wound roll.

NOMENCLATURE

E=Young's modulus, Pa
E_c=core stiffness, Pa
E_r=nonlinear radial roll modulus, Pa
E_θ=circumferential roll modulus, Pa
h=web thickness or caliper, cm
N=nip pressure, N/cm
T=wound on tension, Pa
T_w=tensile stress in outer layer of roll, Pa
σ_r=radial stress in wound roll, Pa
μ=coefficient of friction
ν=Poisson's ratio

INTRODUCTION

Historically there have been many different types of measurements of roll structure[2]. If the discussion of these measurements is confined to those roll structure measurements which are primary measurements of radial pressure the number of measurement schemes is reduced. One type of measurement is provided by the Smith Roll Tightness Tester[2]. This device measures the force required to penetrate a needle to a depth of approximately 1/2 in. into the face of a rewound roll. The force measured is the sum of the force required to overcome the frictional force between the web and the needle plus the force required to separate the web layers which may induce a local increase in radial pressure above the pressure due to winding. The values of the measured force are given in arbitrary units as the coefficient of friction may vary significantly from one type of web to the next. Since the device is used upon the roll face, profiles of the radial pressure as a function of roll radius or circumferential position can be generated for both roll faces. The core torque test is a measurement of the torque required to cause the core to slip within the wound roll[3]. The torque required for slippage to occur is related proportionately to the average radial pressure applied to the core and thus yields a single point averaged radial pressure at the core radius. The pull tab test involves winding thin steel or plastic strips into the wound roll at various radial locations[4,5]. After winding has been completed, the force required to cause the tabs to slip within the wound roll can be measured with a suitable force gage. With a known or measured value of the coefficient of friction, the radial pressure upon the tab can be calculated. Inserting the pull tab into a parent material prior to winding provides more consistent results since the coefficient of friction between a steel tab and an envelope of shim brass, for

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[2] Testing Machines Inc., Amityville, New York.

instance, will be more uniform across the width of the transducer than that between a steel tab and the web material. Another measurement which is similar to the pull tab and the Smith Roll Tester, since it relies upon a coefficient of friction, is the axial press test[6]. This test involves placing a male die concentrically upon one face of the wound roll and placing a female die concentrically upon the opposite face. With one die restrained, an increasing load is applied to the die on the opposite face until telescoping of the roll occurs. With this maximum measured load, dies of known diameter, and a known coefficient of friction between web layers the radial pressure can be calculated. Thin capacitance gages have been used for studying the radial pressures in wound rolls as well[7].

All of the measurement techniques discussed are either a measurement of radial stress at the roll faces or are an average measurement of radial stress across the width of the roll. The FSR is the first viable transducer for studying radial stresses across the width of the wound roll at any radial location.

EXPERIMENTAL PROCEDURE

Loading Sequence

The loading sequence applied to the FSR has a very significant effect upon its value of resistance. Two possible loading sequences are "uploading" and "downloading." An "uploading" sequence is defined as a load succession in which the load continually increases and never decreases. A "downloading" sequence is defined as a load succession in which the load is allowed to decrease at some point in the sequence.

The effect of the loading sequence is shown in Figure 3. When applying loads to the FSR, uploading yields different resistance values than does downloading. The uploading sequence was begun by applying a minimum load and incrementally applying additional loads until the maximum load was reached. The downloading sequence then begun by removing the loads incrementally until the minimum load was reached. Resistance measurements were taken at each incremental load. The data shown in Figure 3 is presented again but upon log-log scales in Figure 4. The resistance of the FSR varies linearly with the applied normal load when plotted upon log-log scales. This is helpful during the calibration process as the number of calibration points necessary to formulate a valid calibration curve can be reduced.

Figure 3 illustrates that the FSR experiences as a hysteresis effect due to the loading sequence. Due to this hysteresis effect, it is necessary to evaluate the loading sequence encountered by the FSR for a particular application and use that type of loading sequence to calibrate the FSR. For the case of constant tension center-winding, the roll will experience an upload sequence because the radial pressure is initially zero and progressively increases as the winding process continues. However, for polymeric materials such as polypropylene or polyethylene, the wound roll will experience relaxations due to the viscoelastic properties of the material. Thus, a download condition is introduced to the roll in the form of decreasing radial pressure. If the resistance measurements are made immediately after the roll has been wound, the relaxations of the roll will be small and can be neglected. For these reasons, constant tension center-winding will be considered an uploading sequence. The same arguments can be made for the case of center-winding with the addition of the nip roller.

Dynamic Response

The dynamic response of the FSR to a step input pressure has been observed to be rather peculiar. A typical dynamic response of an FSR under upload conditions is shown in Figure 5. Note that the resistance value of the FSR decays from some initial value in a nonlinear fashion. However, from the tests performed, the response of the FSR does not appear to reach a steady state value of resistance. The maximum time interval used for these tests was three hours. At the end of the three hour interval, the resistance value of the FSR was still observed to be decreasing.

Another point of interest concerning the dynamic response of the FSR is that a linear plot of resistance versus time is obtained when the values are plotted on log-log scales as shown in Figure 6. It is interesting to note that the slopes of the plots at the lower pressures are much greater than the slopes of the plots at the higher pressures. This illuminates the fact that the FSR behaves in a nonlinear fashion with respect to pressure. The different slopes of the plots also indicate that the overall change in resistance at the lower pressures is much greater than the change in resistance at the higher pressures. This is shown more clearly in Figure 7.

The dynamic response resistance data was obtained by direct measurement from a digital multimeter and by measurement of the voltage across the FSR in a ballast circuit. Comparisons were then made between the results of the two measurement techniques. The results of this comparison are shown in Figure 8. Note that the resistance values from both measurement techniques converge on the same value but take different paths in doing so. For this reason, the same measurement technique that is used during the calibration process should be used during the actual experimental winding process.

Because the resistance of the FSR does not seem to reach a steady state value, the same amount of time between loading and resistance measurement should be taken for both the calibration and experimentation measurements. This ensures that the reading was taken at the same point along the time response curve of the transducer. The dynamic response of the FSR limits its use to measuring static pressures.

Calibration Apparatus

A critical element in calibrating the FSR is to obtain a good calibration apparatus. The primary purpose of the apparatus is to apply a known uniform normal pressure to the transducer so resistance values can be obtained to construct a valid calibration curve. Because the FSR functions from microscopic contact mechanisms and the pressure is virtually constant at a given radius of the roll, creating a uniform pressure over the surface of the FSR is vital if an accurate and repeatable calibration of the device is to be performed. The device can be loaded by the use of dead weights or by the use of a materials testing system which is convenient when calibrating the FSRs for use with plastic film webs where the radial pressures can approach 700-800 psi.

It was observed that the calibration apparatus worked better when the mating surfaces were "padded." The padding consisted of approximately one eighth of an inch of the material that was used during the winding experiments and was located on either side of the FSR. The usage of padding is consistent with experiments performed by Interlink Electronics, Inc. The padding used for their experiments consisted of a 1/16 inch thick #50 durometer silicon rubber pad[1]. The padding tends to make the pressure distribution over the surface more uniform and makes the calibration similar to the environment in which the FSR is to be used.

A drawing of the apparatus used for calibrating the FSR's is shown in Figure 9. The apparatus uses dead weights as the loading device. Results from repeatability tests are shown in Figures 10 and 11. Results from this calibration apparatus were repeatable within one percent, which falls within the one percent repeatability range of the FSR.

Calibration Procedure

Due to numerous potential problems associated with calibrating the FSR, a standard procedure is needed to insure that valid results are obtained. As discussed earlier, the primary problems associated with the FSR calibration are the dynamic response of the FSR and the application of the load. For winding applications, the following calibration procedure or a similar procedure should be used:

1. Eliminate possible hysteresis effects by using an "uploading" sequence. Always start the calibration with the smallest load and progressively increase the load until the maximum load is reached.

2. Take the resistance measurements at the same time interval after loading that will be used during the winding experimentation. If this time interval is very large, time dependent data can be extrapolated on log-log scale to determine the corresponding resistance value.

3. Take 4 to 5 data points to establish the calibration curve. The curve should be linear when plotted on log-log scales.

4. Use the average resistance value of the FSR strip resistors to establish the calibration curve if the cross-web radial pressure profile is not desired.

5. Use the least-squares curve fitting technique to determine the calibration equation of the line that "best fits" the calibration data on the log-log scales

The use of this procedure should produce repeatable results consistently. However, the calibration of the FSR should be checked periodically. It has been observed that major changes in the weather, such as, temperature and humidity, can produce changes in the calibration. For this reason, before each use of an FSR, test data points should be measured and compared to the calibration curve to ensure accurate calibration.

CONSTANT TENSION CENTERWINDING WITH AN UNDRIVEN NIP

Experimental Procedure and Results

The winding experiments were performed upon an unwind/rewind facility in the Web Handling Research Center (WHRC) Mechanics Laboratory. A drawing of this machine is shown in Figure 12. The web tension is controlled by a magnetic hysteresis brake on the unwind roll and is measured by cantilevered roller load cells. The winder is equipped with a undriven nip roller which can be impinged upon the winding roll at various pressures.

The initial winding experiments for this empirical study were performed with a light weight coated paper. Each experiment was conducted at a winding tension of 3100 kPa. Nip pressures of 1.75, 3.5, and 7.0 N/cm were applied with nip rollers which were 7.62, 10.16, and 12.7 cm in diameter.

The effect of the nip diameter is shown in Figures 13,14, and 15. Each data point in these figures represents the average of the results of three different experiments. In view of the uncertainties associated with each data point in these plots, it was concluded that light weight coated paper web material used for this study does not exhibit any notable sensitivity to the diameter of the nip roller.

The effect of nip load is shown in Figures 16, 17, and 18. These figures illustrate that increases in the nip pressure result in increases in the magnitude of the radial pressures within the roll. The nip appears to produce the same effect as increasing the winding tension in constant tension center-wound rolls.

When winding with an undriven nip roll the maximum wound-on-tension can never exceed the web line tension, T_W, plus the tension difference across the undriven nip roll. The maximum tension difference which can exist across the undriven nip roll is the nip load multiplied times the coefficient of friction between the wound-on-layer and the layer beneath. This tension difference exists due the nip and the mechanism by which the nip induces tension has been reported by this author[8]. Thus the maximum wound-on-tension, T, for this winding configuration is:

$$T = T_W + NIT = T_W + \mu\ N/h \qquad \{1\}$$

where NIT is the nip induced tension, μ is the coefficient of friction, N is the nip pressure in units of load per unit width, h is the web caliper which yields units of stress for the tension.

Extension of Center-winding Models to Account for the Nip

Some winding models included an assumption that the elastic modulus in the radial direction of the roll was constant. The work of Pfeiffer [9] took into account that the radial elastic modulus behaved in a nonlinear fashion. Hakiel [6] then developed a finite difference procedure that was capable of obtaining numerical solutions to various center-winding cases based upon the nonlinear radial modulus. The numerical solutions for the cases presented herein were obtained from a computer code that implemented Hakiel's finite difference procedure. Hakiel's model for center-winding involves the solution of a second order differential equation in radial pressure. One of two boundary conditions required for the solution of this equation is that the web line tensile stress is assumed equal to the circumferential stress in the wound-on-layer. To extend Hakiel's center-winding model to account for the undriven nip roll the maximum wound-on-tension, calculated from equation {1}, is assumed equal to the circumferential stress in the wound-on-layer.

Results from the Extended Model

Shown in Figures 19,20, and 21 are results from the extended model, the center-winding model (assuming no N.I.T.), and experimental data obtained from winding experiments using FSRs. Since the radial pressure profiles were shown to be more dependent upon nip pressure than nip diameter, all the radial pressure data for all nip diameters at a given nip pressure were averaged and standard deviations were calculated. Thus each experimental data point in Figures 19, 20, and 21 represent the average of nine tests and the standard deviation is shown overlaid as an error bar. The extended model works quite well for the light weight coated paper.

For a polypropylene material similar results are shown in Figures 22, 23, and 24. Again the extended model predicted the wound roll stresses quite well. Thus the extended model seems to be accurate for a range of materials.

The web and stack property data are presented in Table I for both the light weight coated paper and for the polypropylene materials which were wound.

CONCLUSIONS

Calibration of Force Sensitive Resistors

The calibration of the FSR is one of the most critical aspects pertaining to the use of the FSR as a pressure transducer. The response of an FSR under applied normal pressures has the following distinguishing characteristics: a nonlinear resistance versus pressure profile, sensitivity to loading sequence, and a slow dynamic response. The nonlinear response of the FSR places great emphasis upon correct calibration because slight errors in calibration are magnified and can result in large errors in experimental values obtained from the transducer. In order to obtain good results, great care must be taken to calibrate the FSR. The two principle factors affecting the calibration of the FSR are the response of the FSR to applied normal pressures and the equipment used to perform the calibration. The apparatus should be designed and manufactured with the following two goals in mind: the FSR should be placed between two "padded" mating surfaces; the load should be centered directly over the FSR being calibrated. If these two goals are met, then the apparatus will yield repeatable results.

The Extended Winding Model

The empirical study proved that for center-winding with an undriven nip roll that the diameter of the nip roll has a lesser effect upon the radial stress profile in the wound roll than the magnitude of the nip pressure. If a new boundary condition is implemented which equates the wound-on-tension in equation {1} to the circumferential stress in the wound-on-layer, an extended version of Hakiel's model provides results which are accurate for center-winding with an undriven nip roll.

ACKNOWLEDGEMENTS

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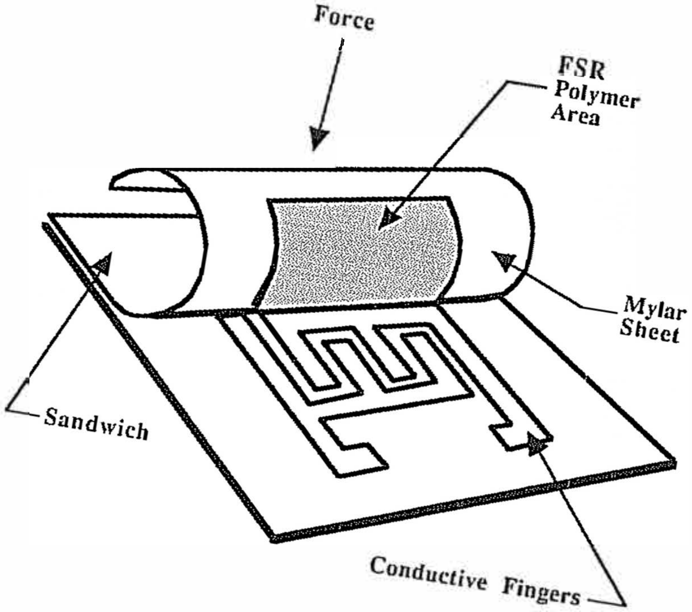

Figure 1. A Shunt-Mode Style Force Sensing Resistor

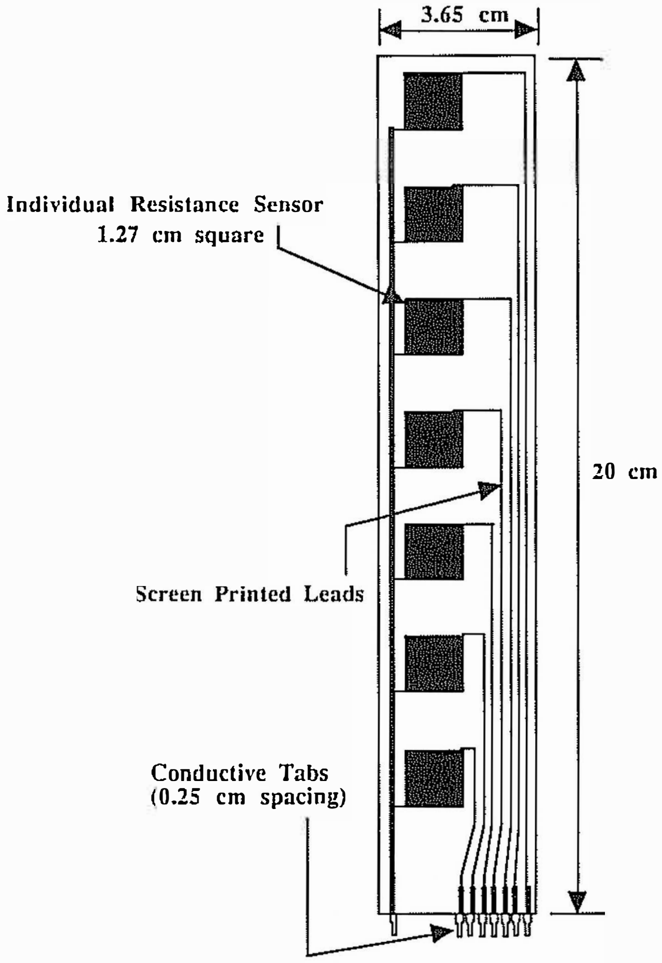

Figure 2. Force Sensitive Resistor, 3M Screen Printed Pattern

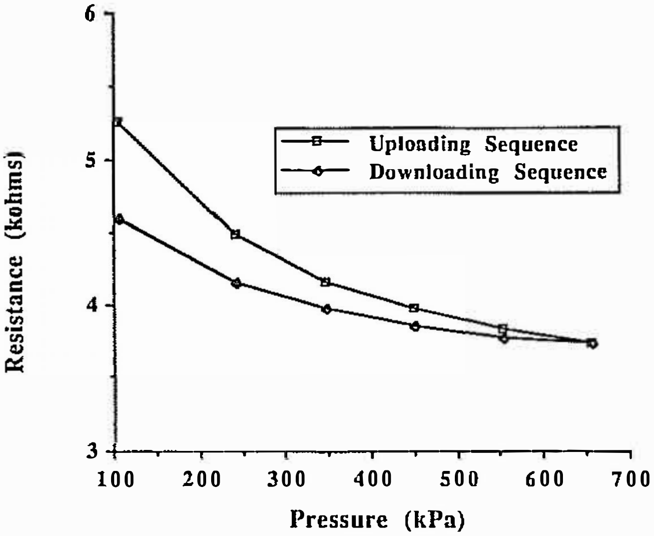

Figure 3. - Hysterisis of FSR Resistance Values Produced by Loading Sequence

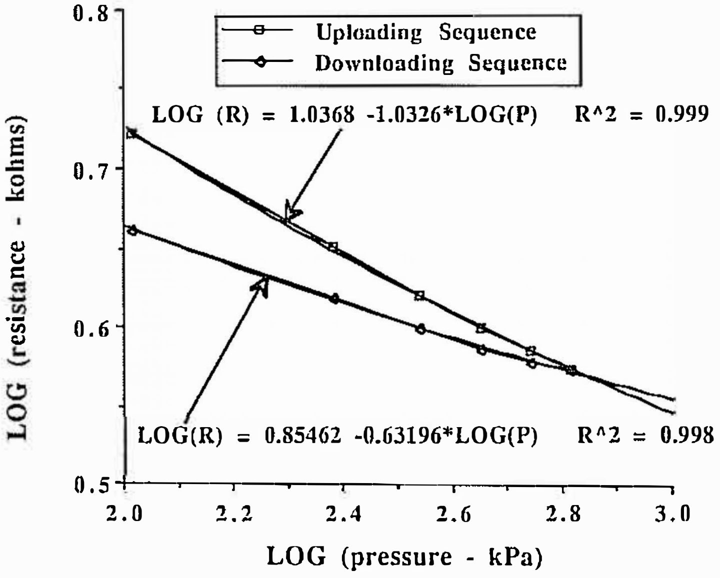

Figure 4. - Effect of Loading Sequence upon FSR Resistance

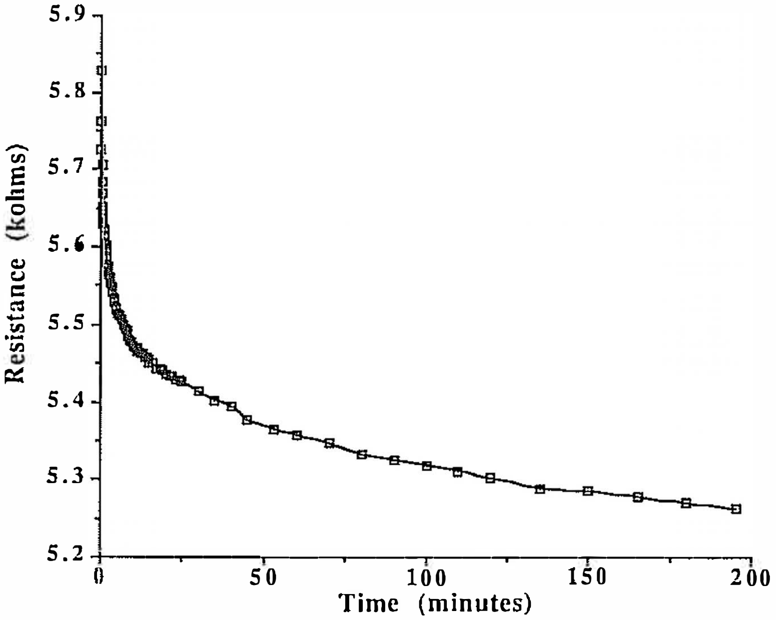

Figure 5. - Typical Dynamic Response of an FSR to a Step Input Pressure

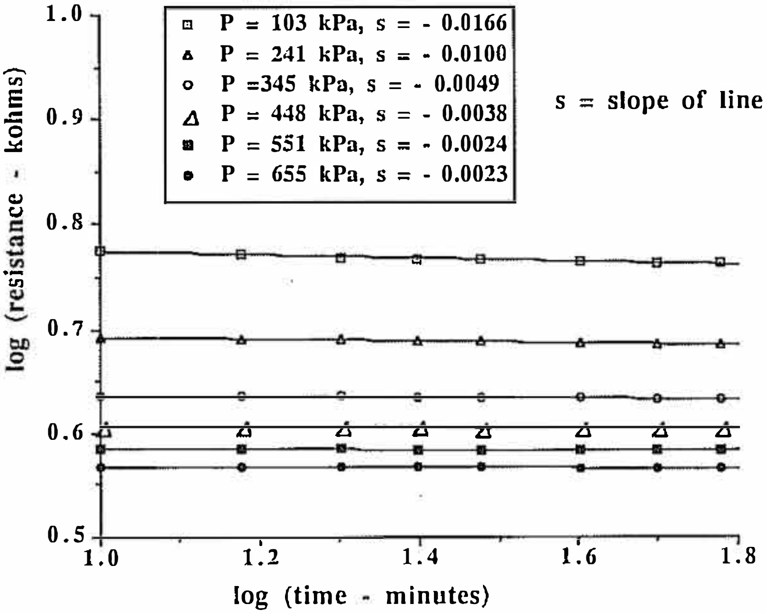

Figure 6. Dynamic Response of an FSR to Step Input Pressures

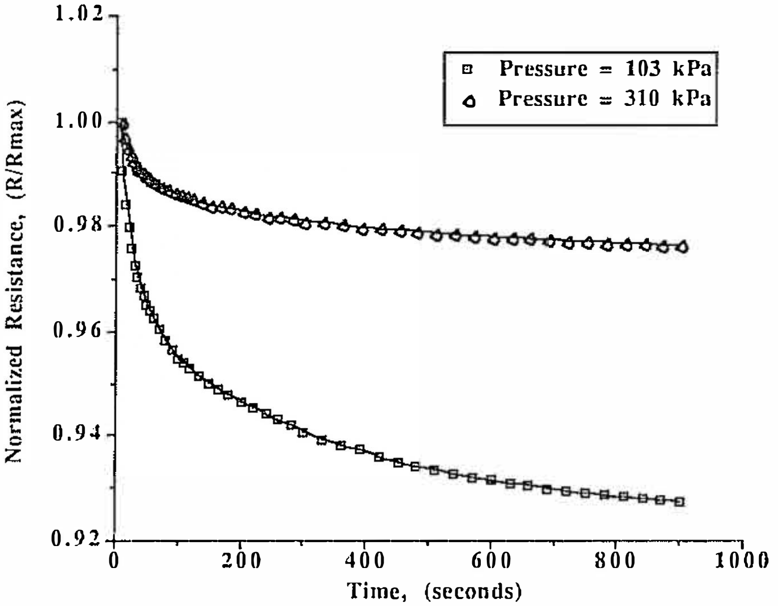

Figure 7. Effect of Pressure upon the Dynamic Response of the FSR

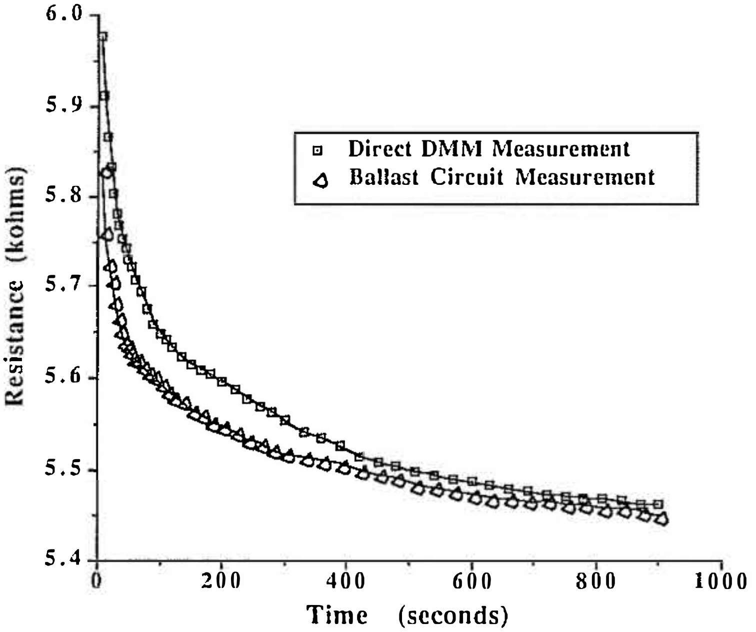

Figure 8. - Effect of Measurement Technique upon the Dynamic Response of the FSR

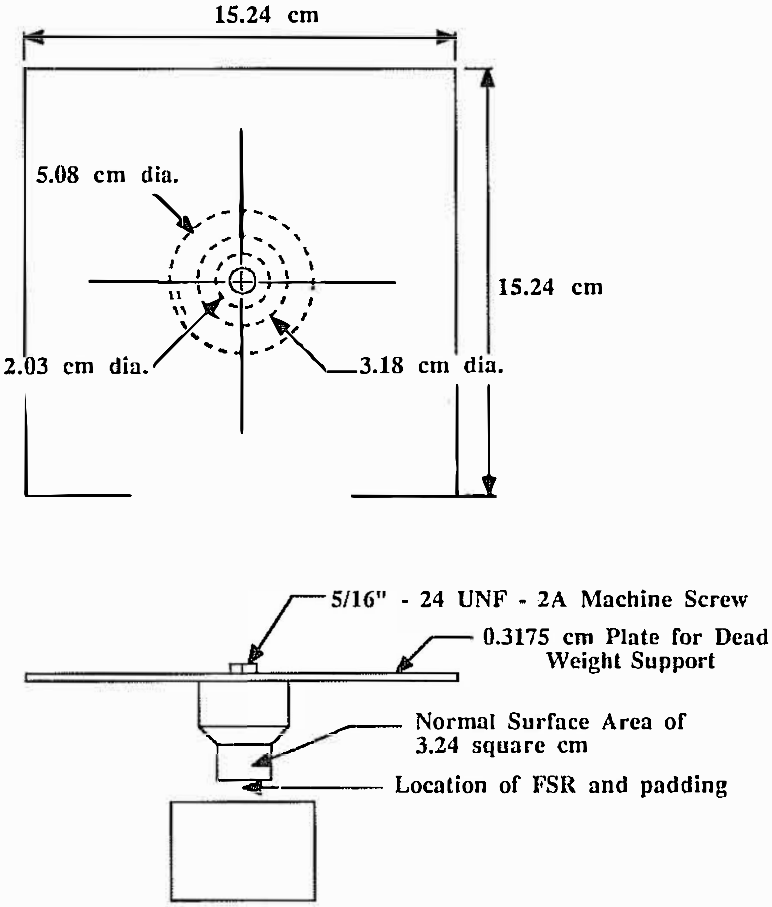

Figure 9. - Calibration Apparatus for Dead Weight Load Application

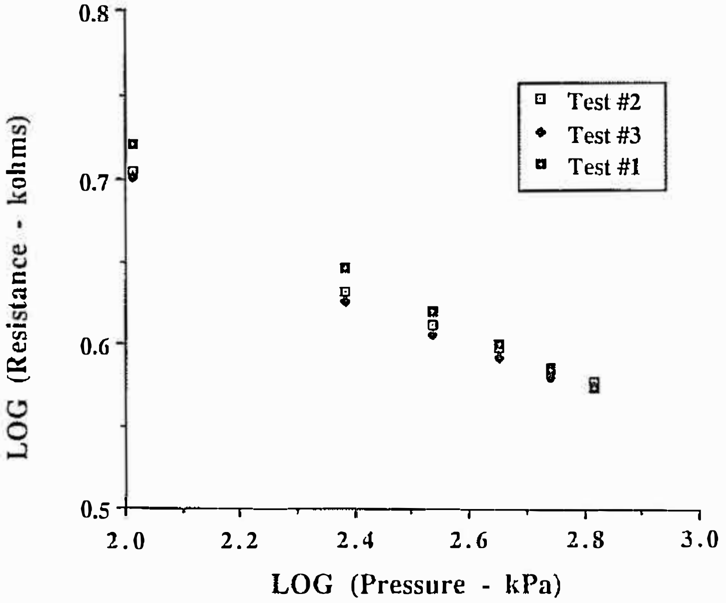

Figure 10. - FSR Repeatibility Experiment #1

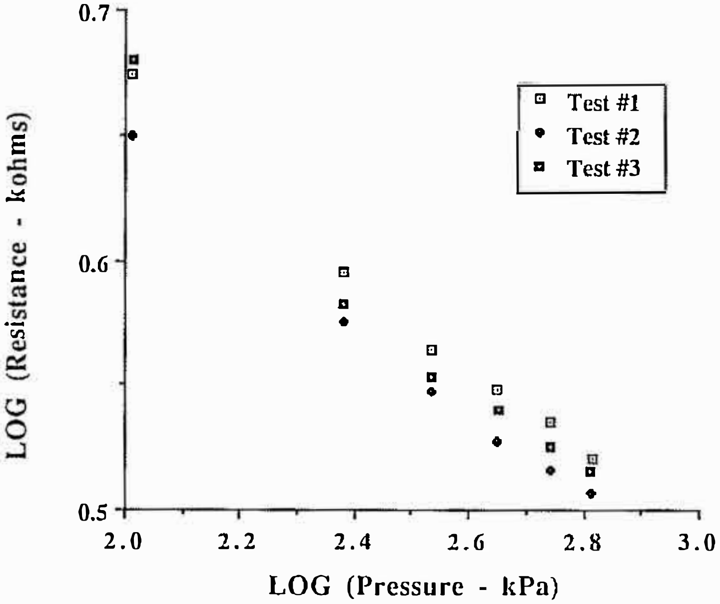

Figure 11. - FSR Repeatibility Experiment #2

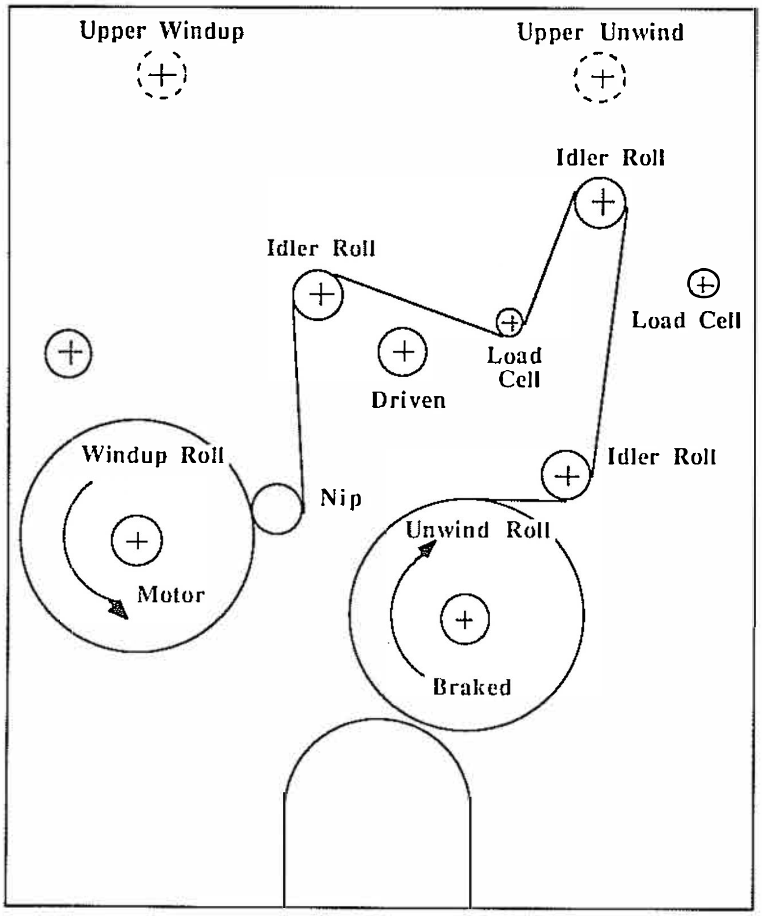

Figure 12. Unwind/Rewind Facility

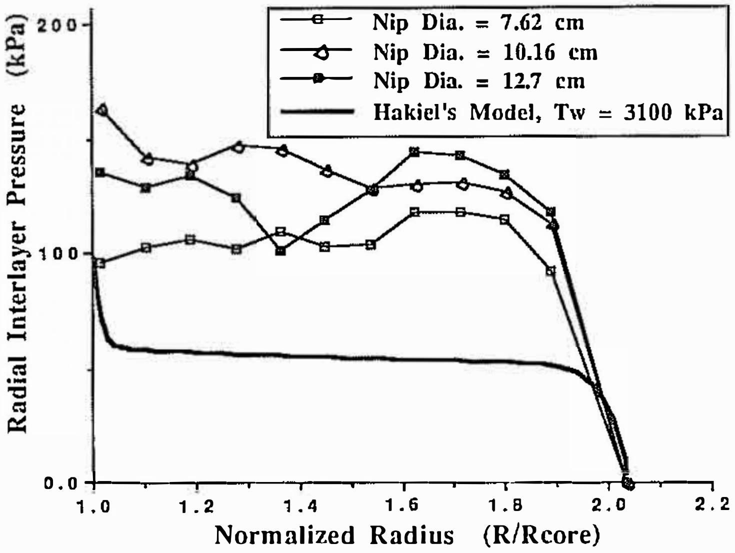

Figure 13. - Effect of Nip Diameter upon Radial Pressure, Nip Pressure = 1.75 N/cm

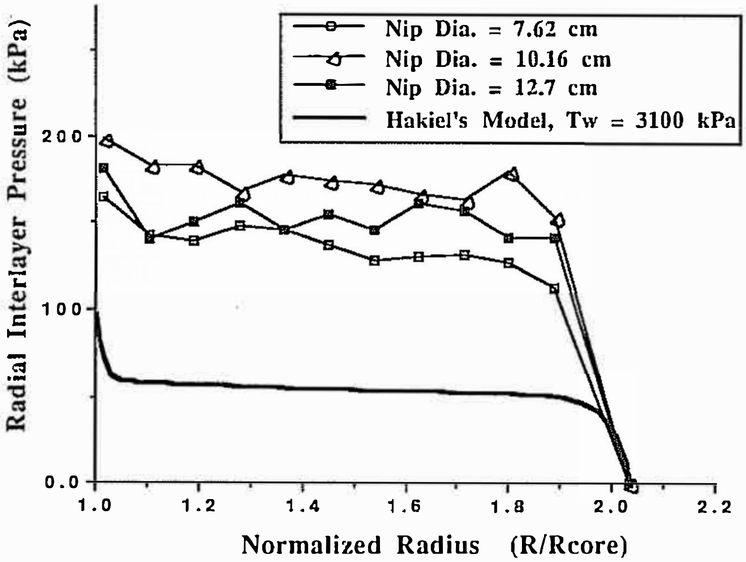

Figure 14. - Effect of Nip Diameter upon Radial Pressure, Nip Pressure = 3.5 N/cm

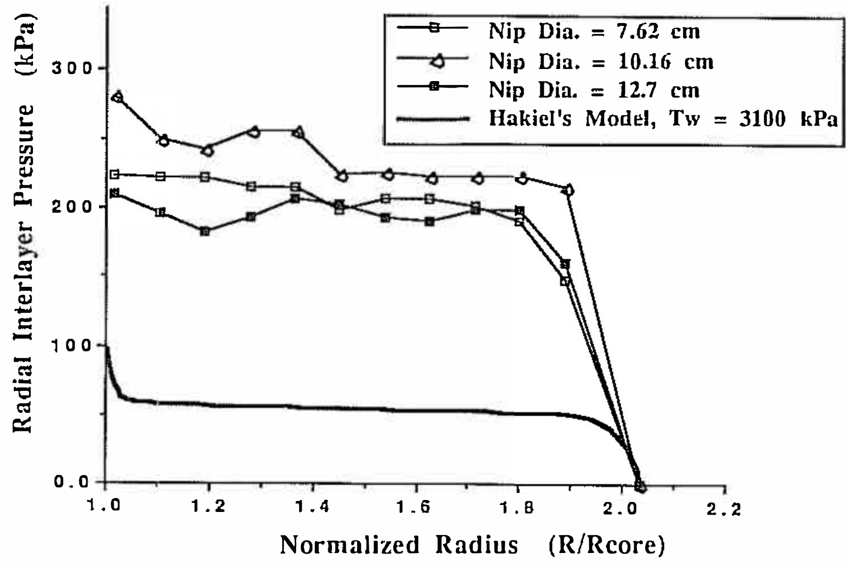

Figure 15. - Effect of Nip Diameter upon Radial Pressure, Nip Pressure = 7 N/cm

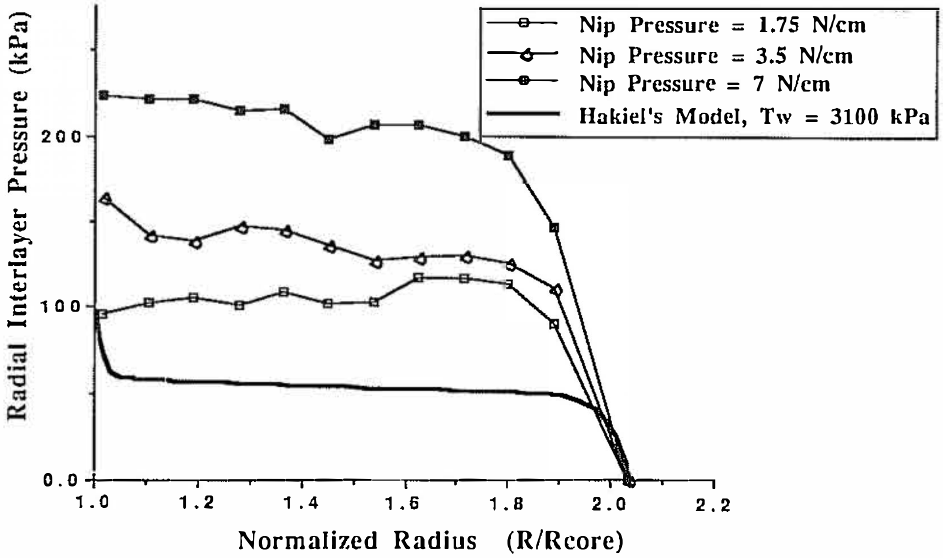

Figure 16. - Effect of Nip Pressure upon Radial Pressure, Nip Diameter = 7.62 cm

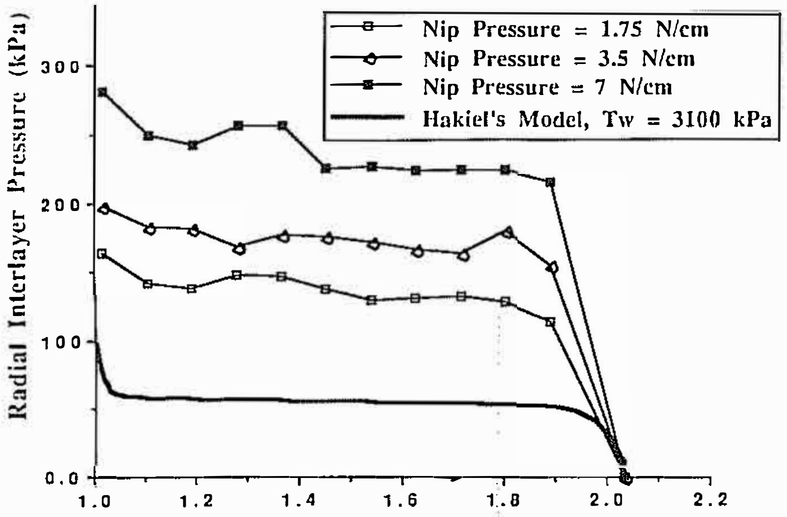

Figure 17. - Effect of Nip Pressure upon Radial Pressure, Nip Diameter = 10.16 cm

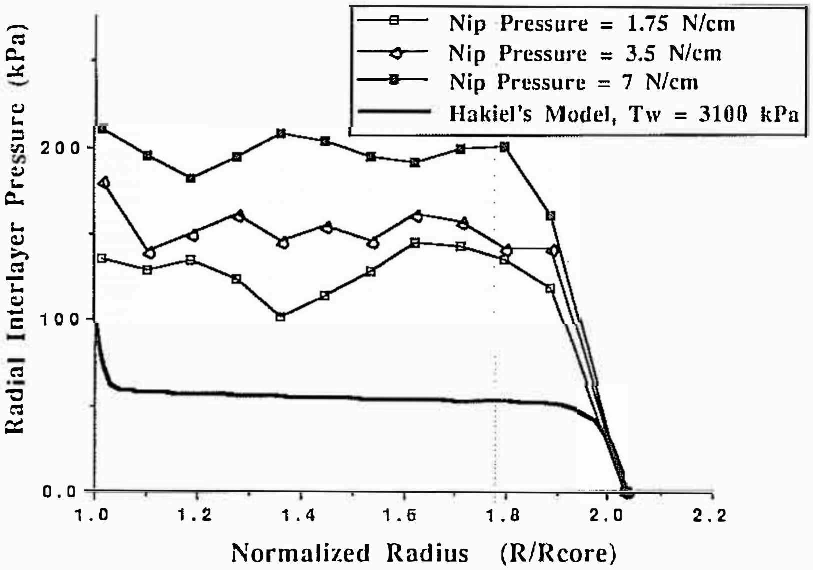

Figure 18. - Effect of Nip Pressure upon Radial Pressure, Nip Diameter = 12.7 cm

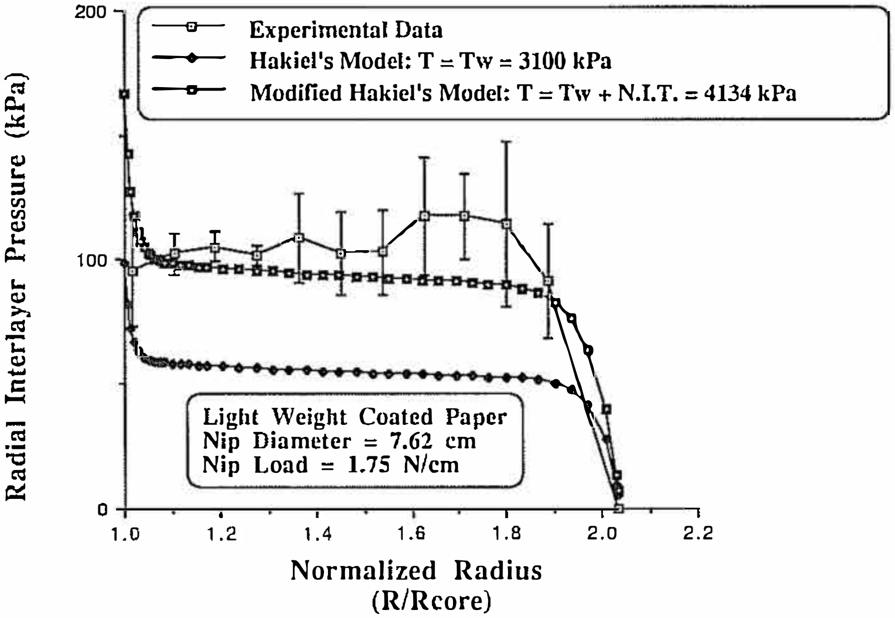

Figure 19. - Comparison of Experimental Results with Hakiel's Modified Model

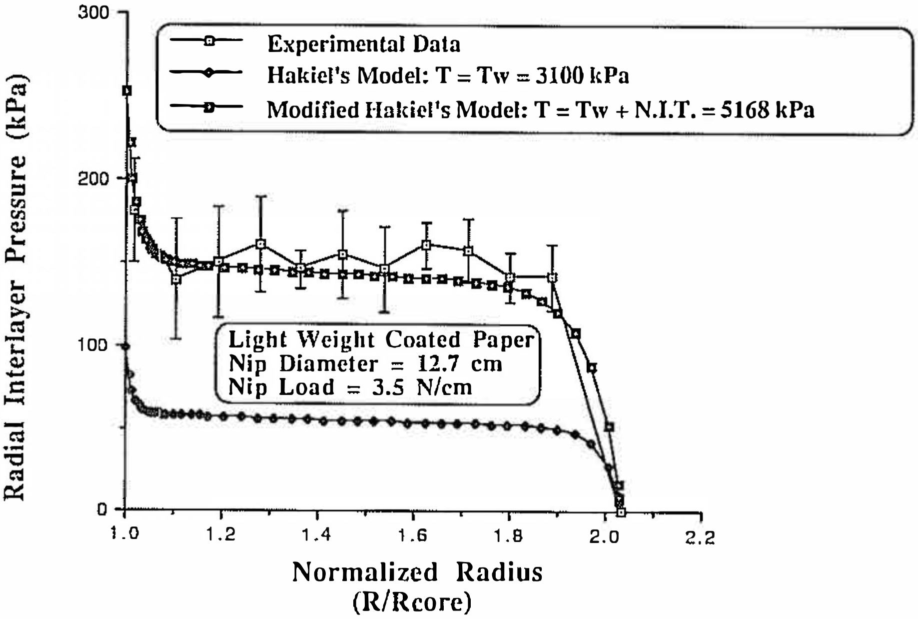

Figure 20. - Comparison of Experimental Results with Hakiel's Modified Model

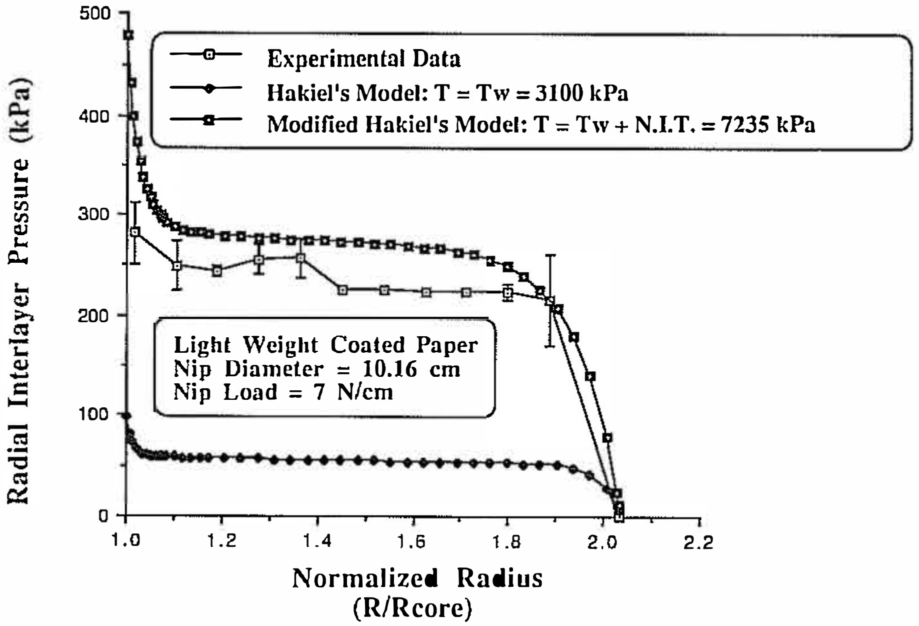

Figure 21. - Comparison of Experimental Results with Hakiel's Modified Model

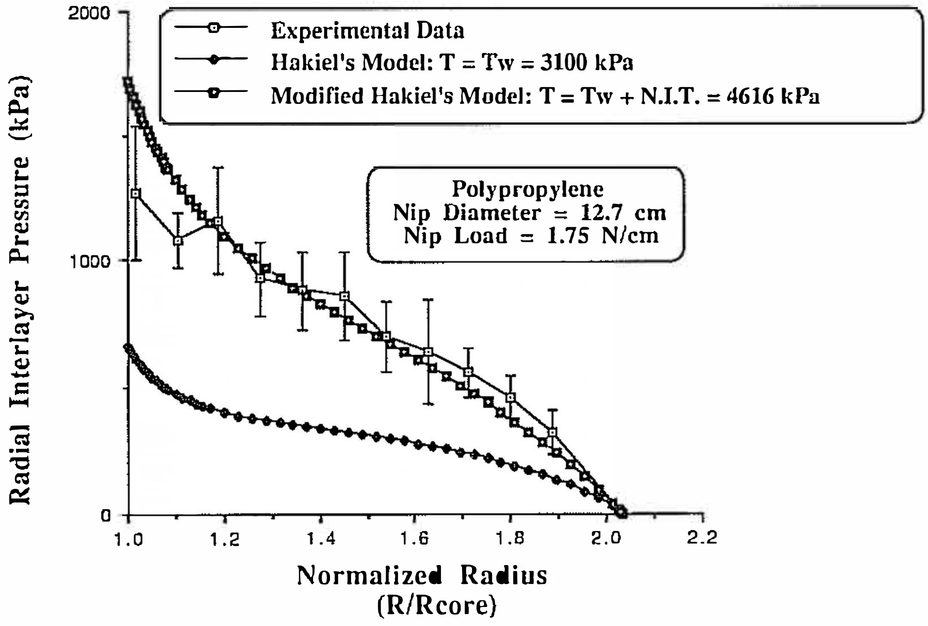

Figure 22. - Comparison of Experimental Results with Hakiel's Modified Model

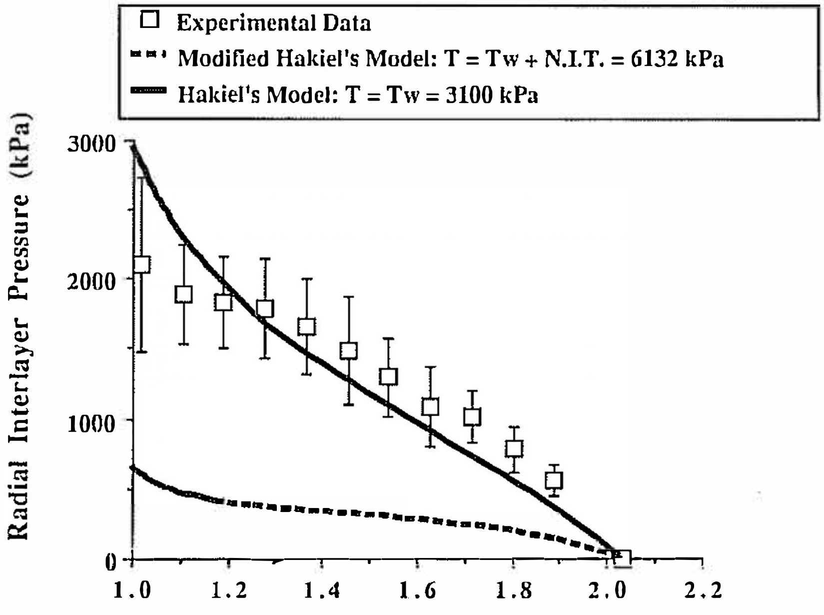

Figure 23. - Comparison of Experimental Results with Hakiel's Model
Polypropylene, Nip Pressure = 3.5 N/cm

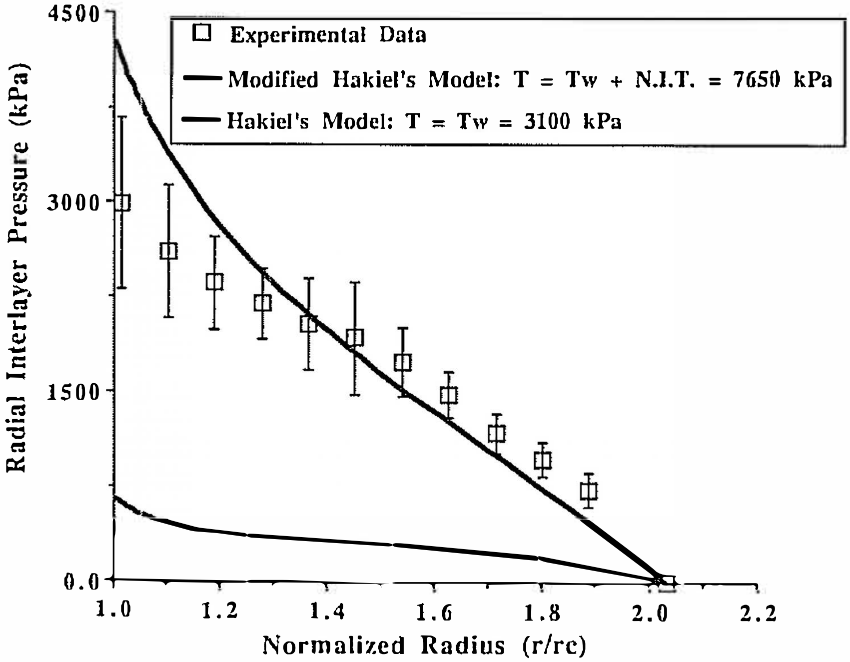

Figure 24. - Comparison of Experimental Results with Hakiel's Model
Polypropylene, Nip Pressure = 5.25 N/cm

Table 1
Web Properties and Winding Parameters

	Light Weight Coated Paper	Polypropylene
thickness(cm)	5.08E-03	2.54E-03
width(cm)	15.24	15.24
Poisson's ratio($\nu_{r\theta}$)	0.0[1]	0.0[1]
Er(kPa)	$72.8*\sigma_r$	$260.0*\sigma_r$
E_θ(GPa)	8.268	3.101
coefficient of traction	0.30[2]	0.22[2]
core i.d.(cm)	7.71	7.71
core o.d.(cm)	8.75	8.75
core stiffness steel(GPa)	27.1	27.1
final roll diameter(cm)	17.78	17.78

1. Poisson's ratio as a stack property was assumed to be zero as assumed by
   Hakiel[15].

2. Kinetic values of the coefficient of friction.

USING FSRS TO MEASURE RADIAL PRESSURE IN WOUND ROLLS

J.K. Good

You showed several experimental curves of pressure versus diameter for different nip pressures. Did you obtain curves with no nip for direct comparison with the results of the Hakiel model?
Dilwyn Jones, ICI Films

No.

Do you think there is an effect of the presence of a nip roller without any applied nip pressure?
Dilwyn Jones, ICI Films

The extended wound roll model described herein would predict that in this case the radial pressure within the wound roll to be equivalent to a centerwound roll with the same web line tension. If we stray from the model however, I do believe that the presence of an unloaded lay-on roll affects wound roll quality. Some winders perform what is known as gap winding where an unloaded lay-on roll tracks the outside of the winding roll. There is usuallly a small gap between the lay-on and winding rolls, thus the term "gap winding." The purpose of the lay-on roll in this type of winding is not to increase wound roll stress or to exude air but to simply guide the web in the near vicinity of the winding roll to attempt to reduce wrinkling. Lightly loaded nips are often used to exude air from winding rolls. In this case the extended model described is appropriate even though the nip loads are small. In such a case the stack properties may have to be altered to account for whatever air may have been entrained.

How did you measure coefficient of friction and does it take account of air entrainment?
Dilwyn Jones ICI Films

The test results shown herein were the results of winding at low speeds (7.5 - 15 M/Min). We wound at low speeds since current winding models do not account for entrained air. The kinetic coefficients of friction were measured using the ASTM Standard D1894.

From earlier discussions it has been mentioned that FSR's are sensitive to pressure which we want, but they also are sensitive to time, temperature and humidity and maybe even with the phases of the moon. Has there been any conversation with the supplier to reduce these unwanted sensitivities? Do you have any other thoughts on that subject?
Bob Lucas, Beloit Corp.

Bob is absolutely right. You can not expect to receive an FSR, to calibrate it and expect that calibration to last accurately for more than a period of probably a couple of weeks, because there are a lot of things that affect the output of an FSR. He says humidity, temperature, yes those are both effects. So whenever we employ FSRS in research studies we always take a few data points to re-establish the slope of the calibration curves with respect to pressure and respect to time, and we try to do that within a day or two of when we are going to be performing the winding. With regard to the phases of the moon, we've not done any calibration based upon moon phase yet, although that's the sort of thing that usually intrigues graduate students.

We have had conversations with suppliers to reduce unwanted sensitivities, but if you read the papers on these devices you will find they were originally intended to be digital on/off devices such as switches on keyboards and this sort of thing where a large change of resistance was needed to distinguish a digital zero to a digital one. They were really never intended in the beginning to be used as an analog pressure device. they might have hoped they would, but due to the various calibration problems that we talked about, it really wasn't feasible.

Were the nip rolls of various diameters of known hardness? Could the roll hardness explain the relationship between radial pressure and nip diameter?
Ardre Thill, Mobil Plastics Europe

The nip rolls were all uncovered aluminum rolls. A hardness measurement would be difficult on such a surface but in answer to your first question let us say that the nip rolls were very hard compared to the winding rolls. In answer to the second question, I believe there is no relationship between nip diameter and radial pressure for this winding configuration at speeds where air entrainment is negligible.

How much of a problem is the change in wound in stress induced by the FSR itself contaminating the roll in thin films?
Larry Schultz, 3M Company

This is not a nondestructive test as we are winding in a device, similar to a pull tab in an envelope, which can only be removed by unwinding the roll in most cases. To what extent the FSR contaminates the wound roll stresses depends upon the material which is being wound and the winding parameters but the total effect has not been documented. The Smith Needle Test and pull tabs also disturb the web locally in the wind, so against what error free standard do we compare the FSR?

Did you try (or is it possible) to wind without a nip to see if your results were consistent with Hakiel's Model?
Dave McDonald, Pulp and Paper Research Institute of Canada

As in response to Dilwyn Jones question the answer is no. These pressure sensors were calibrated in a device which exerted uniform pressure upon them and then used in a winding study which has not been previously documented. Both Hakiel (6) and Pfeiffer (9) have documented and verified centerwinding models which do not consider nip rolls.