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The Effects of Wet-Pressing and Degree of Refining Upon the Strength Properties of Paper

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THE EFFECTS OF WET-PRESSING AND DEGREE OF REFINING UPON THE STRENGTH PROPERTIES OF PAPER

BY

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ABSTRACT

The dynamic press simulator has great potential to become a reliable tool in the study of wet pressing. This instrument allows the researcher to duplicate wet press nip conditions in the laboratory.

I was unable to complete my planned study concerning the relationship between refining and wet pressing as they effect the development of fiber bonding because of equipment failure. The press loadings and drop heights used in my experiment caused the development of stresses which exceeded the press simulators design limitations.

If the dynamic press simulator is to be used to study the wide range of pressing conditions found in the Paper Industry today, design modifications must be made to increase its load sustaining ability. Such modifications would include expanding the base of the simulator to a four post configuration to increase structural rigidity, housing the bearings directly inside the hammer plate eliminating external bearing housing and distributing the load weight over the entire width of the hammer plate to decrease deflections in impact caused by central loading. Finally, the ratchets in the catching mechanism must be extended to perform their function at greater rebound heights.

Keywords: PRESSING; SIMULATION; REFINING; MECHANICAL PROPERTIES

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INTRODUCTION

During these times of energy-conscious decision making in the Paper Industry, wet-pressing, the first stage of water removal after sheet formation on the wire, is quickly becoming an acute consideration in further process development to enhance its drying capabilities. The behavior of sheet strength characteristics from the wet-pressing stage, with all its parameters, is coming under increasing scrutiny in relation to the amount of pressure and refining to determine which method of increasing density gives better strength properties.

Also, the hydraulic pressure and the mechanical pressure, and their corresponding interactions involving the function of compression upon the sheet are of viable interest.

THEORETICAL DISCUSSION

Fiber Bondings

As noted by Marton (1) and others, the strength of paper depends to a great extent on the number of bonds formed between the surfaces of the adjacent fibers. The number of bonds formed is determined chiefly by chemical composition and physical characteristics of the outer layers of the fiber cell wall. These factors can be altered by delignification, beating, wet-pressing, and other

processes.

According to the text, THE PULPING OF WOOD, during the beating of chemical pulps, fibers are reduced in length, and their primary and secondary layers are damaged. (2) The partial and/or complete removal of these layers makes the underlying layers more accessible to swelling. Hence the main action of the beating process is the disintegration of residual fiber bundles into individual fibers.

Wet-pressing can cause an effect similar to that obtained by increasing the beating time. Both actions accomplish the closer contact of fibers in paper, or in other words, increased density. Doughty (3), on the basis of his work, proposed that apparent density is one of the best indices of the inter-fiber bonding. As revealed by his investigation, large changes in density and breaking length occur with relatively small increments in swelling for wet pressing. However, spontaneous density increases do not follow with increased "swellability" until sufficient lignin has been removed.

The summary of Doughty's results revealed that wet-pressing had little effect on the removal of the primary and the first of the secondary fiber walls in all cases studied. However, its application promoted strength development to a significant degree. Its effects varied

depending upon the product derived from the parent pulp. For the parent pulp, wet-pressing of the fibers produced hardly any effect on the swellability of the fibers. Upon removing more and more of the lignin, and after some limited beating, wet-pressing was observed to produce a change in the fibers similar to that obtained through ball milling.

MECHANICS OF BONDING

Van Den Akker (4) had written "that the most exciting fact about paper, known and appreciated over the eighteen-and-one-half centuries since the invention of the product by Tsai Lun, is that a tough, strong sheet of material is obtained when cellulosic vegetable fibers are mechanically beaten in the presence of water and are felted together from an aqueous suspension by the forming on a screen and then dried". When we consider the mechanism bonding of cellulose fibers in the making of paper, we find that there are three fundamental factors involved. First we have to think of what surfaces are to be brought together, next we have to consider what surfaces are to be bonded, and finally, how they are to be locked in position.

From "THE PULPING OF WOOD" et al, the fiber surfaces are important where beating and/or refining increases the amount of surface area available for bonding via the production of fibrillar membranes which comprise the walls of each fiber. The fiber wall is typically comprised of four

layers commonly labeled S1, S2 and S3, and the primary layer. These layers are concentric around a central cylindrical lumen. During beating, the primary wall is usually pealed (or "beaten") off the fiber exposing the secondary layers. Increased mechanical action on the fibers releases "fibrils" or a fraying of these layers into their composite fibrils. As these fibrils are released and projecting out from the parent fiber suspended in water, a mechanical interlocking comes about, establishing close clearances between the fibers. Thus structural strength is enhanced via interfiber bonding and a corresponding increase of surface contact area. These secondary layers, especially the S1 and S2 layers, are the layers that are subject to water penetration and the subsequent swelling of the fibers.

Van Den Akker also pointed out that wet pressing enables the "bringing together" of the available bonding sites of the fiber mass where the load has to be carried by the interfiber contact areas. Since these areas are much less than the total areas of the sheet, the pressure per unit area is many times greater than the load pressure, especially when there are voids present. Obviously, the pressing operation has an importance other than water removal.

Further water removal by drying enhances the "bringing

together" of these bonding sites as noted by Van Den Akker. Evaporation of this water is accompanied by shrinkage. Cellulose itself, which makes up the fiber bundles, does not shrink. It is the tension force of the water that further enhances the degree of bonding and the resultant strength of paper. One component of this strength is due to the bonding of hydrogen bonds; that is, to regions where the hydrogen atom of a chemical group such as hydroxyl (OH^-) finds itself in close proximity to an atom of oxygen or some other element possessing one or more pairs of unshared electrons. (5) This mechanism occurs as soon as the amount of water in a cellulose fiber or a mass of cellulose fibers such as paper pulp becomes low enough to be in equilibrium with the relative vapor pressure (less than 100%). This tension force (the surface tension of water) comes into dominance to draw the solid surfaces together. That is, provided the solid surfaces are already close enough to each other so that the space between the solids is filled with water when the humidity goes below the one-hundred percent point.

The sheet entering the press from the fourdrinier can contain from 80 to 85% water, depending on the machine speed and the grade of paper, and since it is extremely costly to remove water by steam drying, the efficiency of the press section is of critical importance in minimizing the cost of converting the pulp slurry to finished paper.

It is well known that a wet sheet is difficult to run on a paper machine since the stress applied by the draws between the sections can produce tensile failure of the web because the failure point of wet paper becomes lower as the moisture content increases. The more efficient the press section is in removing water from the sheet, the stronger the sheet is, thus contributing to more efficient machine operation.

According to Bliesner (6) the basic principle of wet-pressing a sheet of paper involves the compression of the sheet to squeeze water from the interior of the web. The more the paper sheet is compressed, the more water is removed.

This simple definition becomes more complicated as one reviews the dynamics. Wahlstrom (7) pointed out that the total press load is counter-balanced by other forces generated within the nip, all expressed in pounds per lineal inch (pli). This counter-pressure can be divided into two parts: the hydraulic pressure involving the water present in the felt and the paper, and the mechanical pressure. The total pressure at any point in the nip is equal to the sum of these component pressures.

Wahlstrom further establishes and defines four specific regions or phases describing the interaction of these two component pressures (Figure 1). Phase 1 is represented by the entrance of the sheet and felt into the nip. Here,

only the mechanical pressure is present and continues to increase until the web voids are filled with water, that is, are completely saturated with water. Thus the onset of the hydraulic pressure commences, introducing Phase 2. Phase 2 proceeds now to the point of maximum pressure at or near the midpoint of the nip. As the hydraulic pressure increases, water is squeezed from the web into the felt. Phase 3 continues from the midpoint to the point of maximum paper dryness. Mechanical pressure on the sheet continues to increase as long as the dryness of the sheet increases (Phases 1 & 2), hence maximum mechanical pressure corresponds to the maximum sheet dryness. Phase 4 represents the rewetting region where the expansion of both the paper web and the felt causes water to move along the interface and reabsorb back into the sheet. This phase continues until the final physical separation of sheet and felt.

Wahlstrom continues to discuss the factors which influence wet-pressing:

1) The Press Load, which is under direct control of the papermaker. However, in high-moisture sheets, crushing can result, hence limiting the press load. The loss of caliper and/or bulk are two of the quality parameters one must consider when increasing the press load. Press roll covers can be a limiting factor due to the heat buildup. In a typical press section one roll is a plain

roll usually made of stone or synthetic stone and the other roll is usually covered with rubber. The rubber covered roll influences the nip length which determines the amount of time the sheet and the felt are in the nip; the "residence time". With hard rolls the felt (other than the sheet) is the only compressible material in the nip.

2) The Drainage Forces, also referred to as the hydraulic pressure difference, or its pressure uniformity across the sheet, will improve water removal.

3) Sheet Quality Factors, such as formation, fine retention, and furnish components are believed to be major considerations. Unfortunately, no published research was found in this area.

4) Paper Compression Properties, as summarized by Han (8) is the best literature available to date. It is shown that for static compressibility of synthetic fiber mats, the data can be represented by a simple power function over a wide range of compacting pressures, (i.e. the mat density is proportional to the applied pressure). Also, for woodpulp fibers, which are viscoelastic in nature, irreversible factors become important, loss of absorbed water at contact points has an effect along with the time-dependent variables. Finally, since the flow of water is in-

volved in wet-pressing, moisture content into the press has a direct bearing on the compression of the web.

5) The Flow Resistance of Paper, is the major resistance to sheet-water-removal, where its primary determinants are the basis weight and the degree of refining as indicated through the Canadian Standard Freeness (CSF).

Nilsson and Larsson (9) commented that except for very light-weight paper (e.g. tissue) it is quite likely that the flow resistance of the paper web itself is the major deterrence to higher sheet dryness. And Busker (10) concluded that one major controlling factor is the resistance to water flow out of the paper.

6) The Time Duration of Pressing, is coming under greater scrutiny. The variables here involve the nip residence time which is a function of machine speed and nip length, where the nip length is a function of rubber cover hardness and/or felt compression properties and the applied stress load.

Briefly, rewetting mechanisms (11) are also parameters of wet-pressing which are now only beginning to be understood. Recent developments to offset rewetting problems includes the advent of grooved rolls, double-felted presses, blind-drilled rolls, and the incorporation of vacuum inside a press roll to aid in water removal.

Mention is now given to D.J. MacLaurin and J.F. Whalen of the Institute of Paper Chemistry, Appleton, Wisconsin, concerning their work involving wet pressing. (12) In their research, they cite Doughty, et al, about an extensive study of relationships between wet-pressing of handsheets and the properties of the dried sheets, using unrefined spruce sulfite pulp. They showed that dry sheet density, tensile, fold, and burst increased with increasing pressure. Doughty, through subsequent research, showed that at the same wet pressure, sheets of shorter fibers were denser and had higher tensile strength than sheets of longer fibers. The amount of shrinkage increased rapidly to a maximum at relatively low pressures. Sheets from short fibers showed greater shrinkage than those of long fibers at any particular pressure. These studies led to the generalization that wet pressing has the same kind of effects on dry sheet properties as typical refining.

Another author cited by MacLaurin and Whalen is Campbell. (13) Campbell says that if the fibers are sufficiently flexible and fibrillated, bonding is not increased by wet-pressing. Lindman (7) made an extensive study of the strength along the drier section of a of a paper machine. He concluded that excessive wet-

pressing could give a lowering of dry sheet strength. He also found that the sheet had a higher fold and density immediately after the set presses than after the first few driers. Arlov and Ivarsson (14) (other authors cited) showed how stretch could counter-act the effects of wet-pressing.

MacLaurin and Whalen theorized that, because of the general relationships between wet sheet pressing and dry sheet strengh, it was predicted that the dry sheet burst could be raised by additional wet-pressing alone, thus avoiding slowing the stock through refining. Their experiments indicate that repeated pressings at lower pressures are not as effective in raising burst as a single pressing at higher pressures. Other conclusions include the fact that a sheet can be compacted so far and no further, unless perhaps very high pressures are used which are sufficient to crush the fibers and remove internal water. It is interesting to note that sheet density-strength relationships are not independent of refining. It is quite apparent that refining is more effective than wet-pressing in raising burst. Lastly, it was concluded that for purposes of increasing the bursting strength through wet-pressing, two or possibly three pressings at pressures not over 300 to 400 pli, but otherwise as high as possible, would give maximum gain. Pressing to a moisture content of

about 50% appeared to be optimum.

EXPERIMENTAL PROCEDURE

EQUIPMENT

It is the purpose of this experiment to determine which method of increasing density (refining or wet-pressing) will give the maximum sheet strength. This study will be carried out on an instrument called a dynamic press simulator.

The dynamic press simulator (Figure 2) used was originally developed by Warren and Zotterman (15) The press nip consists of a hammer and an anvil. The anvil consists of a 3.5" diameter piece of steel made to cover a force transducer. The force transducer is connected to an oscilloscope which measures the pressure pulse. On top of the steel is a 3.5" diameter piece of hard rubber drilled in a pattern similar to a blind drilled roll. The holes are drilled to about 3/8" depths, with 1/8" holes. Each rubber piece is 3/4" thick. This arrangement corresponds to a blind drilled press but can be used to simulate a suction press. The function of the vacuum applied to a suction press is not to suck water from the paper web but to suck it from the felt and pass it through the roll shell to prevent rewetting of the felt and sheet. In the press simulator rewetting of the felt is not important (the felts are conditioned by hand) and

rewetting of the sheet is likely to be insignificant. It is important, however, that the hole pattern used gives the same small-scale pressure distribution as the press nip to be simulated. The hammer consists of a steel plate which has a hard rubber disc, the same as just described for the anvil. The hammer travels on two hard-cased posts with ball bearings on the steel plate. The steel plate has a place on top where various amounts of weight are placed. A pad of a wet hand sheet with a felt on top and bottom is placed between the two pieces of hard rubber and pressed with varying amounts of weight.

This configuration uses a simple drop mechanism. The hammer is attached to a cable with a quick release mechanism attached. The hammer is raised to a desired drop height and released by the quick release mechanism. When the hammer hits the felts and pad of wet paper, it rebounds and is caught by a spring-loaded catch system which consists of two rachets one on each side. This configuration gives a rapid unload time and enables short dwell times to be readily attained.

For a paper machine nip, the press impulse is equal to the linear load divided by the machine speed. In the press simulator, the press impulse equals:

$$\left[\frac{MV_1 - M(-V_2)}{A}\right] ?$$

Where: M = mass of hammer

V_1 = velocity before impact

V_2 = velocity after impact

A = area of sample ?

Theoretically,

$$V_1 = (2gh_1)^{\frac{1}{2}}$$
$$V_2 = (2gh_2)^{\frac{1}{2}}$$

Where: h_1 , h_2 = drop height and rebound ht. respectively

g = acceleration of gravity

STOCK PREPARATION

Four 360_g, ODF Valley beaters of pulp were required to supply enough stock for this investigation. The stock used is a 50:50 blend of Southern bleached hardwood and Northern bleached softwood.

Refining of the stock was done in a Valley beater with 23 liters of tap water at a consistency of 1.57% and refined to freenesses of 300, 400, 500 and 600 C.S.

TEST SAMPLE PREPARATION

Handsheets were made, utilizing the British handsheet mold, to a constant humidity basis weight of 150 g/m^2 Since the sample size required for the dynamic press simulator is 3.5" in diameter, I had to modify the British handsheet former. A piece of 3.5" ID plastic pipe 2 in-

ches long was placed on the screen of the former, and the sample was formed inside the pipe. This procedure seemed to work quite well.

Sheets were couched from the forming wire onto a blotter. The handsheet was then placed between two new blotters and rolled to just below the desired moisture of 30% and stored in a polyethylene Ziploc baggies. For each handsheet, a second baggie was weighed ("B") which will receive the sheet just after pressing. This was done for 200 handsheets (50 at each of 4 freenesses).

FELT

A used piece of felt from a press section was used. Each piece was cut 3 1/2" in diameter. The felt was dried in an oven and weighed bone dry. The amount of water necessary to get them to a 1.4:1 moisture ratio (28.6%) was determined. These felts were then all conditioned to the desired moisture and stored in baggies.

PRESSING

To do the pressing, the following sequence must be carried out quickly:

1. Two felts are removed from their baggies and the web will be placed between them, making sure the felt and web are at the desired moisture. To get the felt and web at the desired moisture, I had to weigh each just before pressing and I had to either spray more water on it or

blotter more water out of it. The weight of the wet web will be called "A".

2. The felt sandwich is then placed on the bottom anvil.

3. The weight is dropped onto the sandwich. The weights used will be 15, 30, 45, 60 and 75 lb.

4. The handsheet will be picked up and sealed into the preweighed baggie.

The empty baggies will be weight "B". The weight of the baggie with the pressed sheet is "C". After testing, each handsheet is dried and weighed as "D". The calculation of the initial and final consistency is as follows:

Initial consistency $= \frac{D}{A} \times 100\%$ Final consistency $= \frac{D}{C-B} \times 100\%$

Pressed Sheet Drying

After each handsheet is pressed they are to be air dried at a constant temperature and humidity. Each handsheet should be restrained from shrinking during drying. The handsheets are restrained by placing each on a polished aluminum plate (the plates used from the British handsheet mold). On top of the handsheet is placed a rubber canning jar ring 3" in diameter and on top of this is placed an aluminum ring one inch high and 3" in diameter which has 6-1/2" holes drilled around its circumference to allow air circulation. The plates and rings are stacked

5 high on top of each other and a five pound weight is placed on top of the stack. (Figure 3) The drying process takes place in a 36 hour period. Ten hand-sheets are pressed at one freeness and one weight. (Figure 4) The moisture and density are calculated on each sheet. For each set, five each of tensile, Scott bond, brightness and opacity tests will be run.

The Scott bond test is used to measure the degree of bonding within a sheet of paper. Opacity, brightness, and tensile are used to measure relative bonded area.

The method of determining relative bonded area centers on the determination of the Kubelka-Munk scattering coefficient. Light is scattered when passing through the interface between two materials of differing indices of refraction. The scattering coefficient, S, is dependent upon the interfacial area and the nature of the materials. For a sheet of paper, S, is proportional to the unbonded area within the sheet. Thus,

Where: $S_u = k A_u$

Where: Su = recorded scattering coefficient value

K = a proportionality constant

Au = unbonded fiber specific surface area

Ratliff[16] has shown that fiber surfaces that are in optical contact(i.e.: close enough not to contribute to light scattering) are probably close enough to be bonded.

Relative bonded area is the ratio of the bonded area to the total area available for bonding. Ingmanson and Thode, (17) propose measuring the total area available for bonding by plotting scattering coefficient as a function of tensile strength for sheets made with various degress of wet pressing. The line is extrapolated to a zero tensile value and the intercept, S_t, is proportional to the total area available for bonding. Relative bonded area is then calculated as follows:

$$RBA = \frac{A_b}{A_t} = \frac{S_t - S_u}{S_t}$$

Where: A_t = total available surface area for fiber bonding

A_b = bonded area

Su = recorded scattering coefficient value

S_t = calculated scattering coefficient value

RESULTS AND CONCLUSIONS

I was not able to conclude this experiment due to the failure of the bearings on the dynamic press simulator. The design of the original simulator was fashioned after the press simulator at the Institute of Paper Chemistry located in Appleton, Wisconsin. This original press was designed for a load of 13 pounds maximum with a drop of one foot giving a maximum pressure of 700 psi on a 1 1/2" diameter sheet.

After consulting with a researcher familar with the apparatus, I was led to believe that the loadings and drop height considered in my experimental plan would not exceed the simulator's design limit. This, however, turned out to be an erroneous assumption.

At a loading of 50 pounds and 34" of drop height, bearing failure occurred twice at the base of the housings of the bearings after only about 15 tests. The failure occurred when the hammer rebounded after impact and landed on top of the catch mechanism.(Figure 5) The catch mechanism supports the hammer at its outer extremities only (Figure 5 points A & B) The loading on the hammer, however, is centrally located and, upon impact, caused the hammer to deflect.(Figure 5) This deflection caused stresses in the bearing housing which were greater than design limitations and failure occurred.

RECOMMENDATIONS

The dynamic press simulator has great potential to become a valuable tool in the study of wet-pressing. However, in its present form the simulator is limited to relatively small loadings and drop heights due to structural deficiencies. This reduces the simulators ability to duplicate the wide range of press conditions found in the paper industry today. In order for the simulator to be a truly

valuable piece of research equipment, design modifications must be made. I have four suggestions for improvement in the dynamic press simulators structural design aimed at increasing its load sustaining ability.

First, by expanding the base of the simulator to a four post configuration and adding two more sets of bearings, the structural rigidity of the entire simulator would be increased. These posts could also be anchored in the floor if the simulator was to be a permanent lab fixture. The stresses developed upon impact with the anvil or catching mechanism would then be distributed over a larger area reducing the strain upon each individual set of bearings.

Second, by housing the bearings directly inside the hammer support plate, any stresses developed upon impact would be absorbed by the plate itself and would then eliminate the external bearing housings. The purpose of the previous two design modifications are intended to dissipate the stresses developed upon impact. It would also be fruitful to explore the possibilities of design modification that reduce the magnitude of these stresses.

When the hammer impacts the anvil and rebounds, the ratchets of the catching mechanism are supposed to stop the plate from descending after it reaches the top of its

initial drop heights used in my experimentation, the plate rebounded past the catch mechanism. As the plate redescended, it impacted the top of the catching mechanism. The plate then deflected due to impact because it was supported at its outer extremities only. The combination of the stresses developed in the bearing housings due to impact of the plate and the deflection of the plate caused the failure of the bearing housings. The deflection of the plate was maximized because it was loaded centrally.

Third, if the load on the plate could be distributed over its entire width, the deflection would be decreased, decreasing the stresses developed in the bearings.

Fourth, since it is the purpose of the catching mechanism to stop the hammer plate at the top of its initial rebound, design modifications must be made to facilitate the catching of the plate at greater rebound heights. This could be accomplished by extending the length of the catch mechanism ratchets. This would allow for a wider range of rebound heights, and therefore, the simulation of a wide range of press conditions.

With these design modifications, the usefullness, reproducability and reliability of the dynamic press simulator would be greatly increased. The redesigned simulator would be of more value to the researcher because of the

increase in the experimental parameter ranges (i.e. drop height and load).

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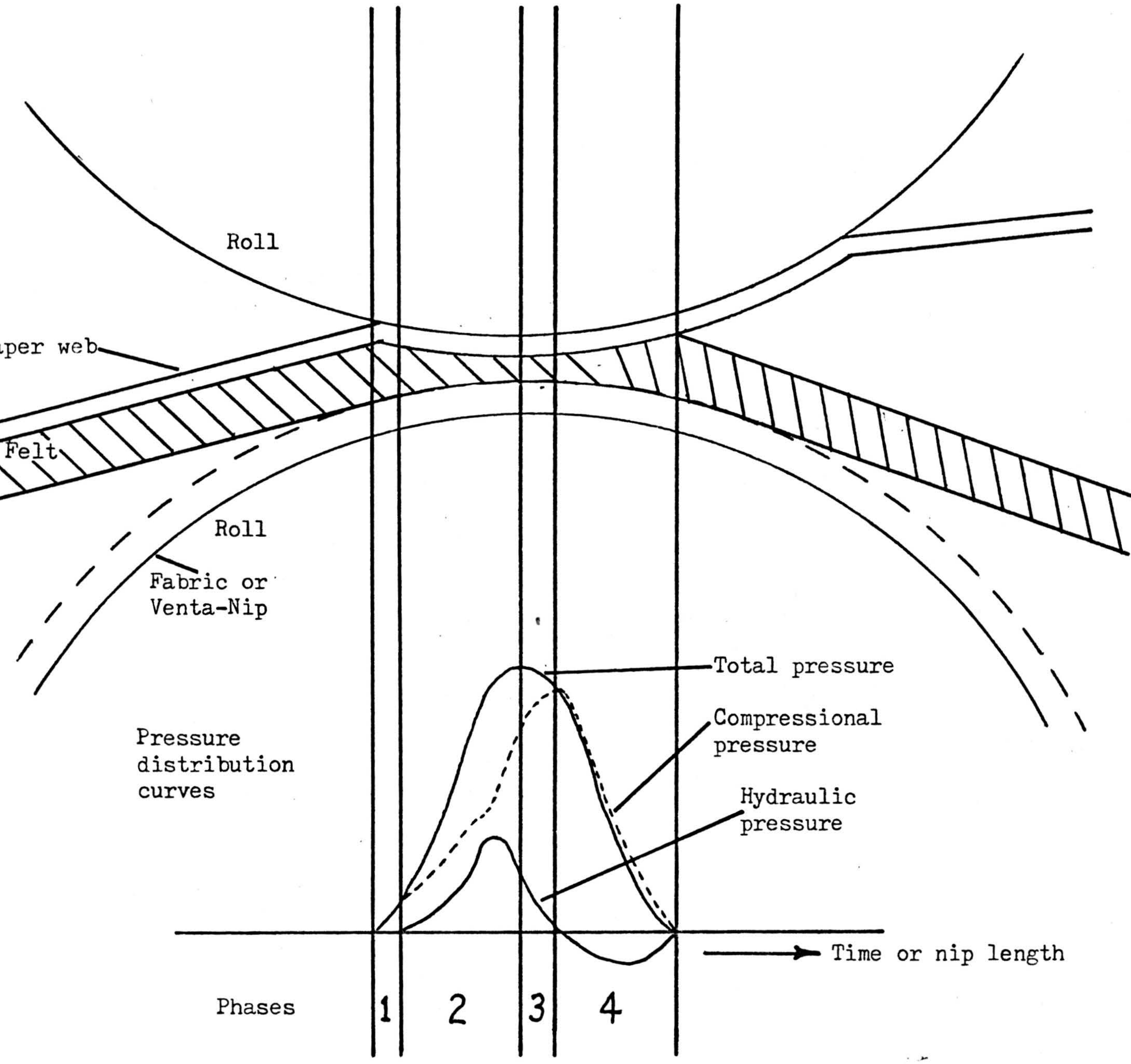
Lindman

APPENDIX

FIGURE 1

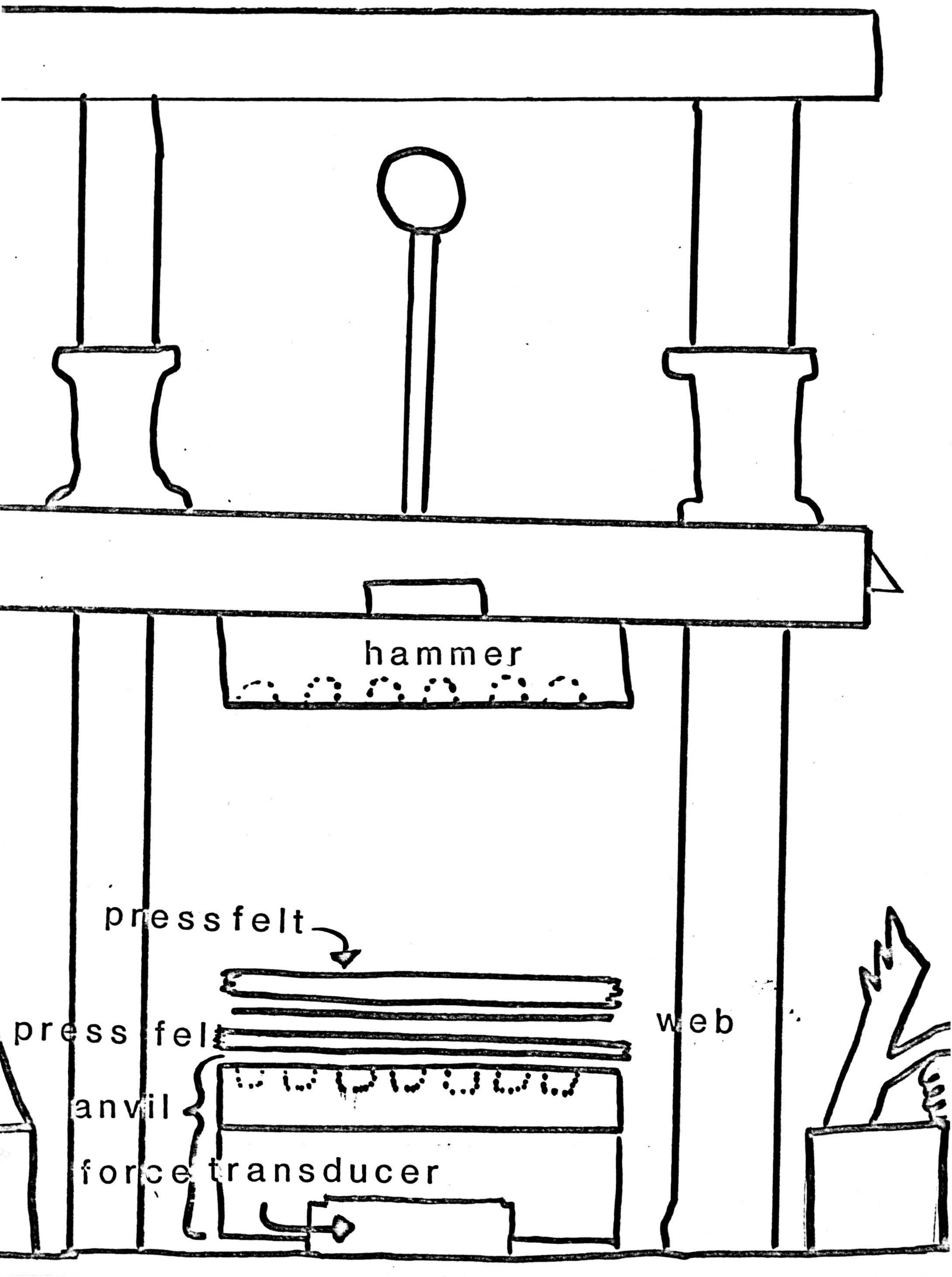


PRESSURE PROFILES

(Wahlstrom's theory)

Figure 2

DYNAMIC PRESS SIMULATOR



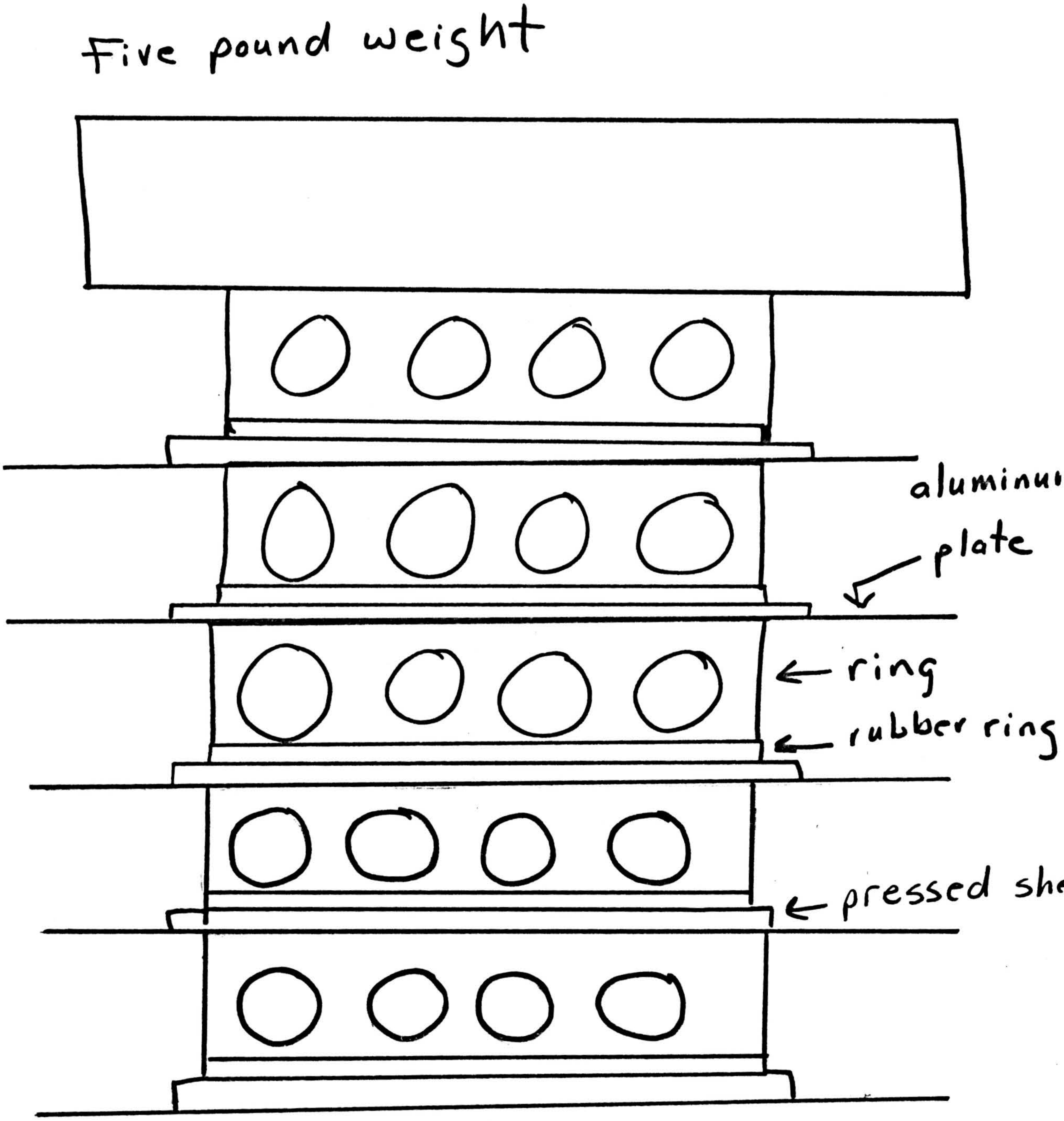
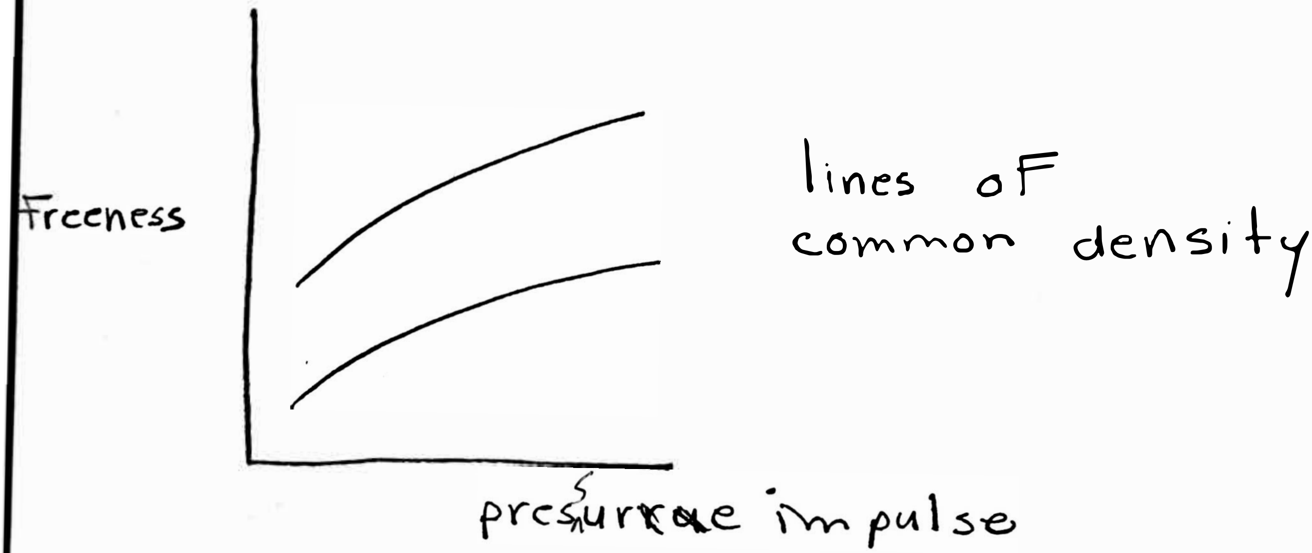

Five pound weight
aluminum
plate
ring
rubber ring
pressed she

Figure 3



Weight / Freeness	15	30	45	60	75
300	10	10	10	10	10
400	10	10	10	10	10
500	10	10	10	10	10
600	10	10	10	10	10

Figure 4

Figure 5

DYNAMIC PRESS SIMULATOR