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Separation of Southern Pine Pulp into its Springwood and Summerwood Components by Centrifugal Means: Savings in Refining and Other Possible Economic Justifications

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ABSTRACT

Keywords: Summerwood, Springwood, Earlywood, Latewood, Centricleaner, Separation, Fractionation, Refining, Fiber

A study of Southern Pine pulp separation into its springwood and summerwood fiber components was undertaken. Separation was accomplished through the use of two Bird Triclean centrifugal cleaner devices. Separation occurred mainly because of different apparent pulp densities in the two fiber fractions. Springwood collapsed during pulping, creating a flattened fiber, forty-five to sixty-five microns in length and ten to twelve microns in width. The thicker walled summerwood fibers, on the other hand, maintained their twenty-five to thirty-five micron diameter tubular shape. The greater surface area present in the springwood fibers allowed a greater hydraulic force to be exerted to this surface, and thus they were pushed towards the center and out the top of the cleaner. A greater centrifugal force to hydraulic drag ratio acting on the lower surfaced area summerwood fibers caused them to move to the walls and out the reject nozzle at the bottom of the cleaner. The major factor governing separation (consistency) was .07% in the final run. Separation efficiencies of 73% springwood in the accepts line and 64% summerwood in the rejects line were obtained.

The main thrust of the thesis dealt with separate refining of the two fractions after separation. The pulp was then recombined in various configurations. Refining, which was done in a PFI mill, seemed to lower freeness in a similar fashion for both pulps. This is contrary to the literature on the subject. Handsheets were then made using the Noble & Wood procedure, and various tests were then run on these sheets. Springwood formed a more dense sheet with higher tensile, burst, and density, and lower porosity and tear. The two most important results were: springwood reached very high tensile and burst properties at very low refining levels and then dropped off as the individual fibers weakened, summerwood maintained high tear, tensile, and porosity simultaneously at medium to high refining levels. These results seem to indicate that the two fractions might be used to create paper with special properties. They also indicate that springwood is overrefined in almost all conventional refining processes. A simple cost analysis indicated energy savings alone to be insufficient to warrant cleaner installation, but added benefits may render the separation process viable in certain specialized cases.

INTRODUCTION

The following thesis deals with a springwood-summerwood separation of pulp using a centrifugal cleaner.[1] Pulp thus separated was refined to varying degrees and was subsequently recombined before the final sheet of paper was made. The major justifications for such a process is the possible reduction in refining costs along with possible improvements in paper properties. Information gathered indicates that the added capital expense of the separation operation does not prove favorable when compared with the possibility of reduced cost in refiner capital. However, energy savings could be substantial depending on the percent reduction of refining realized. This factor becomes increasingly important as energy costs continue to climb.

A commercial application of a springwood-summerwood separation by centricleaners was previously attempted by International Paper Co. around the mid sixties.[2] In this application, distinct paper properties produced by the separation were the primary justification for the added expense of the cleaners. However, no work was published relating refiner studies and possible savings in this area. Also, since the oil embargo in 1973, energy costs have skyrocketed. For the above reasons, a review of the economic feasibility of a springwood-summerwood separation, it was felt, may be deemed necessary.

Separation of pulp into its springwood and summerwood components is possible due to the fact that the springwood-

summerwood fibers exhibit different apparent densities causing different settling rates to occur in the cleaners. Springwood shows up in the accepts portion and summerwood in the rejects portion of the centrifugal cleaner if the centricleaner is run at optimum conditions. Variations affecting the separation operation include: temperature, consistency, pressure drop, flow rate, fiber type (refined-unrefined, bleached-unbleached, neverdried-dried, pulping method etc.), cleaner size, special cleaner features. It should be emphasized, however, that the major thrust of this thesis deals with the separate refining of the pulp and not with the determination of optimum separation conditions (which could be a thesis project in itself).

Separations have been done with many southern pine pulps, but longleaf and slash pines seem to exhibit the greatest differences when the two separated components are tested.[3] The difference in thickness of the springwood and summerwood fibers is what causes the apparent density difference to occur and hence the separation. This wall thickness is also responsible for the behavioral differences of these two fractions with respect to refining. Separate refining, it is hoped, will lead to an optimum amount of refining to be done on each fraction resulting in better paper properties. The following report will relate some of the above mentioned ideas in greater detail and will outline an experimental procedure that will be followed to determine whether the proposed thesis is economically feasible.

THEORETICAL EVALUATION

Naturally Occurring Fractions:

Before separation using a centricleaner is discussed, it should be noted that natural differences in springwood and summerwood percentages can be found in different portions of some trees. As the height above the tree stump increases, springwood content also increases. The greatest difference in springwood percentage was found in a slow growing southern longleaf pine. Springwood content was around seventy percent at the top of the tree while springwood content at the base of the tree was only around twenty-eight percent. Large differences were also found in fast and slow growing shortleaf, slash, and loblolly southern pines.[4] Seventy percent springwood or summerwood in a pulp may not sound very pure, but the literature indicated that a significant difference in paper properties was found at this percentage and even lower.[5]

As more and more trees come to be planted, grown and harvested like crops with ever increasing growth rates, these percentage differences may become even more pronounced. Separate harvesting, pulping, and papermaking using various portions of these new trees might become feasible. One mill could use the upper portion of the trees and another use the bottom portion acquiring totally different paper properties. Of course this is all speculative.

Basic Principles of Centricleaners:

It is desirable to understand the basic principles of centricleaner operation in order to see how these devices

will be used to bring about a separation of pulp into its summerwood and springwood components. Centricleaners are usually truncated cones with cylindrical extensions attached to the top end. They come in a variety of sizes ranging from three to twelve inches in diameter with cone angles of five to fifteen degrees. Accept, reject, and feed openings vary considerably. Feed capacities range from seventeen to around 1000 gallons per minute and can process between less than a ton to up to thirty tons of air dry pulp per day depending on the inlet consistencies.[6] Inlet consistencies are usually around .5% for conventional cleaners and .2-.3% for reverse cleaners.[7]

The stock is injected tangentially into the centricleaner at the periphery under a pressure of around fifty pounds per square inch. It immediately starts to travel downward and inward with a spiraling motion. The angular velocity of this outer vortex constantly increases as it nears the apex of the cone. Due to the fact that the reject diameter is not large enough to discharge all of the material entering, a portion of the material changes direction and starts to ascend in an upward vortex that discharges out the top of the cleaner. A free vortex containing air is usually at the center of the cleaner and a vacuum can be created if tangential speeds are great enough.

Two major forces act upon liquid and particles alike. The pressure differential caused by the different angular velocities causes motion toward the center and the apex of the

cleaner. The extent of this hydraulic drag force is determined by the shape, surface area, and mass of a particle. Disk shaped particles will acquire greater hydraulic drag forces than spherical objects which possess a lower surface area to volume ratio. Hydraulic force is opposed by the increasing centrifugal force nearer to the center of the cleaner. When an equilibrium between these two forces is reached, the particle will tend to migrate in its respective layer down to the apex of the cone. Outer layers consisting of more dense particles will be discharged. Shear forces are also important in determining how easily particles will transfer to their respective areas of balance. Complicated flow patterns occur with spinning particles. Flow patterns are also complex in the apex region of the cleaner. This is mostly due to the fact that the solids concentration is a lot greater in this area and shear forces therefore play a much greater role. Wall effects also cause some unpredictable particle paths.[8]

One way to decrease the deleterious effects of increased solids in the apex region of the cleaner is to use a device known as an elutriator. This device is attached to the bottom of the cleaner. It basically acts as a small secondary cleaner. Its basic function is to decrease the consistency in the rejects region so that efficient separation can again occur. Consistencies of rejects are normally three times as high as inlet consistencies if elutriators are not used. Water used in an elutriator usually enters tangentially at around eighteen to thirty pounds per square inch of pressure.

Most of the elutriation water follows the pulp out the accepts line. Efficiency increases when using elutriation are shown in figure 1.[9]

Efficiency can also be increased by two other methods. The Bell overflow nozzle is used to prevent a short circuiting of flow from the top of the cleaner to the accepts line. As liquid in the top portion of the cleaner moves around the cleaner, it comes in contact with the outer wall of the overflow nozzle. It follows this wall down to its opening and a portion flows around the bottom and joins the accepts causing a decrease in efficiency. The Bell overflow nozzle is just an enlargement of the outer wall near the lower end.[10] This device also allows the cleaner reject nozzle to be submerged in its own rejects. A greater elutriator orifice can then be utilized resulting in greater cleaning efficiency. A picture of a complete centricleaner setup is shown in figure 2.[11] Cone angle does not affect separation efficiency to a great deal because velocity and pressure differences are not great. This can be shown in figure 3.[12]

Efficiency Of Centricleaners:

As efficiency of cleaners and of separation will be talked about a great deal in the remainder of the report, a short definition of efficiency is given in order to understand exactly what is meant by this term. Efficiency of cleaners in general is different than the efficiency of separation of springwood and summerwood fibers. The basic definition of centricleaner efficiency is: Efficiency equals number of impurities in the feed - number of impurities in the accepts

divided by number of impurities in the feed. For example, if feed has ten impurities per gram and the accepts have two impurities per gram then efficiency is equal to 80%.[13] Total separation efficiency, on the other hand, is defined as the springwood separation efficiency plus summerwood separation efficiency divided by two. Springwood separation efficiency is defined as the dry weight of springwood fibers in the accepts fraction of the pulp divided by the total dry weight of the fibers in the accepts fraction of the pulp. Summerwood separation efficiency is defined similarly for the rejects fraction.

Factors Governing Separation:

In many respects, the equations governing the exact effects that a centricleaner has on a particular object are not easily calculated. However, basic laws apply to all centrifugal cleaners with a free vortex. Settling is affected by solution viscosity and density, particle density and diameter, and centrifugal acceleration. An equation for speed of settling is as follows: $vs=(D^2/18u)(dp-ds)(v^2/r)$ where vs is sedimentation rate in m/s, D is particle diameter in m, u is viscosity of the suspension in $kg\text{-}s/m^2$, dp is particle density in $kg\text{-}s^2/m^4$, ds is the density of the suspension in $kg\text{-}s^2/m^4$, v is the tangential velocity in m/s and r is the radius in m.[14]

The ratio of v^2/r is the centrifugal acceleration. These are the only two variables that are affected by centricleaner design. It can be noted that the ratio of v^2/r needs to be

held constant in order to obtain a requisite centrifugal force. Because velocity is directly related to pressure drop across the centricleaner, separation can be accomplished in a smaller cleaner at a lower power consumption. Velocity is also directly related to volume throughput. A doubling of throughput will increase tangential velocity and thus separation efficiency, but power consumption will be almost tripled.[15] Greater velocities at the wall will also cause a much greater wear, especially in the cone portion of the cleaner. The extent of the forces in a centrifugal cleaner can be realized more clearly when a three inch cleaner operating at the rated twenty gallons per minute is looked at. Velocity at the wall will be thirty-three feet per second whereas velocity at a one half inch diameter will be 198 feet per second. Centrifugal force at these locations will be 286 and 61,900 g's respectively.[16] It can be seen, therefore, that a compromise between satisfactory separation and operating costs must be made.

As can be seen from the equation, separation is affected considerably by viscosity, which itself is affected mainly by temperature. As temperature is increased sedimentation also increases due to a decrease in viscosity. This is due to a decrease in the hydraulic drag. Particles in the suspension therefore tend to flow through the liquid more freely. The viscosity decrease tends to increase the reject amounts. This is shown in figure 4.[17] One way to decrease these rejects is to use a

smaller reject nozzle size. However, these smaller nozzles tend to plug up because pulp is dewatered to such a great extent. The logical solution, therefore, is to use elutriation. Amounts of stock rejected at different temperatures with elutriation is also shown in figure 4. Temperature effects on separation efficiency of springwood and summerwood pulp is shown in table 1.[18] It can be seen that springwood percent in the accepts continously increases whereas the summerwood fraction in the rejects remains relatively high at around seventy percent.

The sedimentation equation also shows that the density difference between the particle and the suspension is also an important factor governing separation. A temperature change will affect the density of the suspension, but it will not appreciably affect the density of the fiber or other particles. The fact that much of the fiber is filled with water tends to negate these suspension density changes, however. The average density of the cell wall is around 1.5 grams per cubic centimeter.[19] When the water that is located in the fiber is also taken into account this average density seems to become even less. This makes the density difference between the fiber and suspension very low. For this reason separation of fiber and suspension is very difficult. Separation between springwood and summerwood by density difference is even mor difficult. As stated above, densities are around 1.5

grams per cubic centimeter with no distinction between springwood and summerwood. Summerwood does have a higher crystallinity, however. This tends to allow less water to penetrate into these fibers and apparent density remains greater.[20] If density differences were relied upon to separate springwood and summerwood fibers a reasonable separation could not be accomplished.

Fibers do differ in shape, however. This is the basic premise that separation is based upon. As wood is pulped, the springwood fibers of some species tend to collapse. This is most prevalent in fast growning southern pines where lumens are large and cell walls are thin. As these fibers collapse the lumens disappear and ribbon-like structures are formed. These structures are forty to sixty-five microns wide and ten to twelve microns thick. Summerwood fibers, on the other hand remain in basically a tubular form with a diameter of around twenty-five to thirty-five microns.[21] The ribbon-like fibers tend to act more like disks. They thus act as bluff bodies and have a higher drag coefficient than cylindrical bodies, especially at high Reynolds numbers.[22] This higher drag coefficient, along with increased surface area, produces a higher drag force and tends to move the ribbon-like springwood fibers towards the center and out the accepts line of the cleaner. The summerwood fibers do not have as great a drag force thus pushing them to the periphery of the cleaner and out the bottom along with other heavy rejects.

A drawing of opposing forces in a cleaner is shown in figure 5.[23]

The amount of pulp damage is another important variable in pulp separation. This is basically due to changes in fiber surface area as mechanical damage is done to a fiber. Major fiber damage can be done during refining. If refined pulp is run through a centricleaner, the centricleaner no longer separates between springwood and summerwood fractions, but between refined and unrefined pulp. Pulp that is refined tends to have a greater surface area to volume ratio and therefore ends up in the accepts portion, while unrefined pulps and fines end up in the rejects. Table 2 shows the effect of refining on separation efficiencies.[24] As more refining is done, efficiencies of separation are decreased with both accepts and rejects portions. Lesser fiber damage is caused by bleaching and repulping fiber that has already been dried. This is the reason why unbleached fibers that have never been dried separate more easily than dried or bleached fibers.

Efficiencies are also affected by accept and reject percentages. It is quite apparent that the accepts and rejects ratio must equal the springwood and summerwood ratio respectively if maximum efficiency is to be obtained. This ratio is usually around 50:50 for southern pine. It already has been shown that temperature affects the accepts/rejects ratio. Other factors include cleaner tip size, operating pressure, backpressure, and elutriation

amount. These factors should all be manipulated in order to obtain the desired accepts to rejects ratio.[25] Pressure differential can be varied just so much and still maintain a satisfactory separation. This pressure differential range is a factor of cleaner design. A typical range is shown in figure 6.[26]

The single most important factor, however, in creating efficient separation is consistency. At low consistencies pulp is a lot more free to move inward or outward in the centricleaner depending on the balance between centrifugal force and hydraulic drag. An adequate separation can not be accomplished at consistencies greater than .25% and lower consistencies are preferable. Table 3 shows separation efficiencies as a factor of consistency.[27] Lower consistencies are extremely important towards the apex of the centrifugal cleaner where entanglement and flocculation of the fibers is the greatest.

Even though most of the variables that affect centricleaner operation are understood, some of the sundry interactions make exact predictions impossible. A kraft pulp might react differently than a sulphite pulp and so forth. Enough is known about centricleaner operation, however, to be able to estimate a separation efficiency that can be obtained.

Thickening After Cleaning

Pulp is diluted a great deal in order to attain an

adequate separation. The rejects portion, containing the summerwood pulp fraction, will be at a much higher consistency than the feed, but a great deal of water will need to be extracted from this pulp in order to refine at a typical consistency. Even more water will have to be extracted from the springwood pulp fraction to get pulp up to an operating consistency. Fortunately the pulp is unrefined at this point and can be thickened quite easily. A cylinder mold type device or a simple decker can be used for this operation.[28,29]

Refining of Separate Pulp Fractions

The major factor for the possible springwood-summerwood pulp separation (the different cell wall thickness of springwood and summerwood) is also the major reason these two fractions behave differently towards refining. The thicker summerwood fibers tend to be a lot more rigid and consequently develop freeness reduction more rapidly than the thin walled, flexible springwood fibers. The springwood fibers, being less crystalline, are more forgiving in the refining operation. This can be seen in table 4 and figure 7.[30,31] The above observation seems to indicate that more optimum conditions of refining for each fraction could be realized with separate refining. Lower intensities could be used on the summerwood pulp fraction.

Individual fiber strength changes are a little hard to explain in some cases. Table 5 and 6 show some refining effects on hollocellulose and kraft pulp properties

respectively.[32,33] In both cases springwood fiber tensile increases and cell wall area decreases with increased refining. Tensile increases are due mainly to these cell wall area decreases. This is because breaking load increases or stays the same. A logical explanation for this seems to be the fact that even though cell wall area is decreased due to mechanical damage, rearrangement of the walls improves the stress distribition and consequently fiber strength. Young's modulus also increased during refining showing an internal strength development. Summerwood fiber reactions to refining seem more complex and much disagreement exists in the literature. More thorough reviews along with possible explanations are given in articles by McIntosh and Leopold.[34,35] In any case, more work seems to be necessary in this area.

Refining affects mostly fiber conformability, but it also has a slight effect on actual bond strength. Table 7 shows that this refining effect is similar for both springwood and summerwood, with a decrease in each case with increased refining.[36] This is primarily due to a different surface being exposed after refining, which has a lower hydrogen bond capability than the original fiber surface. It can also be seen from the table that the bond strength is lower for springwood. If bond strength were the primary factor governing strength, springwood paper would be bonded to a lower degree resulting in a lower tensile strength. Fiber bonding area, dependent on fiber

conformability, is the primary factor influencing paper bonding, however.

Pulp and Paper Properties

Paper made with summerwood fibers differs radically from springwood made paper. This is partially due to the inherent strength differences of the two fiber types, but it is due to fiber flexibility differences to a much greater extent. Tables 5 and 6 show that unbeaten summerwood fibers have over twice the tensile strength as do springwood fibers. This is partially due to a greater cell wall thickness in general, but is more specifically due to the fact that summerwood contains a far wider S2 wall and less developed pits. The S2 wall has the greatest amount of fibril orientation making it the major contributor to tensile strength. Less developed pits in summerwood also creates less fiber tensile failures in these regions.[37]

The stronger summerwood fibers don't make a stronger paper, however. This, of course, is due to the fact that fiber bonding affects paper properties to a much greater degree than fiber strength, especially in unrefined pulp. As has been previously stated, springwood fibers tend to collapse during the pulping operation. These ribbon-like fibers are very flexible and form a very dense and tightly bonded sheet of paper. This paper exhibits properties more closely related to a sheet made of refined pulp. It has a high tensile, density, burst, smoothness and can be bleached more easily. Along with these properties are

exhibited a low tear, bulk and porosity. Summerwood fibers form just the opposite type of sheet. These bulky stiff fibers bond loosely creating a bulky, porous sheet with a high tear strength and low tensile, burst, and smoothness.[38] Sheet properties at various springwood and summerwood concentrations can be seen in table 8 and figures 8 and 9.[39,40] These properties can also be seen in figure 7 at various refining levels. It can be seen in table 8 that separation of pulp to a greater efficiency than around 70% is not beneficial from a strength standpoint. Tensile and burst values level off at a springwood content of around 70% and tear levels off at a summerwood concentration of around 70% also. This does not hold true for porosity and smoothness values, however. Fold and zero span tensile test results were eratic. This was probably due to the more complex nature of these tests.

PROPOSED THESIS

This thesis is based on the assumption that a "better" sheet of paper might be able to be produced. By "better" it is meant that a sheet more applicable to a particular specfic job could be made. In production of printing and wrapping grades, where density, good formation, smoothness and high burst and tensile strengths are desireable, a pulp with a high proportion of springwood fibers could be used. This would also decrease bleaching costs as springwood is more easily bleached than summerwood. On the other hand, production of un-

bleached bags, boards and other coarse papers that require high tear strength along with high porosity and bulk could be accomplished using a pulp that has a high concentration of summerwood fibers.[41]

Refining of pulp fractions separately with recombination also seems to indicate a potential for savings and/or improved quality. As previously stated, optimum conditions for refining probably differ between the two pulp fractions. These optimum conditions will probably not be realized in the following experimentation, but optimum freenesses may at least be able to be reached. The already much weaker springwood fibers may have to be refined to a lesser degree. Improved bonding could be obtained almost exclusively from fibrilation of the stronger summerwood fibers. This method could possibly save on refining costs along with the benefit of greater paper strengths.

In order for this project to be economically feasible, increased capital and operational costs for the separating operation must be offset by reductions in the operational and capital costs in refining and/or an increase of revenue due to a superior or more specific product. Product improvement gains are a hard thing to grasp, so savings in the refiner operation must be looked at.

Cost Comparisons

A lot of grey areas are inherent in most cost comparisons of paper mill machinery, and refiner and cleaner areas are no exception. In fact, these areas may be two of

the hardest to pin down as to definite costs. Nevertheless, rough estimates as to these relative costs may prove helpful in better understanding the systems, not to mention the fact that these estimates are essential in determining the economic feasibility of the proposed thesis. For simplicity sake a 200 ton per day mill was chosen for the comparison. CE-Bauer Company was consulted for cleaner cost estimates while Beloit Company-Jones Division was consulted for refiner estimates. Operational costs were also found to some extent in the literature.

All of the literature agrees that the majority of the energy consumed by the cleaner system is in the form of pumping costs. The pump is used to maintain a pressure differential of around forty pounds per square inch. Estimates in the literature range from 3.1 to 3.2 horsepower days per ton when corrected for a .15% inlet consistency.[42,43] A calculated value at a pressure drop of forty pounds per square inch, a consistency of .15% and a motor efficiency of eight-five percent results in a power consumption of 2.8 horsepower days per ton(hpd/t). These values are all relatively close and a value of 3.0 hpd/t will be used for cost comparisons. Using a value of $375 per horsepower per year this figures to be an annual cost of $225,000.[44] Maintenance costs are very minimal and will therefore be neglected.[45] When operating correctly, these cleaners need to be checked only three or four times a year. Due to the low consistencies used,

This may even be a liberal estimate. Capital expenses will account for a major portion of the cleaner expenses. A bank of 100 cleaners will process twenty airdry tons of pulp per day at .15% consistency. Therefore, ten banks will be required at a total cost of $343,000.[46]

Refiner costs are also basically composed of capital and power consumption. Maintenance costs consist mostly of disk replacement. Disks are usually replaced every four to six months. These costs may be slightly higher than maintenance costs for cleaners, but they can be neglected for this fairly rough comparison. Capital and energy costs are extremely hard to estimate for refiner operations and depend heavily on the paper application. Bag paper is refined very little whereas pulp used for liner in a multi-ply board is very heavily refined. Refiner setups and types also account for large differences in the amount of energy consumed. A typical range of 0-20 hpd/t was given in the literature.[47] As softwood is the fiber type that will be separated, this pulp will be used to determine a possible system for a typical application. Unbleached southern softwood kraft has a typical freeness drop of around thirty-five CSF per net hpd/t. A freeness drop of 350 CSF would therefore require ten net hpd/t. This could be accomplished with four thirty-four inch disk refiners rated at a capacity of 120 tons per day. These refiners have an applied horsepower of 800 and a no load horsepower of 210. This means the four will generate a total of

2,360 horsepower, which calculates to a maximum of 11.8 hpd/t. The yearly cost of energy used in these refiners would be $1,200,000. Capital costs would be around $240,000.[48]

Assume refiner energy and capital costs could be reduced by twenty-five percent with separate springwood-summerwood refining with no loss in pulp quality. This would result in a payback period of around nine years assuming a fifteen percent interest cost on any capital expenditures. It is realized that this cost comparison is very crude, and it has room in numerous areas for error. Holding tank costs and pulp thickening costs are just two of the minor costs not considered that may be significant. The analysis does, however, show that a separate springwood-summerwood operation is not out of the realm of feasibility if strength benefits or other specific property advantages can be realized. It suggests that an evaluation of separate springwood-summerwood refining is warranted. This technique might be practical in some special cases. Benefits realized might also be far greater in older mills presently using inefficient conical refiners.

EXPERIMENTAL PROCEDURES & RESULTS

The experimental plan that will be used can be broken down into seven major segments. These segments are: summerwood-springwood fiber ratio determinations, separation in centricleaners, stock preparation before refining, refining of pulp, handsheet making, handsheet testing, evaluation of results. Hercules bleached southern pine

pulp was used for the experiment as no unbleached pulp was available. The type of the pine pulp used was also not known. The pulp was obtained in a dry lap form although a neverdried pulp would have been preferred.

Fiber Ratio Determinations

For this portion of the experiment, a small sample of pulp was submerged in water and beaten for a short time in a Waring blender to adequately disperse the fibers. The fiber suspension thus produced was then used to make several microscope slide samples. Two types of stain were used to help enhance the differences in the two fiber types. Both the blue dye and the C-stain used helped to accent the fiber differences, so the blue stain was arbitrarily chosen. The microscope operated at 50x magnification, seemed to produce optimum results with minimum eye strain.

A purely subjective visual technique was used to determine the amount of springwood and summerwood fibers present. Fiber geometry and degree of coloration caused by the dye were both used as aids in determining this ratio. As reinforced by the literature, the summerwood fibers dyed a lot darker. The collapsed geometry found in many portions of the springwood fibers also helped to make ratio determinations. In most cases, springwood-summerwood fiber differences were quite apparent and easy determinations were possible. In some cases, however, differences were more subtle, and guesses had to be made. This may have

biased the results slightly, but it is necessary to keep in mind that this initial ratio determination is important only in as much as it serves to give a rough initial accepts-rejects ratio estimate to aim for. Counts were also taken on separate days to help lessen this possible biasing. A more objective means of determination that was cited in the literature used a mathematical ratio of the outside perimeter to lumen perimeter. This method, however, is far too involved for this project.

A total of 674 fibers were counted in this portion of the experiment. The results showed that 54.5% of the fibers were springwood and 45.5% were summerwood. Therefore, in order to obtain a maximum theoretical separation efficiency of 100%, 54.5% of the dry mass run through the cleaners must go out the accepts line and the rest out the rejects line.

Centrifugal Separation

This was probably the most difficult portion of the experiment to control adequately due to the large amount of variables present. A whole thesis could be done just working with all of these variables trying to optimize separation efficiencies. The first obstacle that needed to be decided upon was the type of cleaner to use. As there were no conventional cleaners available, and the Bauer reverse cleaners didn't look favorable, the Bird Tricleans were used. Because the Bird Tricleans have three separate openings, (accepts, light accepts, rejects),

a decision had to be made as to where the two separate fractions were to be obtained. An initial trial was therefore set up to make this determination and also to manipulate cleaner variables in order to get a rough estimate as to what the final run conditions would be.

In the first cleaner run, variables were kept as constant as possible. Initially, all lines were left open. This resulted in a rough mass balance of 80% of the dry mass out the accepts' lines and the remainder out the rejects. In order to get this ratio closer to the desired one the light accepts line was plugged. This resulted in a 54/47 accepts/rejects ratio at an inlet pressure of 50 psig.

Separation efficiencies for this run were determined to be 73% springwood fibers in the accepts and 68% summerwood in the rejects.

A final cleaner run was then made. This time a magnetic flow meter was used on the inlet so that an accurate mass balance could be accomplished. Fifteen pounds of pulp were slushed in the hydropulper and diluted again to give 2000 gallons of pulp at a temperature of 80°F and a consistency of .07%. This consistency was well below the maximum allowable consistency of .15%. It was hoped that this factor would lead to a good separation efficiency. A final inlet pressure of 55 psig was required to obtain the desired 55/45 accepts/rejects ratio. The two Bird cleaners used operated at around 80 gallons per

minute with an accepts consistency of .04% and a rejects consistency of .48%.

Efficiencies obtained in this final run were not as favorable as was initially desired. Seventy-three percent of the accepts fibers were springwood which was adequate, but only 64% of the reject fibers were summerwood. This was lower than the initially desired 70% efficiency. However, this separation efficiency was deemed adequate to produce substantial pulp differences. Subsequent data seems to indicate that this initial assumption was warranted.

Stock Preparation

The pulp was then prepared so that it would be ready for subsequent operations. This basically meant thickening the stock prior to refining. The rejects (henceforth called summerwood) were thickened, using a fine wire, immediately preceding separation. The accepts (i.e. springwood) on the other hand were pumped into a holding tank. They were thickened using this same screen, but remained in the holding tank for about 48 hours prior to thickening. The may be, in part, the reason that the springwood exhibited lower brightness in subsequent testing (iron in the water may have attached to the fibers). In both cases, screening was done with lettle or no loss of fiber due to the high freeness of the pulp at this stage of the operation.

Following the screening operation, the two pulp fractions were dewatered further in a centrifugal cleaner.

This brought the consistencies up to about 40%. The pulp was then broken into small pieces and placed in plastic bags so that it could be stored neatly in a refrigerator. This helped insure minimum pulp deterioration while it awaited refining and handsheet making.

Refining

The PFI mill was used for the refining portion of the project. This enabled the exact revolutions of each refinement to be known. A relative amount of refining for each run was thus able to be calculated. The number of revolutions were chosen on the basis of freeness. Several different refining levels were obtained for each pulp. The freenesses desired were from around 700 CSF down to 300 CSF so that a wide range of properties could be obtained. Three basic sets of pulp were refined, including the springwood, the summerwood, and the unseparated pulp to be used as a control. Summerwood refining levels were 4,6,8, and 10,000 revolutions, springwood levels were 2,4,and 8,000 revolutions, and unseparated levels were 2,4,6, and 8,000 revolutions.

Based on the moisture content of the thickened pulp, 35 grams of oven dry pulp was mixed with enough water to obtain 350 grams total. This resulted in the 10% consistency level that all refining was accomplished at. After refining a sample for the required number of revolutions, the pulp was placed in a British disintegrator along with enough water to obtain 1750 grams total. This suspension,

now at two percent consistency, was then run in the disintegrator for approximately two minutes to produce a more uniform suspension. A freeness sample was then done using 150 ml of the sample. When the consistency of the freeness sample had been determined, a portion of the remaining pulp was dewatered on a Buchner funnel in preparation for handsheet making. Handsheets were made using an equivalent of 24 grams of oven dried pulp so that 10.8 grams of summerwood and 13.2 grams of springwood were required. This ratio insured that the pulp was recombined in the same ratio in which it was separated so that no pulp waste would occur.

Table 9 shows the freeness values obtained at each of the refining levels. Freeness readings were not determined for the combined handsheets as they were deemed unnecessary. The freenesses of these combinations will probably not be a mass ratio of the freenesses of the individual components, but should be fairly close.

Clark classifications were also run on the unrefined and heavily refined springwood and summerwood pulp fractions in order to determine if these two frations reacted differently to refining. Results can be seen in table 10. Originally, the springwood fibers are more flexible and are caught more readily by the larger meshes. Refining seems to be more harsh on these fibers and seems to produce more fines at high refining levels. The differences between the two fractions are not great, however.

Handsheet Making

Handsheets were made using the Noble & Wood handsheet making procedure. A total of 24 grams of pulp (on an oven dry basis) was added to the proportionator for each set of handsheets. Springwood and summerwood were combined in a 55/45 ratio in every refining combination making a total of 34 different handsheet sets. Seven handsheets were made in each set. The handsheets were weighed immediately after drying. Weights of 2.5 grams plus or minus one gram were accepted as being reasonable weights for handsheets. The five handsheets with the best formation were then chosen for final testing. This produced a total of 170 sheets that were subsequently conditioned for handsheet testing.

Handsheet Testing

After conditioning, the handsheets were trimmed to seven and three quarter inches square in order to get rid of the uneven edges. This had the effect of making the handsheets more managable for testing, but it did increase basis weight variations to a certain degree. The tests performed on the sheets included tear, tensile, burst, porosity, opacity, brightness, and caliper. The Sheffield smoothness test was also attempted, but sheet roughness was too great to get any kind of readings. All of these tests were done in accordance with Tappi standards. Densities were also calculated using basis weights and calipers.

The values for the handsheets tested can be seen in

tables 9 and 11. Table 9 shows values for the unseparated pulp, the springwood, and the summerwood, while table 11 shows the various springwood-summerwood combinations. In both tables refining amounts are REFIN x 10^3. Table 11 shows the first four observations to be made up partly of unrefined summerwood and the rest of unrefined, 2,000, 4,000, and 8,000 revolutions refined springwood respectively.

Test Evaluation

As can be seen from figure 10, freeness in general followed a fairly predictable trend, that is, freeness decreased with increasing refining. As would be expected, the bulkier summerwood fibers exhibited the highest unrefined freeness followed by the combined springwood-summerwood pulp, and finally the more flexible springwood fibers. However, contary to what the literature indicated, summerwood freeness fell no more rapidly than springwood freeness. No explanation is given for this phenomenon other than the fact that PFI refining is atypical. Refining in the PFI mill is far more gentle than most conventional refining methods as evidenced by the fact that it sometimes took 35 grams of pulp close to 30 minutes to fall to a freeness of around 300 CSF. This type of refining tends to brush rather than cut the fibers and therefore treats the two pulp fractions more evenly.

Figure 11 shows refining effects on the brightness properties of pulp. As can be seen, brightness falls off much more rapidly in the case of springwood fibers. As

stated previously, this could be due, in part, to the discoloration of this fiber as it sat in the holding tank before thickening. Another possibility lies in the structural differences between the springwood and summerwood fibers causing the brightness of the surfaces exposed after refining to differ to some degree. The combined pulp was very similar to the summerwood with respect to brightness decreases with increasing refining amounts.

As can be expected, density and opacity trends are nearly opposite. That is, as density goes up, opacity goes down. These test results were probably the most difficult to analyze, however, in that they did not seem to exhibit any reasonably predictable trends. Instead of decreasing as it should with increased refining, opacity first decreased but later increased and finally decreased again with the combined and summerwood samples. No logical explanations could be surmised for the unknown springwood and summerwood sample trends due to the unconventional trend followed by the combined sample. One simple explanation could be the fairly large basis weight variations from group to group. But this variation, if responsible for density and opacity variations, should have produced variations in the other tests. This did not seem to be the case. Density and opacity results can be seen in figures 12 and 13 respectively.

Porosity results proved to be fairly significant. Figure 14 shows all three pulp types to decrease in porosity

with increased refining as would be expected. However, springwood and combined sample porosities decreased at a much greater rate than summerwood samples. This enabled the summerwood samples to maintain a fairly high porosity at low freenesses and fairly high strengths. This is most likely due to the bulk inherent in the summerwood fibers. Possible uses for this unique property will be discussed later in the report.

In my estimation, the most significant results were obtained in the tensile and burst tests. As can be seen from Figures 15 and 16, all pulp types increased in burst and tensile as refining began. A low enough freeness was reached with the summerwood to cause these values to taper off at the end. This low freeness was not reached with the combined sample. The springwood, on the other hand, reached this refining level at a freeness of around 500 CSF! As can be seen from the figures, burst and tensile initially increase very rapidly. This is the region where the reorientation of the fiber structure takes place. This not only causes the fiber to become more flexible and thus bond better, it causes the individual fiber strength to become greater, causing a two-fold reason for strength improvement. But, the fiber is very quickly overrefined causing the individual fiber strength to decrease and thus sheet strength. This is very significant in that it shows that the springwood portion of the pulp is dramatically overrefined in most commercial papermaking operations.

It also exhibits a possibility for strength increases and/ or energy decreases with separate refining. These will be discussed shortly.

Tear results are very similar but opposite to the above stated results as can be seen in figure 17. The combined pulp follows a conventional curve. Summerwood, however, increases more slowly in tear but maintains high tear at very low freenesses. Springwood decreases initially as bonding in the springwood increases rapidly but then begins to increase as the springwood fibers begin to break.

Graphs were also made relating all of the above tests when springwood-summerwood combination pulps were used. These graphs were more difficult to interpret and were not as revealing as the above graphs.

ECONOMIC AND OTHER JUSTIFICATIONS

There was little doubt when this project was started that some sort of benefits would occur due to the uniqueness of the springwood and summerwood pulp fractions. However, the added costs of the cleaning operation must somehow be offset by economic benefits elsewhere in the papermaking process or by improved worth of the final product.

One area that savings could possibly come from would be in the refining operation. One of the premises that the thesis was based on is that it is a tangible area to look at. From the previously talked about results, it is known that the springwood requires far less refining than the summerwood to reach maximum strength. For this reason,

a combination of springwood pulp refined to 2,000 revolutions and summerwood refined to 6,000 revolutions is compared to the total pulp sample refined to 6,000 revolutions. Tables 9 and 11 show these two pulps to be quite comparable in most properties, but these properties were attained with 37% less refining in one case. Table 12 shows a revised cost analysis comparing the two samples.

The payback period of 24 years does not seem very favorable, but there may be reasons to be optimistic. For one, energy savings may be only one area in which money can be saved. Also, these comparisons are made using the latest and most efficient refiner equipment. Savings could be a lot greater in older mills using inefficient conical refiners.

Unique properties of the separated pulp are responsible for two other reasons that centrifugal separation could prove to be economically viable. The extremely high porosity of summerwood at high strengths could be very important for products such as filter papers, tissues, or bag papers. Summerwood refined 6,000 revolutions exhibit these properties as shown in figure 13. Also seen in figure 13 is the property of high strength development at low energy inputs inherent in the springwood fiber.

CONCLUSIONS & RECOMMENDATIONS

This thesis indicates that a lot more work is still possible in the area of separate springwood-summerwood

refining. A study could be done focusing totally on optimization of the separate refining of the two fiber types. Work dealing with manipulation of cleaner parameters to attain optimum separation efficiencies may also be warranted. If purer pulp samples were worked with, trends occurring with refining might be more pronounced and more noticeable. Research could also be done in order to find practical uses for the unique properties that springwood and summerwood made papers exhibit.

The unique properties that seemingly could result in special uses involve porosity, tear, and tensile. Summerwood develops a slightly lower tensile strength at slower rates than conventional pulp; but tensile, tear, and porosity all remain very high at medium to high refining levels. Springwood seems to produce very high tensile in an extremely short time. It also begins to be overrefined at very high freenesses and short refining times. This indicates that almost all springwood fibers are refined beyond their optimum point in conventional refining processes!

Footnotes

[1]A. W. Pesch, U.S. Pat. 3,083,927 (April 16, 1663)

[2]E.D. Jones et.al., "Springwood-Summerwood Separation of Southern Pine Pulp to Improve Paper Qualities," Tappi, (Sept. 1966), p.410.

[3]Ibid., p.413.

[4]Mark W. Bray and C.E. Curran, "Sulphate Pulping of Southern Yellow Pines Effect of Growth Variables on Yield and Pulp Quality," Paper Trade Journal, (November 11, 1937), p.40.

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[6]G. Stuart and J. Jacobsson, "Technical Progress In Centrifugal Cleaning." The World's Paper Trade Review, (December 8, 1966) p.1674.

[7]Terry Bliss, "Reverse Cleaning-Its Use in Removing Lightweight and Sticky Contaminants," Tappi, (June 1980), p.88.

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[9]Maurice D. Woodruff, "What About Centrifugals for Cleaning," Pulp & Paper, (March 25, 1968), p.22.

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[25]Ibid.

[26]Woodruff, Tappi, p.1151.

[27]Jones, p.410.

[28]Woodruff, Pulp & Paper, p.23.

[29]Anderson, p.183A.

[30]D.C. McIntosh and L.O. Uhrig, "Effect of Refining on Load Elongation Characteristics of Loblolly Pine Hollocellulose and Unbleached Kraft Fibers." Tappi, (June 1968), p.270.

[31]Bray, p.44.

[32]McIntosh, pp.268-273.

[33]Bengt Leopold, "Effect of Pulp Processing on Individual Fiber Strength," Tappi, (July 1966), p.318.

[34]McIntosh, p.268-273.

[35]Leopold, pp.315-318.

[36]Ulla-Britt Mohlin, "Cellulose Fibre Bonding-The Effects of Beating and Drying on Interfibre Bonding," Svensk Papperstidning, (May 30, 1975), p.339.

[37]Bengt Leopold and D. C. McIntosh, "Chemical Composition and Physical Properties of Wood Fibers." Tappi, (March 1961), p.240.

[38]Bray, p.44.

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[39]Jones, p.412.

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[43]Anderson, p.184A.

[44]Tom Berger, Application Engineer, Beloit Corp.- Jones Div.

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APPENDIX

Table 1

Effect of Stock Temperature on Separation Efficiency

	Feed[a] temperature, °F			
	80	86	92	106
Accepts, % of feed	75	67	61	44
Springwood, %	60	63	65	74
Rejects, % of feed	25	33	39	56
Summerwood, %	70	69	70	67

[a] Bleached pine pulp separated in Bauer 600N, 3-in. Centri-Cleaner at 0.1% consistency, 20 gal/min with 35 psi pressure drop and 1/8-in. tip.

Table 2

Effect of Refining before Separation

	Feed pulp[a]		
	Un-refined	Refined, laboratory jordan	
CSf ml	740	700	572
Accepts, % of feed	37	55	65
Springwood, %	76	60	58
Csf ml	635	685	482
Rejects, % of feed	63	45	35
Summerwood, %	73	66	64
CSf ml	765	765	740

[a] Unbleached pine pulp separated in Bauer 600N, 3-in. Centri-Cleaner at 0.1% consistency, 20 gal/min with 35 psi pressure drop and 1/8-in. tip.

Table 3

Effect of Feed Consistency on Separation Efficiency

	Feed[a] consistency, %				
	0.05	0.10	0.15	0.20	0.25
Accepts, % of feed	31	37	41	42	40
Springwood, %	85	76	70	67	63
CSf, ml	635	650	675	670	700
Rejects, % of feed	69	63	59	58	60
Summerwood, %	74	77	71	65	65
CSf, ml	765	770	770	765	760

[a] Unbleached pine pulp, initial CSf 740 ml, separated in Bauer 600N, 3-in. Centri-Cleaner at 20 gal/min with 35 psi pressure drop and 1/8-in. tip.

Table 4

Refining Levels for Unbleached Kraft Pulps

PFI mill refining time, rev.	Canadian Standard freeness, ml
Summerwood	
0	760
1300	720
2000	640
2500	505
3000	395
3700	260
Springwood	
0	715
2100	690
3000	615
4500	485
5500	395
6700	290

Table 5

Fiber Strength Results—Holocellulose

Sample identity, ml CSf	*Breaking load, g*	*Cell wall area, μ^2*	*Tensile strength, kg/mm²*	*Elongation*		*Young's modulus, kg/mm²*
				At 10-g load, μ	*To failure, %*	
Summerwood						
780	49	595	83	13	4.8	1680
750	51	571	90	12	4.8	1790
610	51	570	89	14	5.4	1660
470	48	596	80	13	5.2	1570
385	52	580	90	15	7.6	1180
260	43	600	72	16	6.3	1160
Springwood						
725	12	324	38	55	6.0	640
440	16	304	52	38	5.4	960
275	19	279	70	31	5.4	1300

Table 6

Effect of Beating on Fiber Properties

	Beating time, min	*No. of revolutions*	*CSf, ml*	*Breaking load, g*	*Cross-sectional area, μ^2*	*Tensile strength, kg/mm²*		*Young's modulus, kg/mm²*
						Average	*Minimum*	
Summerwood								
Norway spruce	0	...	700	21	240	93	60	1640
Norway spruce	5	...	534	20	210	95	68	2180
	10		270	19	194	102	66	2270
Southern pine	..	0	700	32	461	70	48	1010
Southern pine	..	4000	430	33	450	76	56	1260
	..	8000	220	35	408	86	60	1310
Springwood								
Norway spruce	0	...	700	10	214	53	29	1110
Norway spruce	5	...	534	9	168	56	35	1400
	10	...	270	10	153	66	35	1830
Southern pine	..	0	700	15	378	38	13	570
Southern pine	..	6000	405	16	318	49	21	850
	..	9000	270	15	273	55	22	1090

Table 7

Fibre	Mean bond strength N/mm²	Standard deviation N/mm²	No of tests
Summerwood			
unbeaten	4.71	1.50	22
beaten	4.37	1.12	16
Springwood			
unbeaten	4.46	1.12	14
beaten	3.96	1.25	35

Table 8

Effect of Springwood Content on Properties of Unbleached Pine Pulp; Physical Properties of Handsheets at 500 ml CSf

	Springwood content, %									
	86	*76*	*70*	*67*	*63*	*47*	*36*	*29*	*26*	*23*
	636 ml CSf	*650 ml CSf*	*675 ml CSf*	*670 ml CSf*	*705 ml CSf*	*740 ml CSf*	*760 ml CSf*	*770 ml CSf*	*765 ml CSf*	*770 ml CSf*
Burst factor	76	76	76	73	75	68	62	61	62	61
Tear factor	93	105	109	116	118	147	159	169	162	171
Apparent density, g/cm³	0.652	0.630	0.619	0.608	0.614	0.586	0.581	0.558	0.575	0.570
Sheffield smoothness, units	82	122	136	142	151	233	252	257	269	269
Sheffield porosity, units/cm³	11.9	20.6	26.5	29.1	28.7	64.5	98.1	105.1	121.0	127.2
Breaking length, m	10,125	10,385	10,030	9935	9195	9260	8865	8980	9070	9025
Zero span tensile, kg/15 mm	13.1	14.2	15.0	14.2	...	13.9	...	15.1	13.3	13.8
MIT fold, double folds	510	473	664	611	474	698	556	460	487	394

Table #9

OBS	VAR OBS#	POROS	REFIN	BURST	FRENS	TENSL	BRITE	TEAR	OPACY	DENSY	CALPR
Unseparated											
1	1.000	500.0	.0000	5.000	735.0	.8000	84.10	22.00	74.00	.3128	7.600
2	2.000	165.0	2.000	32.00	585.0	3.300	82.50	44.00	67.40	.3848	6.100
3	3.000	195.0	4.000	39.00	475.0	3.700	82.60	44.00	67.60	.3995	5.900
4	4.000	200.0	6.000	43.00	435.0	4.100	82.00	41.00	70.40	.3847	6.100
5	5.000	60.00	8.000	49.00	225.0	4.600	79.50	36.00	66.20	.4064	5.800
Springwood											
6	6.000	500.0	.0000	12.00	700.0	1.500	84.60	33.00	70.90	.3680	6.900
7	7.000	135.0	2.000	50.00	555.0	5.700	77.80	26.00	66.70	.4102	5.500
8	8.000	145.0	4.000	47.00	455.0	5.000	77.20	32.00	67.20	.4209	5.500
9	9.000	125.0	8.000	42.00	310.0	4.200	76.60	44.00	72.60	.3717	5.900
Summerwood											
10	10.00	500.0	.0000	3.000	740.0	.5000	83.60	16.00	70.50	.2985	7.900
11	11.00	450.0	4.000	26.00	580.0	2.800	81.40	50.00	66.90	.4029	6.000
12	12.00	425.0	6.000	32.00	465.0	3.500	80.90	54.00	72.20	.3114	6.600
13	13.00	230.0	8.000	36.00	380.0	3.600	79.60	48.00	74.70	.2866	6.800
14	14.00	180.0	10.00	35.00	235.0	3.600	78.40	52.00	73.40	.2989	6.600

Table #10(Clark Classifications)

	Mesh				
	14	30	50	100	Fines
Unrefined Springwood	38%	35%	16%	8%	3%
Unrefined Summerwood	37%	37%	18%	7%	1%
Springwood(8000rev.)	18%	37%	15%	7%	23%
Summerwood(8000rev.)	23%	40%	12%	5%	20%

Table #11

OBS	VAR OBS# / BURST	REFIN(Sgr) / TENSL	CALPR / TEAR	BRITE / DENSY	OPACY	POROS
1	1.000	.0000	7.400	84.00	73.10	500.0
	4.000	.7000	17.00	.3181		
2	2.000	.0000	7.000	82.50	70.90	500.0
	14.00	1.600	29.00	.3338		
3	3.000	.0000	6.900	81.40	70.30	500.0
	15.00	1.900	34.00	.3405		
4	4.000	.0000	6.900	79.10	70.80	500.0
	18.00	2.200	39.00	.3418		
5	5.000	4.000	7.000	81.00	76.40	500.0
	18.00	2.100	41.00	.3372		
6	6.000	4.000	6.300	80.00	68.50	350.0
	31.00	3.300	45.00	.3743		
7	7.000	4.000	6.300	80.60	70.80	340.0
	30.00	3.300	47.00	.3730		
8	8.000	4.000	6.100	77.20	70.40	185.0
	37.00	3.100	42.00	.3866		
9	9.000	6.000	7.100	82.20	79.70	500.0
	19.00	2.100	32.00	.3315		
10	10.00	6.000	6.000	80.00	66.60	270.0
	32.00	3.800	42.00	.3931		
11	11.00	6.000	6.100	80.40	68.20	250.0
	37.00	3.500	52.00	.3898		
12	12.00	6.000	5.700	76.50	65.60	165.0
	42.00	3.900	37.00	.4134		
13	13.00	8.000	6.900	82.00	79.20	500.0
	21.00	2.400	43.00	.3443		
14	14.00	8.000	6.200	81.70	69.80	320.0
	31.00	3.100	47.00	.3793		
15	15.00	8.000	6.000	78.40	68.00	200.0
	38.00	3.500	43.00	.3930		
16	16.00	8.000	6.000	76.10	68.10	140.0
	40.00	4.200	41.00	.3930		
17	17.00	10.00	6.600	81.50	77.70	335.0
	20.00	2.900	35.00	.3589		
18	18.00	10.00	6.100	82.80	67.30	210.0
	34.00	3.200	47.00	.3866		
19	19.00	10.00	5.800	80.60	66.60	140.0
	38.00	3.700	40.00	.4096		
20	20.00	10.00	5.900	78.50	67.50	85.00

Table #12

	Summerwood(6000rev.) Springwood(2000rev.) Combination	Unseparated Pulp (6000rev.)
Cleaner Costs:		
Energy-	$225,000per year	----------
Capital-	$343,000	----------
Refiner costs:		
Energy-	$618,750per year	$900,000per year
Capital-	$137,200	$186,000

With 15% interest on all capital expenditures the payback period is around 24 years.

Table #13

	summerwood(6000rev.)	unseparated(6000rev.)	spring(2000rev.)
Tensile	3.5	4.1	5.7
Tear	54	41	26
Porosity	425	200	135

Figure 1

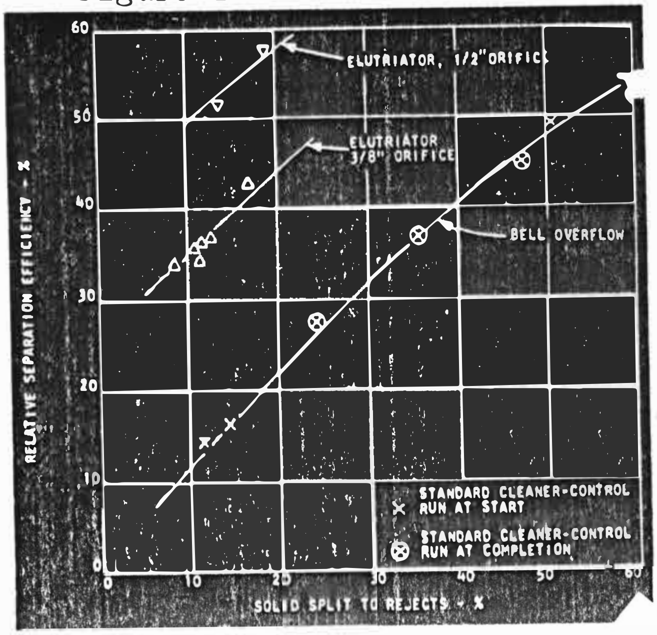


Figure 2

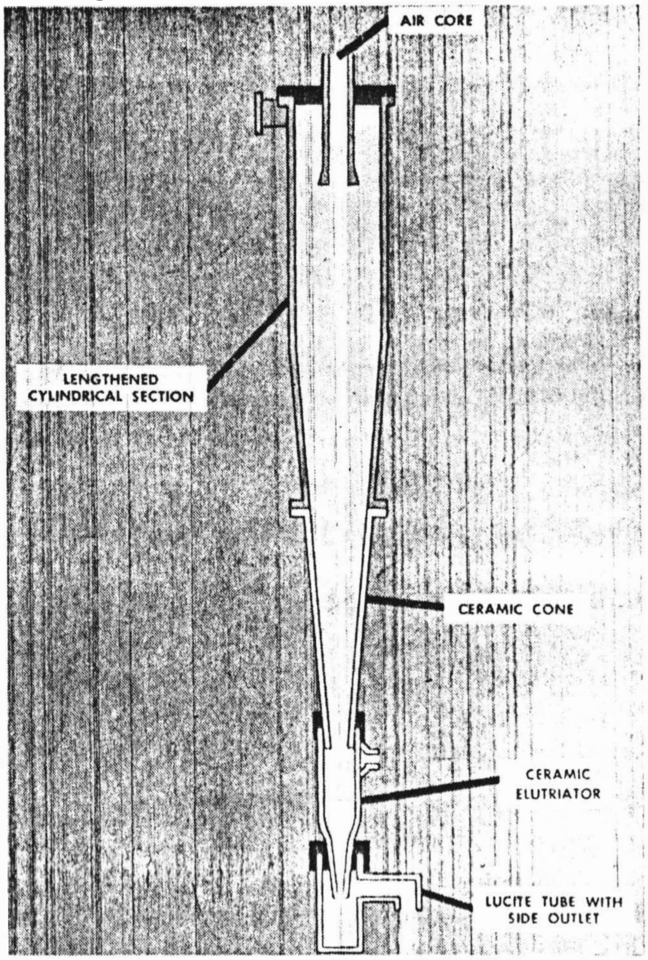


Figure 3

Distribution of pressure and velocity in a hydrocyclone as a function of the cone angle, at a throughput of 2,000 l/min., pressure drop p = 17 m cw. From the wall to the centre of the cyclone, there is an increasing tangential velocity and a decreasing static pressure. At the centre, the tangential velocity falls to zero and the static pressure may have negative values

A = Distribution of velocity B = Distribution of pressure

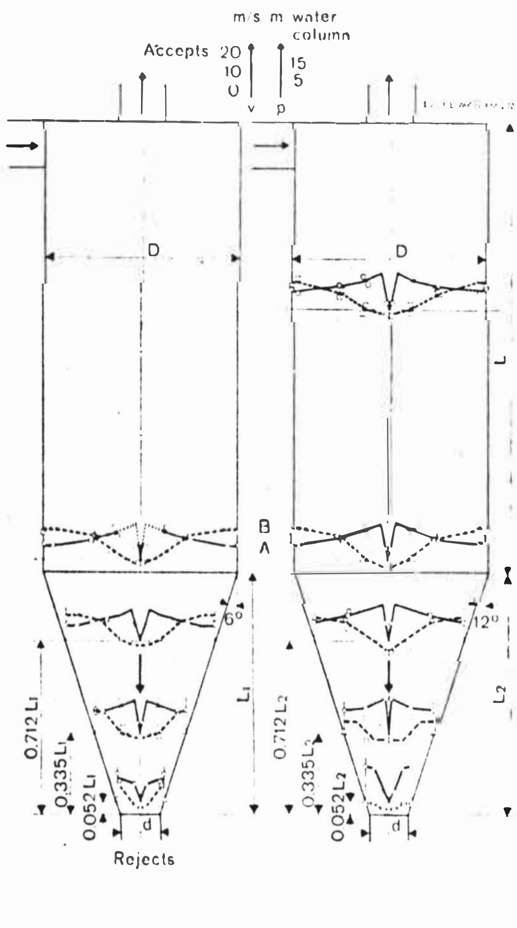


Figure 4

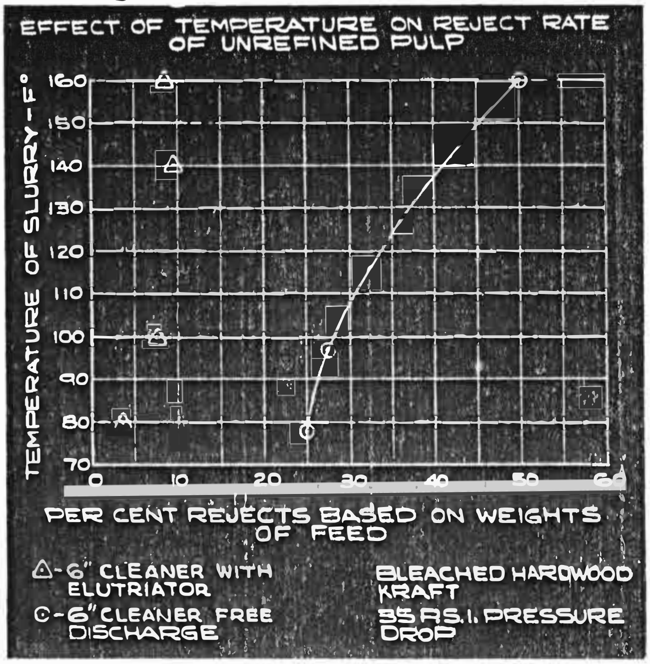


Figure 5

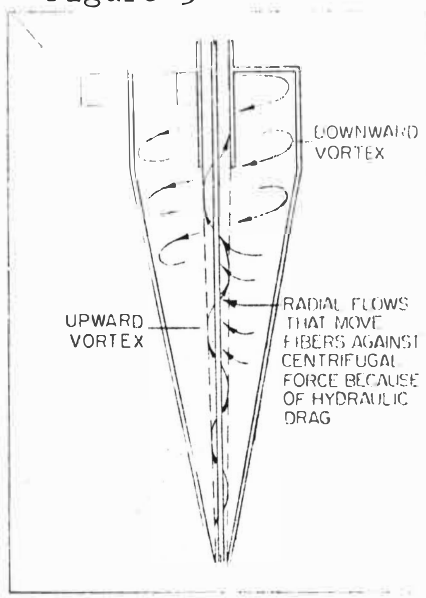


Figure 6

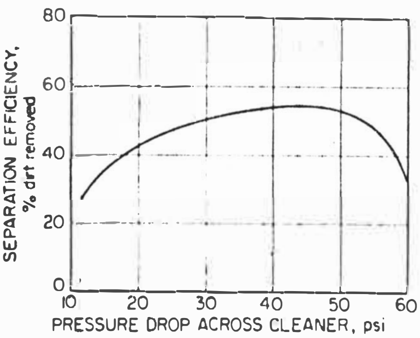


Figure 7

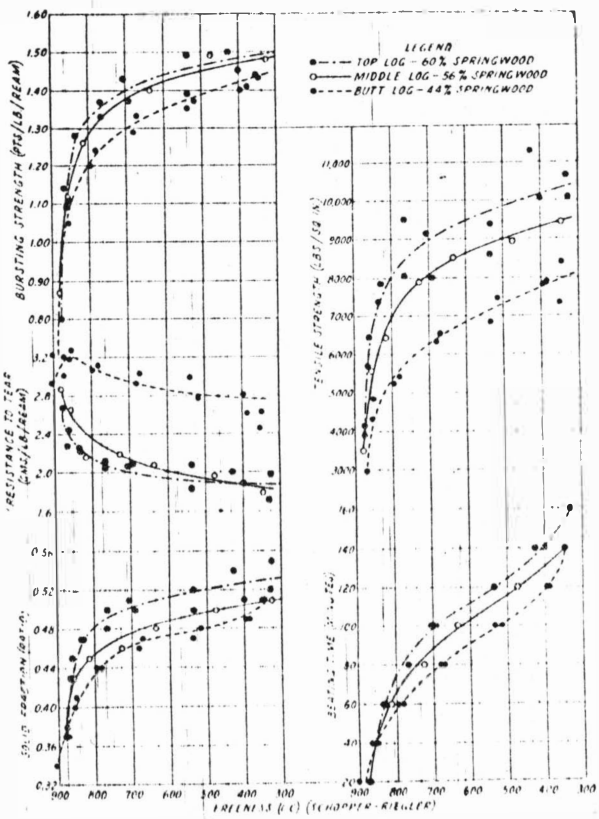
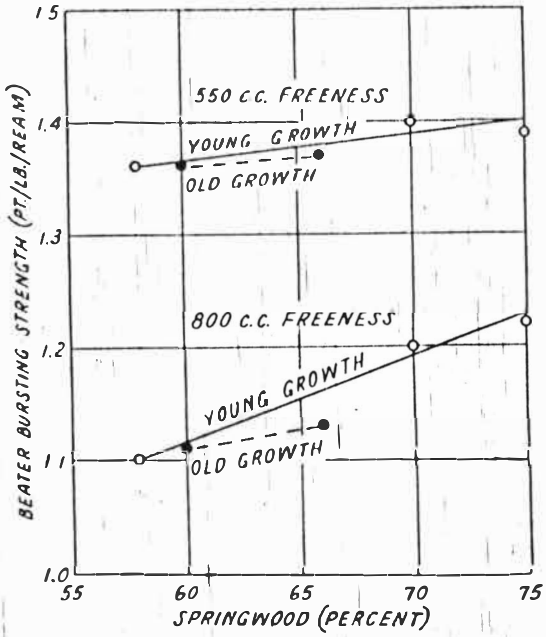
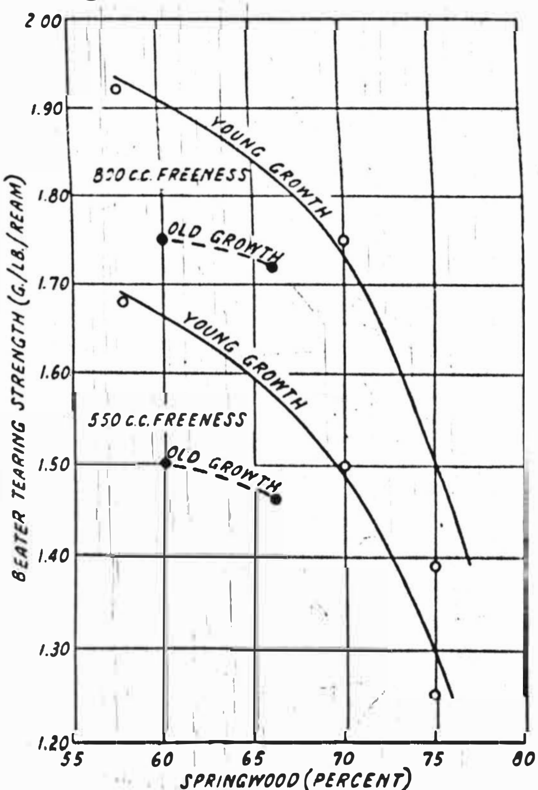


Figure 8



Relations Between Beater Bursting Strengths and Springwood Contents of Western Hemlock of Five Growth Types.

Figure 9



Relations Between Beater Tearing Strengths and Springwood Contents of Western Hemlock of Five Growth Types.

Figure # 10

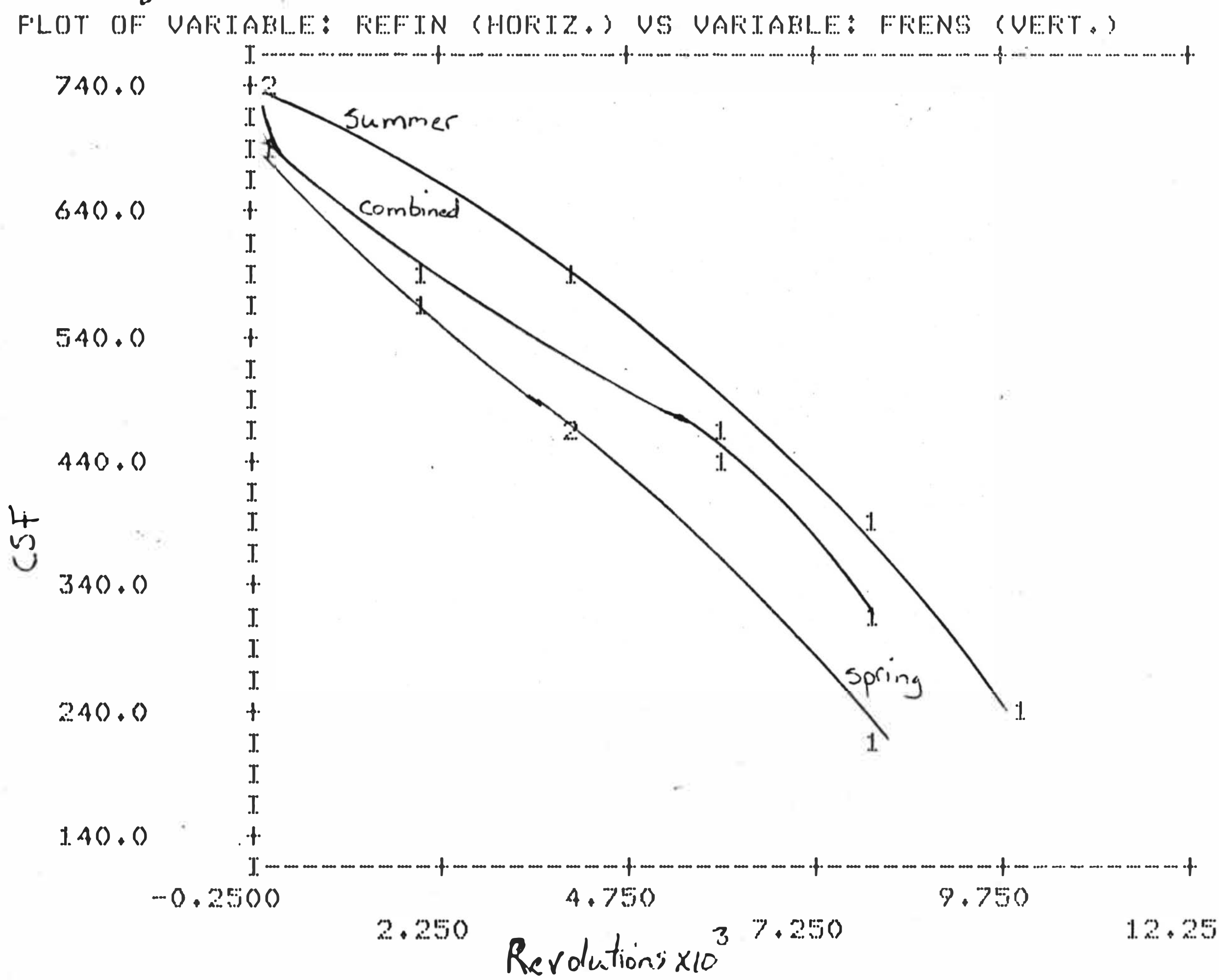


Figure # 11

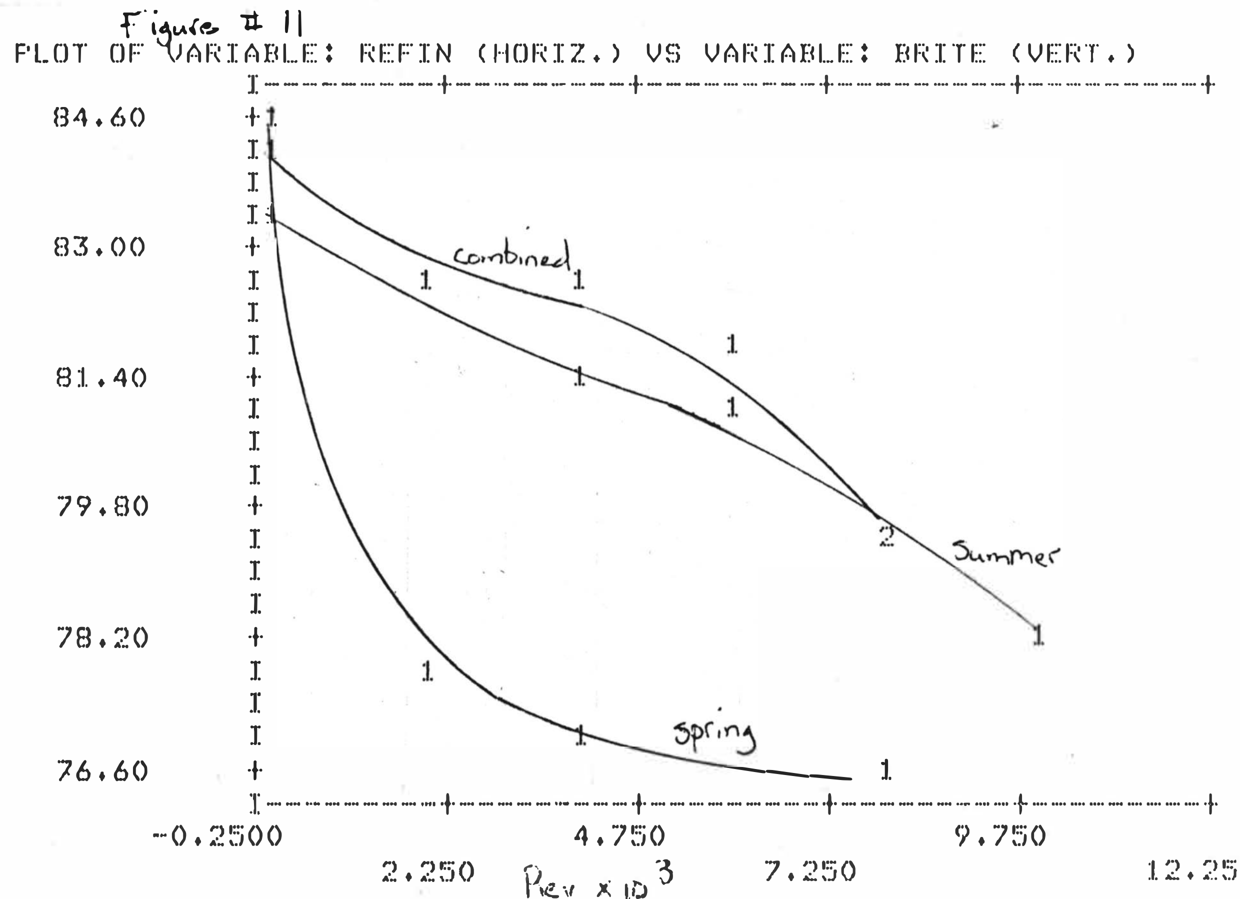


Figure #12

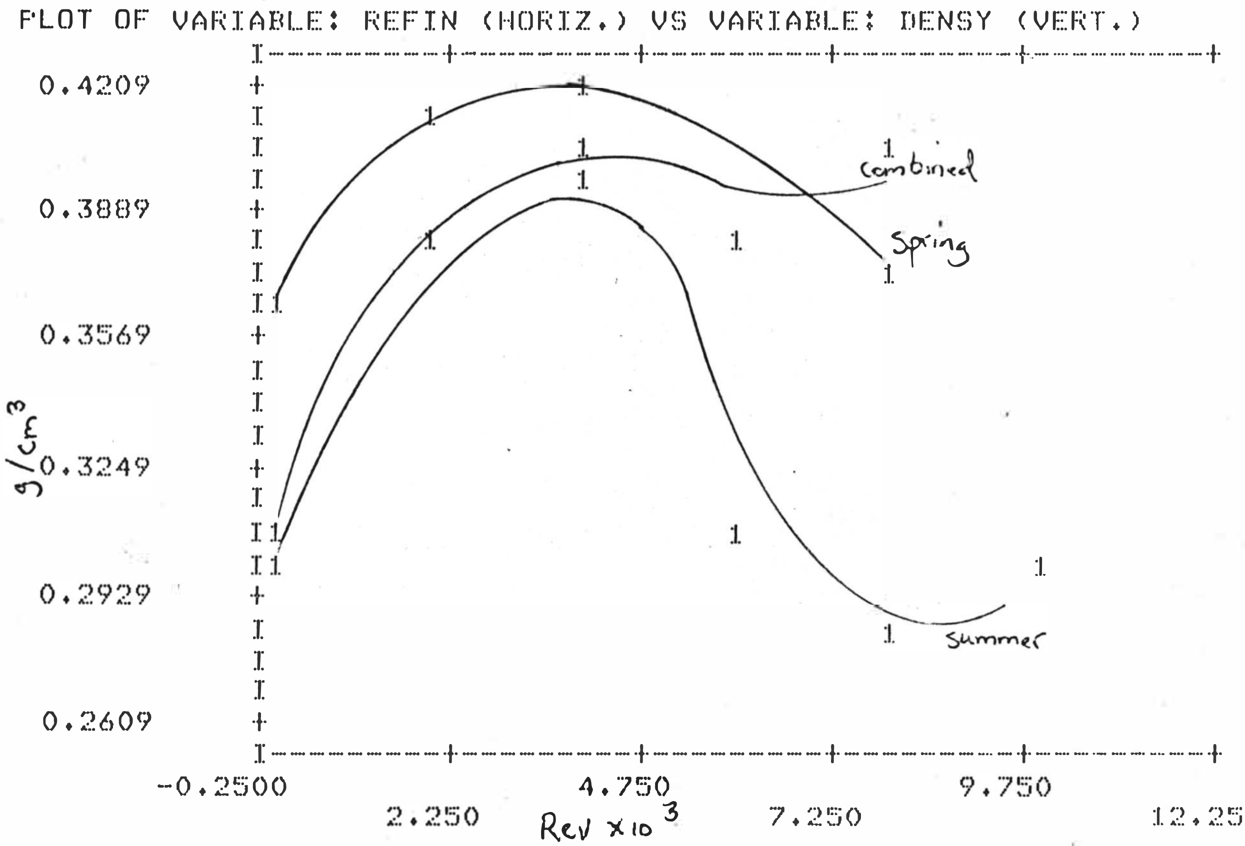


Figure #13

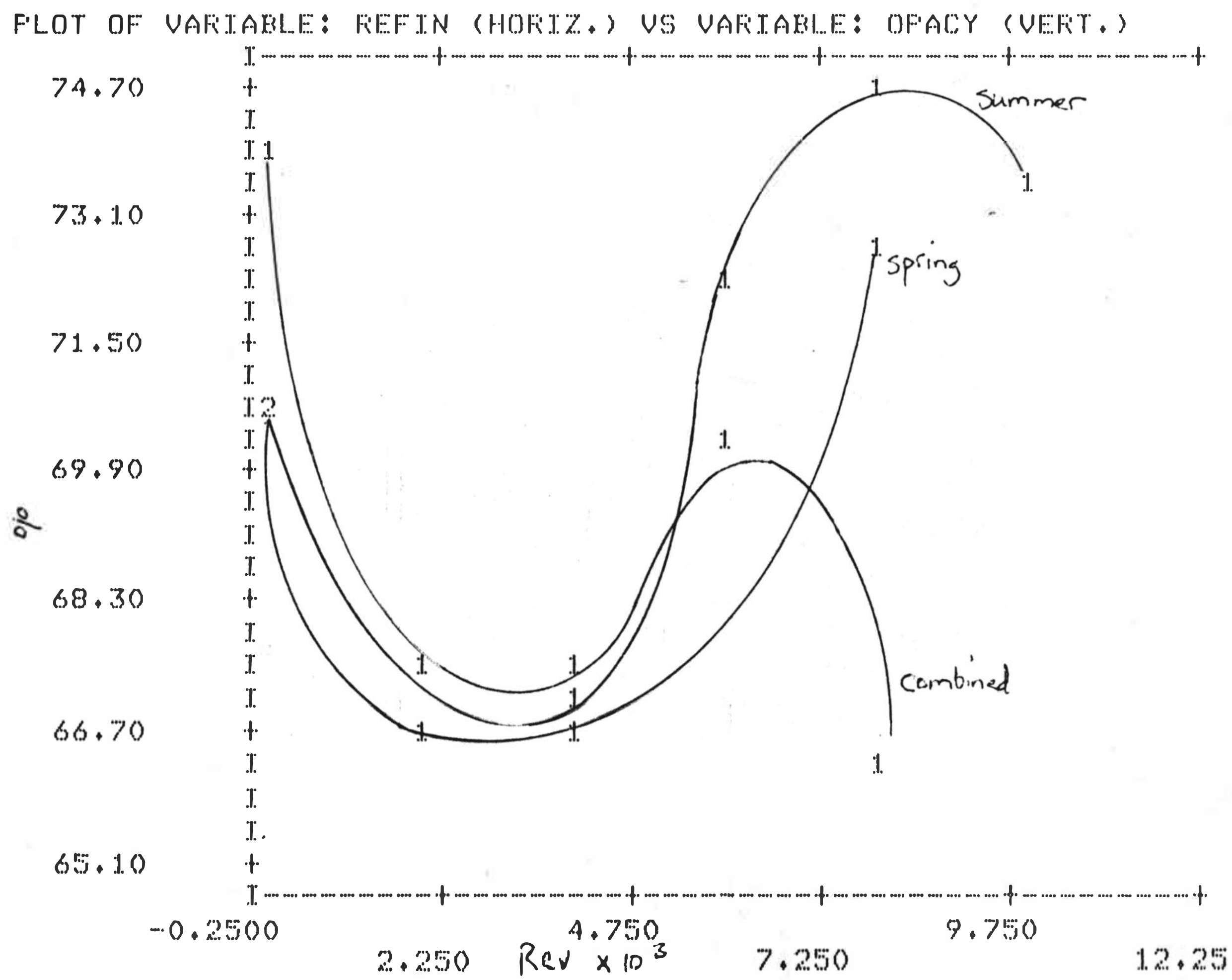


Figure #14

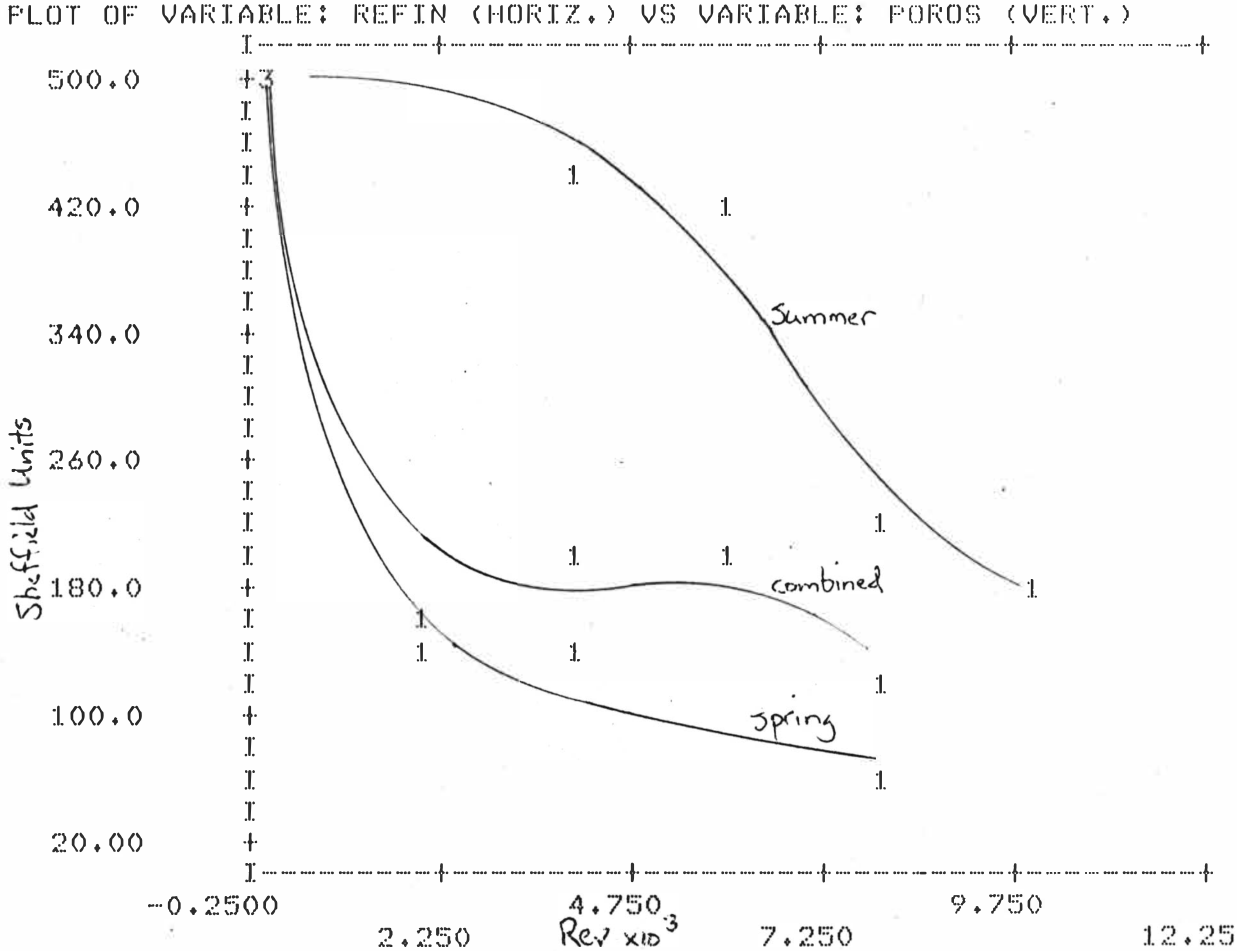


Figure #15

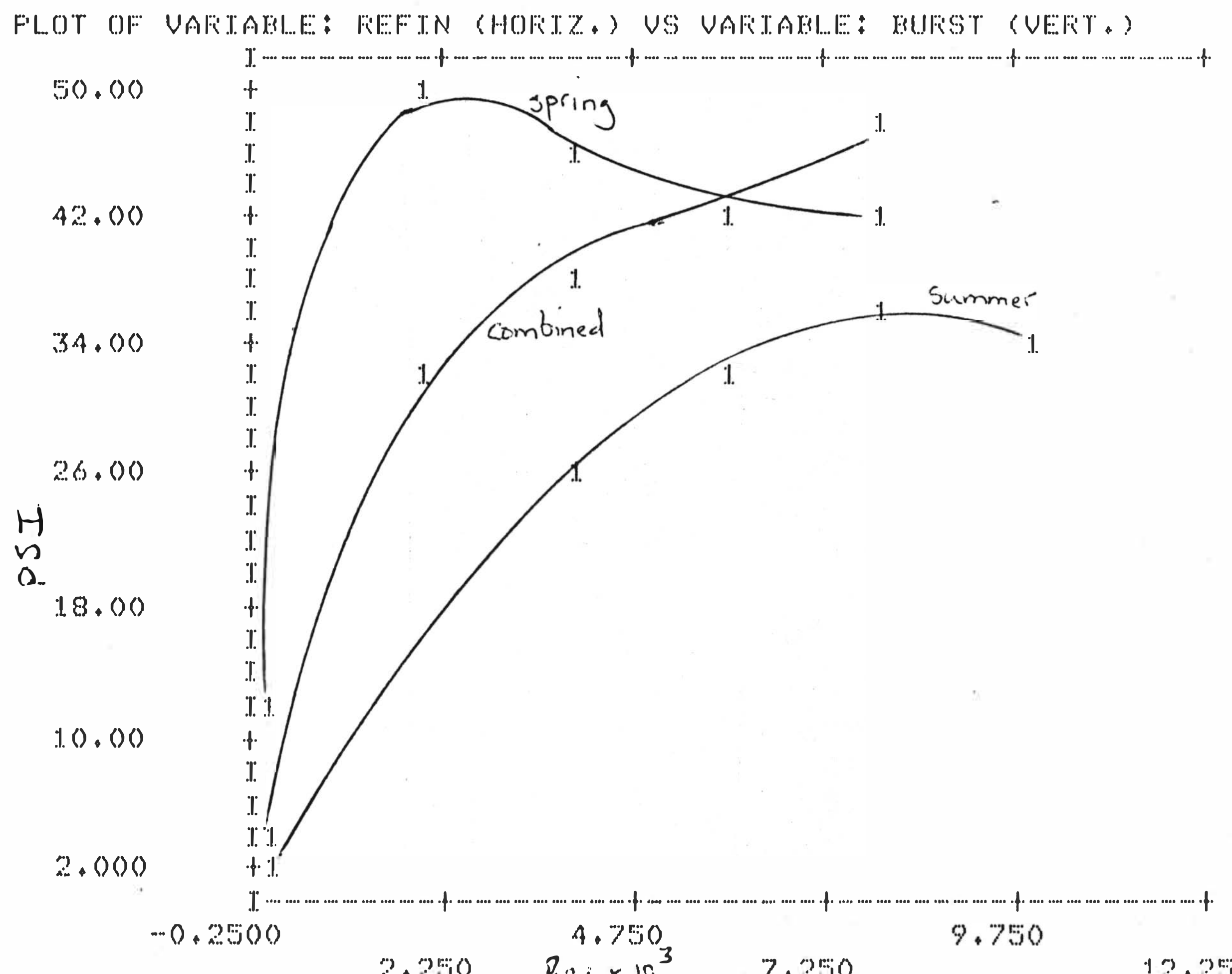


Figure #16

PLOT OF VARIABLE: REFIN (HORIZ.) VS VARIABLE: TENSL (VERT.)

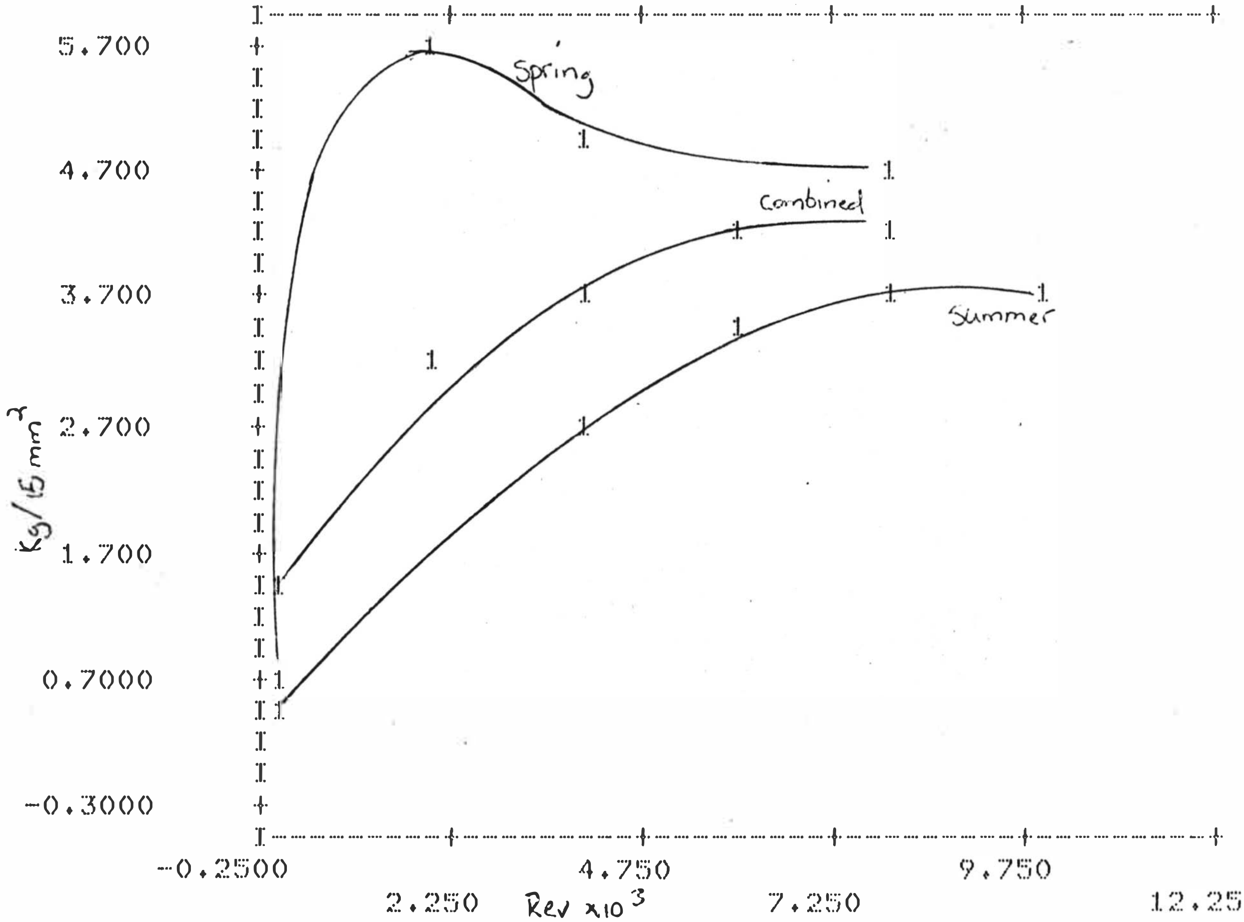


Figure #17

PLOT OF VARIABLE: REFIN (HORIZ.) VS VARIABLE: TEAR (VERT.)