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# VESSEL ELEMENTS AND EUCALYPTUS PULPS


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**April 2007**

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## CONTENTS

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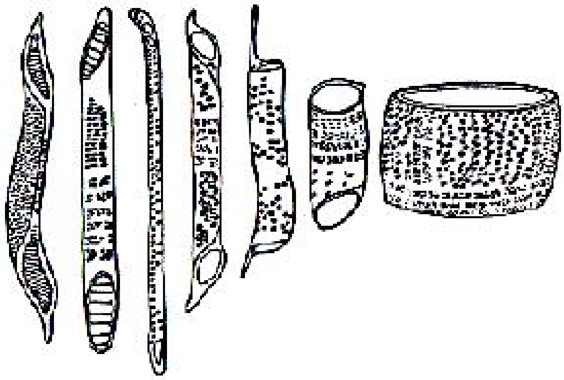
## INTRODUCTION

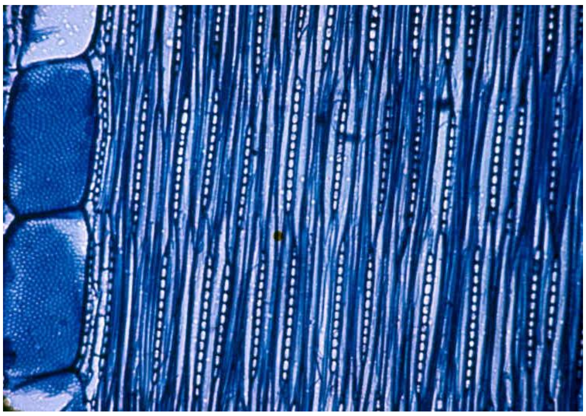
Along the evolutionary process in the Vegetable Kingdom, the dicotyledonous angiosperms (foliage trees or hardwoods) resulted in better physiological specialization than the gymnosperms (conifers or softwoods), both with regard to their reproductive aspects (flowers and fruits) and to the way of transporting the mineral sap from the roots to the top of the trees, through the xylem. For this transportation, they have developed perfect tubing systems within the xylem or the wood. On the contrary, the conifers have developed the utilization of their tracheids or fibers to do this sap transportation. The hardwood ducts succeed in doing the sap transportation as well in longitudinal (preferential) direction, as they cooperate to the sap motion in lateral direction, to the cells adjacent to them. This is because those ducts are connected to adjoining parenchyma cells through small openings called pits. Each element forming those ducts is interrelated to about 10 to 30 adjoining side cells. Each pit or micro-perforation, which establishes this interconnection to the neighboring cells and the vessels, measures from 2 to 15 μm i.e. they are really minute, but are numerous and efficient. These pits are in general of a simple kind i.e. just a small and simple circular, oval or rectangular little hole in the cell wall. To allow mineral sap circulation more efficiently, the vessels have perforated top and bottom ends. These perforations can be single (just a large opening) or multiple (a perforation plate with several openings). The types of perforations, the vessel element shape and their distribution over the cross section of the wood are characteristics serving even to differentiate species by their anatomy. The wider vessels and having a single (simple) perforation at each end are more specialized for sap transportation and therefore more developed on the evolutionary vegetable rank. The vessel element length is not so important for conduction purposes, but its diameter is very important, because the vessel area is quadratically related to its diameter. On the other hand, the relationship between length and diameter of each vessel cell determines important characteristics of these elements for using these woods for pulp and paper manufacturing. Vessels that are similar to fibers (higher length to diameter ratio) are more suitable, since they adhere to adjoining fibers and are more strongly retained in the network formed by the paper web.



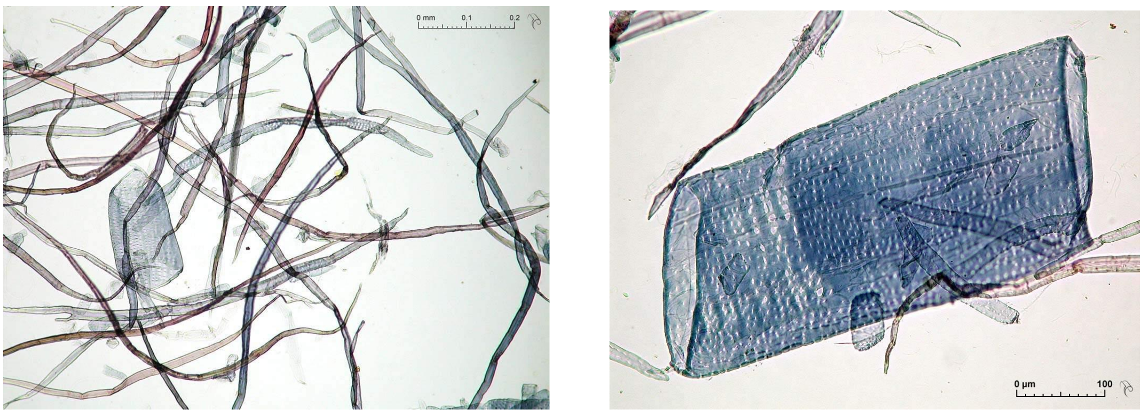
Vessel types and their evolution: the more developed ones are wider and have a single large opening at the ends (Source: Alves, 2005)

Observe now how fantastic is the tree engineering. The eucalyptus trees of commercial plantations are 25 to 40 meters high. The highest trees all over the world are *Eucalyptus regnans* trees growing in Tasmania, reaching almost 100 meters in height. Definitively, it is something deserving much engineering to carry the mineral sap from the roots to the top at heights like these ones. Few of the tubes coming from the root succeed in extending continuously to the top of the trees. In general, as the trees grow in growth layers (annual rings), these ducts have lengths ranging from 10 cm to 10 meters. It is only in trees having a very ample and juvenile sapwood and large diameter vessels that there are canals capable of running through the whole height of the tree. Even if they break off at certain heights, they interconnect through the side interconnections. In other words, the water with the nutrients migrates from one canal to the other, but keeps its ascending direction. Observe how miraculous is this engineering. Tubes of microscopic diameters and great lengths are sustained by the wood structure itself. The neighboring cells (fibers and parenchyma) impart the required sustenance and organization to the tubes. For this very reason, although having very thin walls (2.5 to 5 µm), these tubes are stable and accomplish their mission of transporting the sap. The sap is then "pumped" through these tubings, botanically called vessels, by the action of three main forces: pressure caused by the absorption of the roots, taking water from the soil by osmotic differential; capillarity; and transpiration of the leaves. All these cooperate for the sap to be pulled upwards through the ducts or vessels. As water and mineral ions (nutrients) are vital not only in the leaves, a part of this sap migrates to supply cells adjacent to the vessels. On this basis every tree can receive mineral sap where it is required. Thus, the whole wood becomes very well soaked with water and nutrients. When a eucalyptus tree is harvested, the moisture of the wood ranges from 50 to 55% and this depends very much on the density of the wood and on water availability in the ground. The lower the basic density of the wood, the higher the water amount that it is possible to be retained in the xylem, in the porosity or capillarity of the wood (lumen of the cells, among which the vessels).

The vessels are long ducts in the longitudinal direction of the trees. They consist of tubings formed by the continuous interconnection, one by one, of minute anatomical "glazed clay pipes" in the form of "little barrels", called vessel elements. These elements fit wonderfully well into each other, originating these transportation channels.



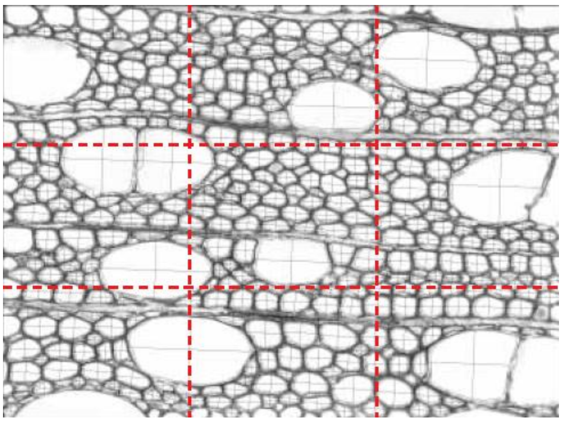
Sap transporting ducts or vessels (on the left on the photo)



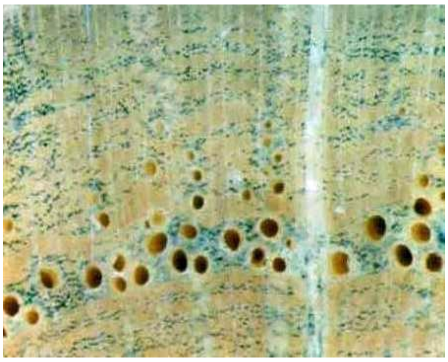
Vessel elements (Photo kindness: Econotech Services Ltd.)

Besides this arrangement in longitudinal direction, the tree tries also to arrange these ducts in an organized way in its cross section. There is even a characteristic model of arranging the ducts in the wood, allowing even to identify wood species as a function of such an arrangement. There are woods with isolated, diffuse or dispersed vessels (long isolated tubes), there are vessels in the form of clusters, there are geminate vessels and there are also some hardwoods having vessels in formation as annual rings (ring-porous hardwoods), which are very characteristic and impart beautiful designs to the wood. The vessels are mostly in the eucalyptus woods either in the isolated, diffuse or dispersed form or in small clusters of two or three near vessels. In the distribution over the cross section the vessels disperse homogeneously and arrange themselves according to a very good distribution pattern. It is well-known that the presence of vessels in eucalyptus trees is only more reduced in the regions of late wood, when for different reasons, the tree grows less and has a lower physiological activity. Under these conditions of less physiology, the wisdom of the tree orientates it to produce less elements of water conduction to the leaves. It is even natural, as in many situations it is during drought that the tree forms late wood or wood similar to that of late wood, with lower vessel frequency and vessel area.

When the wood is sectioned transversely, the vessels appear as openings or voids in the cut cross section. They are similar to pores and for this reason in botany, pore is a synonym of vessel, when it is seen in its cross section.

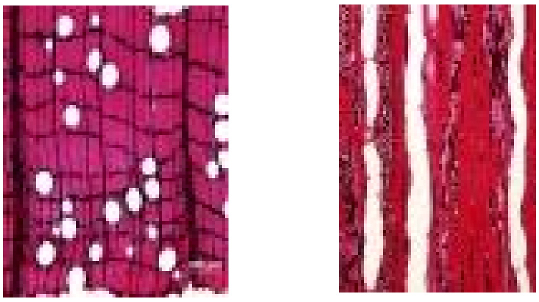


Vessels or pores dispersed in cross section of the wood
(Source: Lundqvist, 2002)



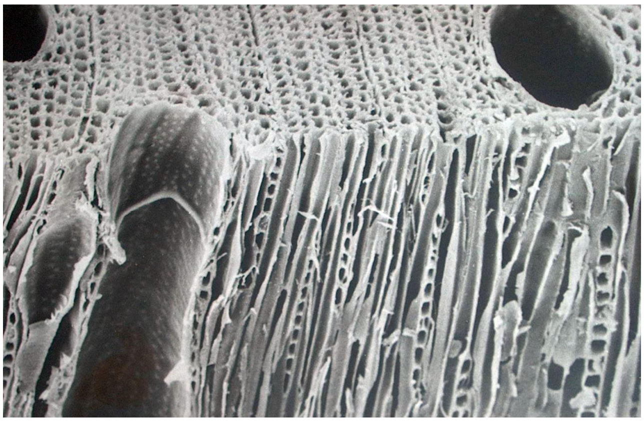
Hardwood with vessels arranged in ring-porous pattern
(Source: http://www.eucalyptus.com.br/GalleryM6/index.php )

The presence of vessels is obligatory in the hardwoods. In case a wood has no vessels, it is not considered to be a dicotyledonous angiosperm. If it has them, it is a hardwood. It is the case of the well-known tree called casuarina. Because of its outside appearance, it is very similar to a conifer pine tree, but as a matter of fact it is a hardwood, it has vessels, which are even quite characteristic. The conifers form wood that has only tracheids (fibers) and parenchyma cells, whereas the hardwoods have fibers, parenchyma and vessels.

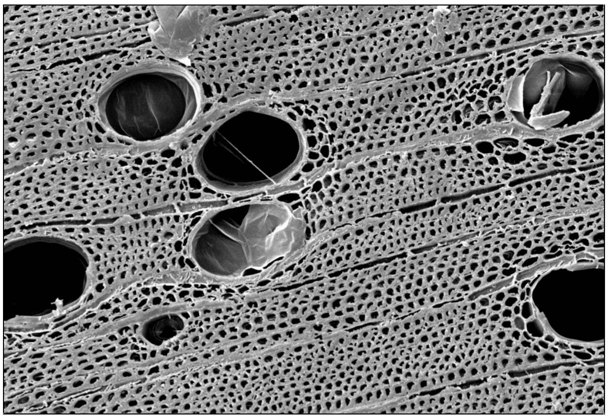


*Casuarina sp.* wood cross and longitudinal sections showing the vessels
(Available at: http://insidewood.lib.ncsu.edu )

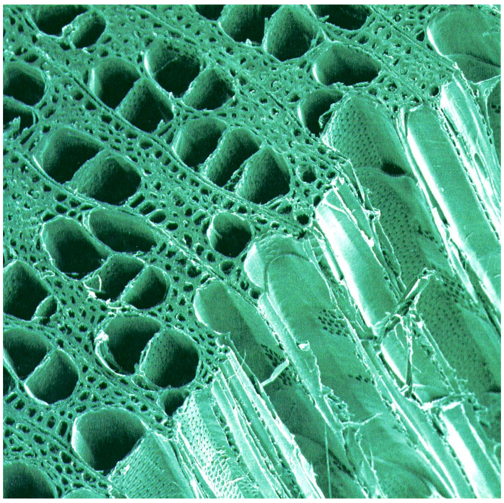
Aerial part of the hardwood tree *Casuarina sp.*



Eucalyptus wood block showing the ducts, pores or vessels

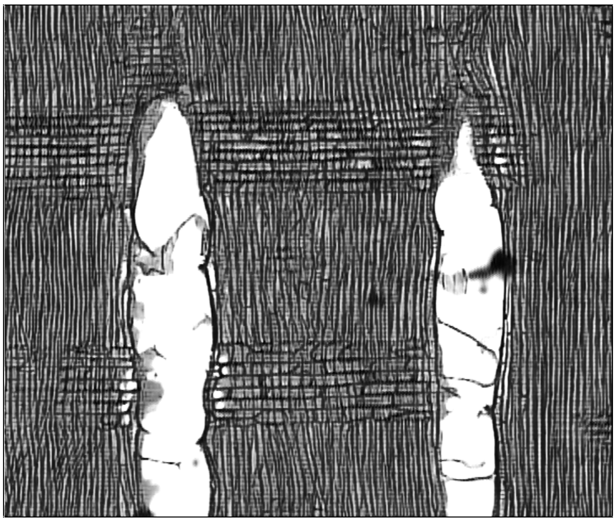


Eucalyptus wood cross section showing the pores or vessels

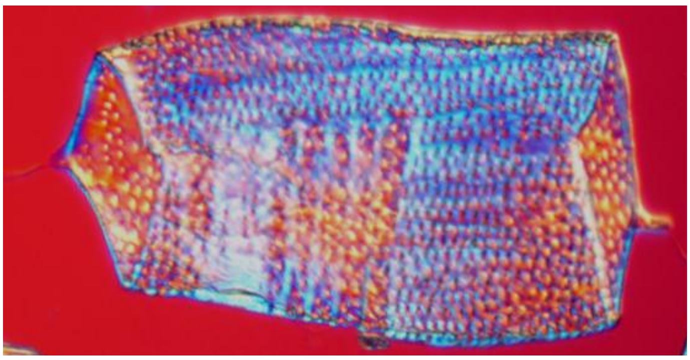


Hardwood block, where the presence of the tubings formed by the vessels can be easily observed

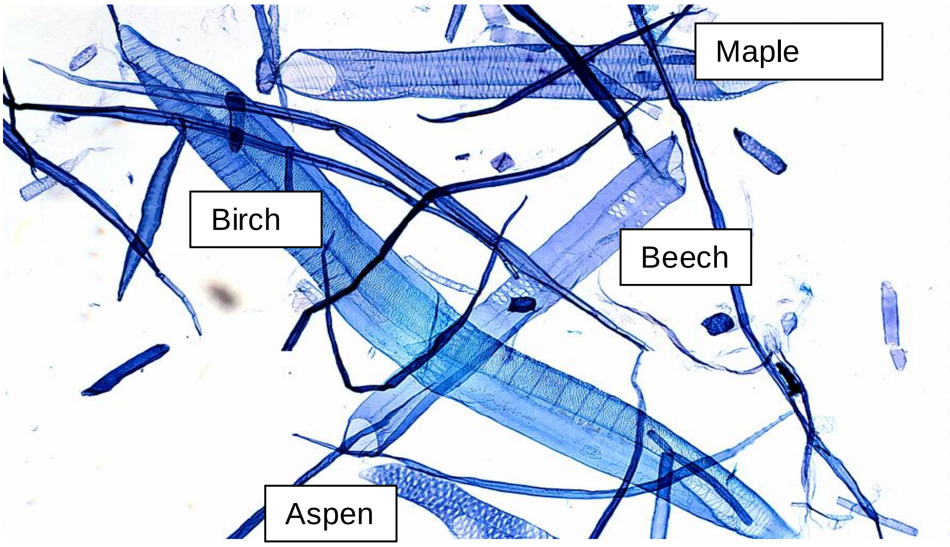
Eucalyptus vessel elements shaped as glazed clay pipes or little barrels



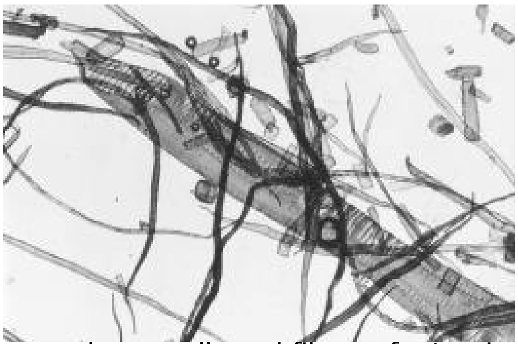
Vessel ducts interacting with radial parenchyma cells
(*Eucalyptus* wood radial section)



*Eucalyptus* vessels and their abundant pitting
(Photo kindness: Dr. S. CHINNARAJ - http://tnpl.co.in )

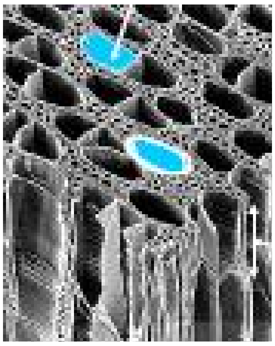



Vessels of different hardwood pulps (Source: PAPRICAN, undated)



Vessel element, parenchyma cells and fibers of a tropical hardwood tree (Source: CANFOR TEMAP, undated)

As the eucalyptus trees are very vigorous and require much physiological activity to guarantee this growth and forest productivity, the sap pumping action through the vessels is intense. To deal with this activity, the eucalyptus trees have developed small units or vessel elements, which are relatively wide and short. These little barrels are fitted in ia standardized and geometrical way and the structure becomes resistant and functional. In general, there are about 3 to 25 vessels or pores per mm² of eucalyptus xylem cross section. Some species have more vessels than other ones. There is also much variation between the dimensions of these vessel elements, but these vessels have mostly a diameter (or width) ranging from 60 to 250 μm and a length between 200 and 600 μm. Definitively, they are robust and wide elements, compared to vessel elements of other hardwood trees. The birch (*Betula* *pendula*, *Betula pubescens*, *Betula papyrifera*) woods have e.g. narrower (60 to 90 µm) and longer (400 to 700 µm) vessel elements.



Vessels and their areas (Source: Wimmer, undated)

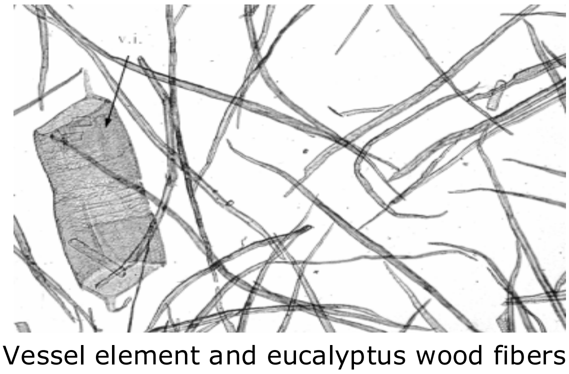
Admitting that there are between 3 and 30 (average of 8 to 15) pores or vessels per mm² of xylem cross section in eucalyptus trees and that their diameter ranges from 60 to 250 µm (average between 100 and 175 µm), it becomes simple to calculate the volume occupied by vessels in the eucalyptus wood. By means of very simple histometry techniques, based on photos or on image scanning, the areas occupied by vessels can be related to the total area of the section. Considering that the thicknesses of the removed slice of wood are constant both for the vessel section and the section of the wood remainder in the cross section, then the ratio between areas will be also the ratio between volumes.

By way of example, a table showing this can be constructed:

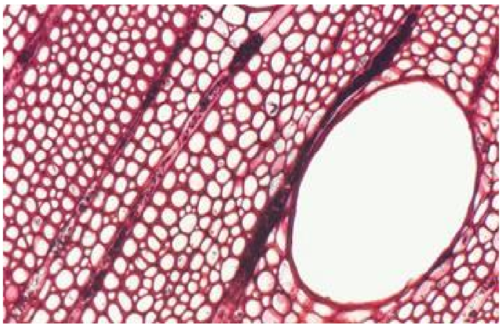
| Number of vessels per mm² | Vessel diameter in µm | Area of each vessel in µm² | Total vessel area per mm² | % of vessel volume in the wood |
|---|---|---|---|---|
| **5** | 75 | 4418 | 22090 | **2.2** |
| | 100 | 7854 | 39270 | **3.9** |
| | 125 | 12272 | 61360 | **6.1** |
| | 175 | 24053 | 120265 | **12.0** |
| **10** | 75 | 4418 | 44180 | **4.4** |
| | 100 | 7854 | 78540 | **7.8** |
| | 125 | 12272 | 122720 | **12.3** |
| | 175 | 24053 | 240530 | **24.0** |
| **15** | 75 | 4418 | 66270 | **6.6** |
| | 100 | 7854 | 117810 | **11.8** |
| | 125 | 12272 | 184080 | **18.4** |
| | 175 | 24053 | 360795 | **36.1** |

Therefore, there is a significant variation in the percentages of the vessel volumes in the eucalyptus woods. This is rather a function of the average diameter of the vessels than of their frequency. Vessel rich woods having very wide vessels in their diameter may have approximately 25 to 30% of their volume represented by a "open space" occupied by the vessels. In most commercial eucalyptus species and clones the proportion of vessels in the wood volume ranges from 10 to 20%.

The vessel wall is relatively thin, practically equal to the fiber wall thickness, between 2.5 and 5 µm, as it can be verified in the various figures presented till now. The vessel walls are similar in their formation to that of the fibers. They originate from initial fusiform cambium cells, in the same way as the fibers. The vessel walls have also 3 layers ($S_1$, $S_2$, $S_3$), but they are much more disordered than the fiber ones. The major reason for this phenomenon is the great incidence of pit openings in the vessel walls. This ends by misaligning the microfibril arrangement model in these walls. In spite of that, the microfibrils try to line up helicoidally to the axis of the cell. The chemical composition of vessel walls is similar in its chemical constituents, but there are some differences between fibers and vessels. Fibers are richer in cellulose, due to the thick $S_2$ layer. Vessels have proportionally more hemicelluloses in the holocellulose and for this reason they end by generating more hexenuronic acids (HexA) during kraft cooking. Their cells of large superficial areas also have more negative superficial ionic charges. On the other hand, there are indications that the vessel lignin is more hydrophobic, richer in guaiacyl (G) units than in syringyl (S). This S:G ratio may reach about 0.5 to 1 for the vessels, while reaching values ranging from 2 to 6 for the fibers.



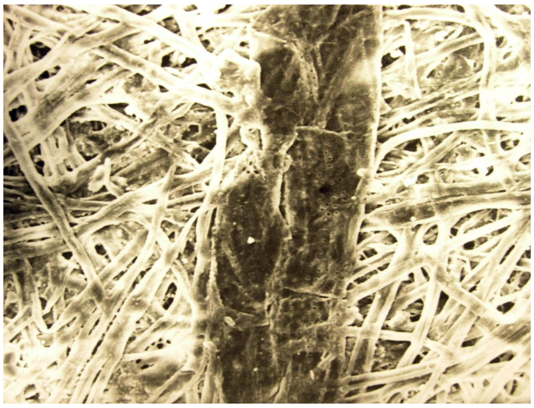
Vessel element and eucalyptus wood fibers



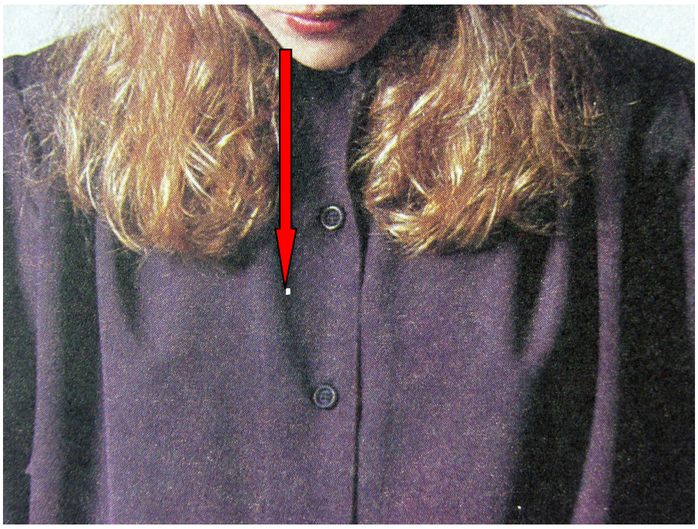
Fibers, ray cells and isolated vessel in eucalyptus wood cross section
(Observe the cell wall thicknesses)

In relative terms, the vessel wall proportion to the eucalyptus wood volume corresponds to 2.5 to 4%. The fiber walls (only walls, without the lumen volume) correspond to approximately 35 to 45% of that volume. Considering also their lumen, the fibers represent about 65 to 70% of the eucalyptus wood volume. Based on the vessel wall volume to fiber wall volume ratio, it can be concluded that there are about 10 to 15 times more fiber walls than vessel walls in the eucalyptus wood. It is evident that this is expressed in average values and in a generic way, just to understand the ratios between these anatomical elements. If a weight ratio is desired, the densities of these walls are required. The vessel wall apparent density is lower than the fiber one, which is due to the great presence of pits in the vessel walls. The cellulose microfibrils surround these pits and the orifices do not add weight to the assembled wall, nor do they add apparent density to the vessel wall. Let's consider by way of approximation that the vessel wall apparent density corresponds to 70% of the fiber wall apparent density, a figure that by way of approximation is a reasonable one. Based on these assumptions, it can be concluded that the vessel weight in a wood represents something about 3 to 5% of its weight, which is corrected by the presence of the walls of the parenchyma elements, equally present in the woods. This same ratio is valid for the pulps obtained from these woods. In other words, the vessel elements, although gigantic in their diameter, as compared to the fibers, represent approximately 5% of the pulp or the wood weight, at the maximum. However, in case a paper maker wishes to separate the vessel elements from their pulps in a fractionated manner, in order to avoid the problems they may cause to his paper, he will be neglecting a significant percentage of the weight of the pulp. For this reason, it is better to get used to the vessel elements and to find other mechanisms to reduce their eventual problems. We will see hereinafter that this is possible, both at the pulp and the paper mill. You have, but to want to do it, if it is cost effective.

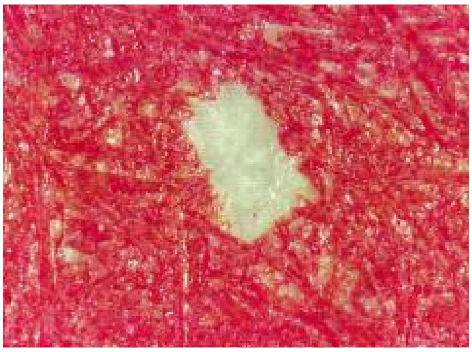
Vessel element with an optimum view of its pits
(Photo kindness: Econotech Services Ltd.)


Comparative view of the dimensional differences between vessels and fibers on the surface of an offset paper sheet

The vessel dimensions and frequency vary according to the species, clones and differences of the environments where the trees grow. There are a genetic and an environmental effect on these dimensions, but the arrangement is rather genetic than environmental. There are fast growing and low basic density eucalyptus species tending to have rather wide vessels (but sometimes not so numerous). *Eucalyptus deglupta* and *E.grandis*, having rather wide vessel elements with large diameters, are well-known. These large vessels favor the development of some characteristics of these eucalyptus trees and thwart that of other ones. For instance, in the pulp converting processes they are excellent to favor chip impregnation by the cooking liquor. Notwithstanding, the originated pulps with large vessel elements present more pronouncedly a defect known as vessel picking, when they are used for printing paper manufacturing.



"Vessel picking at offset printing



Vessel picking area at a printed paper surface
(Source: CANFOR TEMAP, undated)

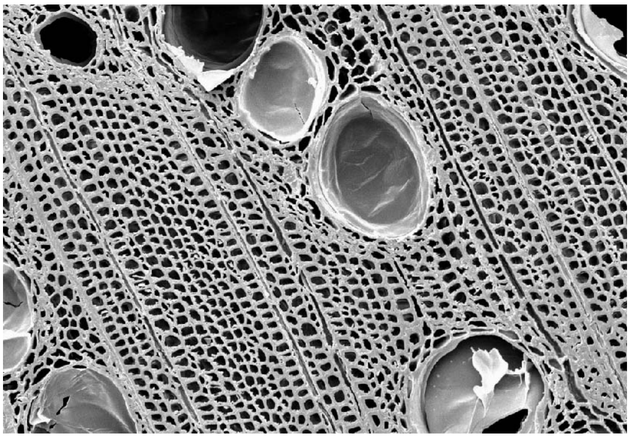
Other species or clones may even present a higher vessel element frequency or population, but as they may have smaller individual dimensions, the printing problems may be not so significant. The best vessel dimensions are those where their length to diameter ratio is equal to or higher than 8 to 10 i.e. long vessels with regard to their diameter seem to be and behave rather like fibers in paper manufacturing.

The vessel element distribution and their dimensions in the xylem have a profound influence on wood porosity, on its capillarity and on its capacity of transporting the sap in the tree. Highly productive, fast growing trees demand quick and abundant sap flows. Then, it is to be expected that the growth rate and the forest productivity are associated with the vessel frequency and distribution maps, as well as with the vessel areas in the eucalyptus woods. It would be very interesting if the forest genetic breeders and even the forest operation engineers could have these maps available, get acquainted with them and understand them, which would certainly help them to plan and to improve still more their plantations. After all, when we want to grow or to improve our forests, we need to understand the tree physiology for better growing and to form the wood.

Considering it all, since the vessels are so important for the sap (and nutrient) flow, they should be better studied with regard to their role in this forest physiology. Nowadays these maps can be much more easily constructed, based on the new and powerful tools and image analysis systems (for instance: Silviscan instrument associated with scanners and softwares for image interpretation).

Based on wood cross sections, at present, the histometric wood analyses can be easily carried out in all main directions of the tree (pith/bark or bottom/top). The modern image systems can detect and separate 4 classes of anatomical elements in the cross sections of the xylem: fibers, ray parenchyma cells, axial parenchyma cells and vessels. This separation is done as a function of the wall thicknesses, by the aggregates and cell distribution and by the empty openings (pores) in the vessels.

The presence of tyloses in the vessels is something that can be also monitored and included in these histometric maps, because when they appear - due to a natural condition and because it is required by the trees -, they cause problems for using the wood for cellulose. We will see hereinafter what are these tyloses and their implications.



Tyloses causing occlusion and closure in eucalyptus vessels

The correlation models between wood density, growth rates and silvicultural aspects of the plantations are not so easy to establish directly with the vessel frequency and distribution, because many analyses, many trees and genetic homogeneity (species or clones) are required to obtain good correlations. It is difficult and almost impossible to try to establish correlations between eucalyptus species not a bit alike and to draw conclusions about correlations between properties that could not be even correlated.

One thing is certain: for the same tree the vessel variation models are absolutely predictable. At any height of a tree being evaluated it is well-known that the frequency (number per $mm^2$) is much higher for the wood formed next to the pith. However, these vessels near to the pith, though they are more abundant, have a much smaller diameter than those formed by the cambium in the more mature wood, nearer to the bark. As the cambium of the tree becomes more matured, this cambium begins to form wider vessels and with lower frequency. This means that in a pith/bark variation model there is higher vessel frequency near to the pith and larger diameter vessels near to the bark. The total vessel area in the cross section is initially small near to the pith (5 to 8 $\mu m^2/mm^2$) and increases in the wood near the bark (15 to 20 $\mu m^2/mm^2$). However, this model is not a straight line increasing in pith/bark direction. As soon as the wood is no longer juvenile, the vessel area per wood section stabilizes at a certain level in $\mu m^2/mm^2$. When the tree reaches maturity and begins to form adult wood, the cells grow in length, become wider and present thicker walls. This is valid for fibers, as well as for vessel elements. The amount of parenchyma may eventually decreases. Due to this all, in the same tree, in its wood in pith/bark direction, the basic density increases, as well as the vessel diameters, even if the wood is thicker in the neighborhood of the bark. Remember that the vessel frequency decreases for the wood near to the bark. Then, it is usual that for a same tree, the thicker woods have wider vessels with a larger unit cross area (of the vessel itself). However, these vessels are in smaller numbers and the total vessel area is practically the same, keeping stabilized in terms of $\mu m^2/mm^2$ after the wood reaches maturity in the tree in question. On the other hand, as far as different species with different densities are concerned, the situation must be explained otherwise. A low basic density species, like *E.grandis*, has wide, long and abundant vessel elements, whereas a higher basic density species, as it is the case of *E.urophylla*, may have even a number of vessel elements which is higher or similar to *E.grandis*, but of smaller dimensions, both in length and in the cross area. As a result of this all it is not possible to state that there is a direct relationship between number of vessel elements and basic density when different interspecific clones or distinct eucalyptus species are compared. This becomes only more evidenced when thicker or less thick wood is compared within the same tree, either in bottom/top or pith/bark direction.

Nevertheless there are some paper making eucalyptus species having admittedly smaller vessel element population, as reported by some authors. Among them ranks *E.globulus* as a standout, which for this and other reasons, is acclaimed in Portugal for offset paper manufacturing by the companies of that country.

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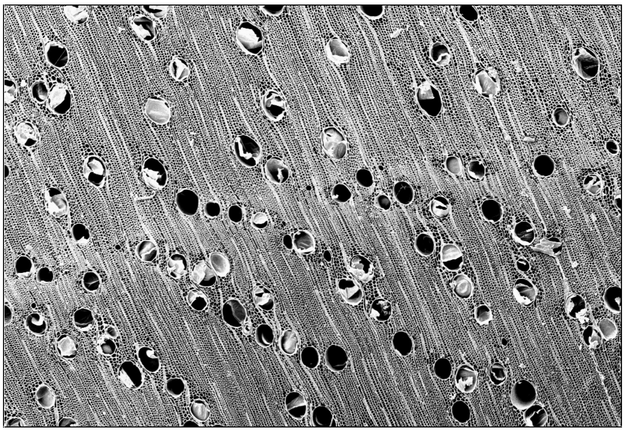
## VESSELS, PULPS & PAPERS

An easy way of identifying whether there is short fibered (hardwood) pulp in a commercial market pulp or in a stock following for paper manufacturing is to search for the presence or absence of vessel elements. It is very simple, just a microscope or even magnifying lens are required, since the vessels are relatively large elements, visible even with the naked eye.

The vessels represent a significant eucalyptus pulp weight percentage, ranging from 3 to 5%, as already seen. This is significant, but only a few technicians or scientists are really aware to this fact. It seems even that the vessels are some kind of a necessary evil or a misfortune that causes some trouble, but as the disturbance is not so great, a better evaluation is constantly postponed.

The vessels are very important both for the tree physiology and growth and the processes of wood conversion into cellulose pulp. Their presence in the hardwoods favors the chip impregnation process by the cooking liquor. As they are large and mostly hollow elements, they provide easy passage for the liquor to penetrate into the chip inside. In addition, the vessel communication with the adjacent cells (radial and axial parenchyma) through the pits allows the cooking liquor to migrate to the chip inside by using these ways of access. For these reasons, the hardwood chip penetration and impregnation by the kraft cooking liquor is rather favored. Vessel rich low basic density woods are more easily impregnated by the liquor. Thus, they can be more easily delignified and result in higher yield and lower reject content pulps. Evidently, there are also other factors involved, such as lignin, extractives and carbohydrate contents. Therefore, these relationships are generic inferences.

During the wood formation and structuration process, there is a moment at which the live and active xylem loses its function and ends by dying. This xylem to be deactivated must be “passivated” by the cells adjacent to it. Then these cells begin to form polyphenolic extractives, waxes, greases etc. and to fill the cell lumen with these substances. The first cells to be impregnated in this way are the vessel elements, since they are easy canals for the fungal mycelia penetration. Thus, the wood begins to form heartwood and to have greater defenses against degradation, decay and against the attack of predators (fungi, insects etc.). The vessels become occluded and plugged by extractives and this type of vessel closure is called tylosis. It is one more wisdom of nature, defending itself against the adversities. However, these tyloses make the chip impregnation process difficult and thus cooking woods from older trees is more difficult. Woods from older trees, having already a high amount of heartwood and being rich in tyloses, are more difficult to be converted into cellulose. Impregnation is worse, cooking must be more drastic, pulp yield is lower and the reject content increases, besides eventual later bleaching difficulties. These extractives getting into the vessel lumen are to a great extent little saponifiable. Therefore, they resist dissolution in alkaline kraft cooking. Thus, tylosis rich woods cause pitch problems more frequently in the pulps manufactured with them. Besides the presence of the abundant saponifiable and non-saponifiable extractives, tyloses are also rich in calcium salts, like oxalate and carbonate. This increases the possibilities of incrustations in digesters and pulp bleaching equipment.

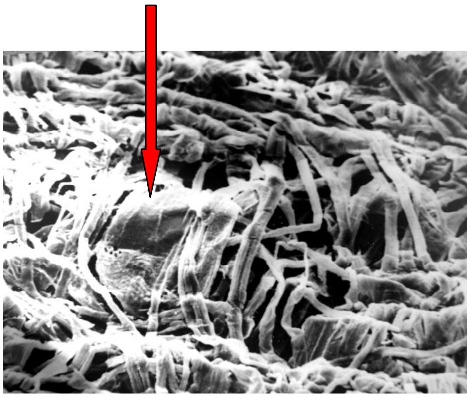


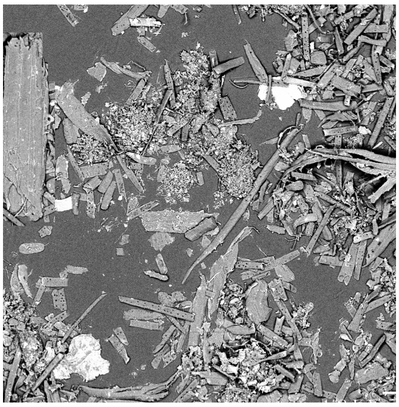
Cross section of eucalyptus heartwood wood very rich in tyloses

After pulp production, the vessel presence may or may not mean problems in using this pulp, depending on the paper grade to be produced. There are paper grades in which the vessel presence practically does not cause any troubles. This applies especially to papers manufactured from well-refined pulps, when the vessels end by collapsing and fragmenting. However, there are paper grades where the vessels are definitively a problem, either in manufacturing or in using this paper. The most notorious case of this problem is the phenomenon of vessel picking from the surface of printing papers when manufactured with little superficial sizing or coating. This occurs when the paper is being printed and the phenomenon is known as *picking*. The printing ink, as it is tacky, tends to stick to the paper surface and to pick loose or weakly bound particles (vessels, dust, pigments etc.). The press becomes dirty and the printing defective. Then, it is possible to observe areas where printing does not occur, because the particle (or the vessel) got loose, or else because the press was dirty and did not succeed in transferring ink to this dirty point, as from this dirt point to paper surface.

Vessel picked by the offset printing machine
(Source: CANFOR TEMAP, undated)

In the tissue paper manufacturing, the vessel gets still more easily loose when hardwood pulp from virgin market cellulose is used. When the tissue paper is made with recycled fibers, the vessels are already very fragmented and collapsed, so that the problem is decreased. Remember that the tissue paper sheets have low basis weights and are very thin, and for the best tissue papers the pulps are very little refined. Thus, the large vessels end by appearing on the paper surface and getting loose after drying. They may be present whole or in fragments in the well-known “dust”, very common in the tissue paper conversion areas. However, much of this dust originates also at the tissue paper roll slitting operations for manufacturing rolls, napkin sheets, towels etc. When the tissue paper manufacturer uses recycled fibers, the presence of fillers (kaolin and calcium carbonate) is also common in these dusts. The best situation is when the tissue paper manufacturer evaluates how vessel rich are these dusts. If the dust is very vessel rich it is better to recycle it to another paper grade, where more refining is applied.


Vessel element in a sanitary tissue paper sheet


Paper manufacturing generated dust (Source: PAPRICAN, undated)

Many technicians tend to mix vessel elements up with fines. Nevertheless, it should be remembered that the very definition of fines considers that to be so called the particles must pass through a 200 mesh wire, which means openings of about 70 $\mu$m. The vessel elements without refining are bigger than this dimension and do not pass through the wire openings. The vessel elements become only secondary fines when they are refined, get fragmented into smaller pieces and thus these vessel pieces can eventually pass through the 200 mesh openings.

Hardwood pulps are very much appreciated for printing and tissue paper manufacturing. Especially recommended are eucalyptus pulps, which delighted the industry of these paper grades because of their advantages both in the operational performance and in the product quality. In spite of the difficulties caused by the vessel elements, the paper making sector and the graphic sector have learned to deal with these problems, developing mechanisms to reduce them. There are no doubts left that the vessels do cause troubles, but the remaining eucalyptus pulp advantages are so fascinating for these paper grades that the problems caused by the vessels have not hindered a continuous increase in using these pulps, even because, as it will be seen hereinafter, several ways of alleviating these problems have been developed, reducing them to a level of tolerance.

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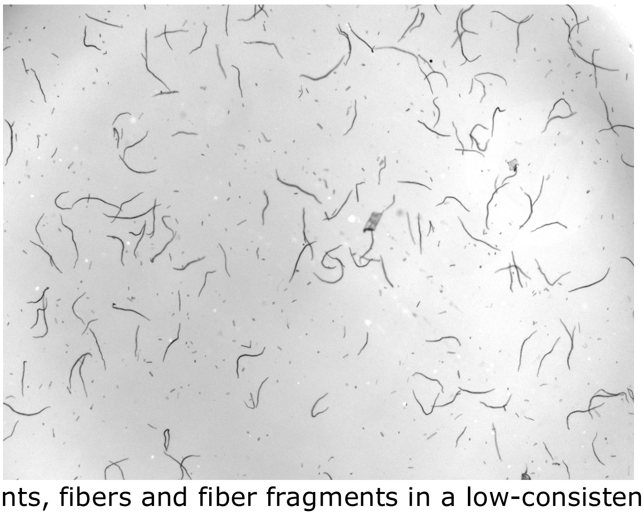
## MEASURING VESSEL ELEMENT IN PULPS

Pulps are mixtures of several kinds of very small sized but very abundant anatomical elements. Their constitutions in terms of distribution of these elements are very important, as the paper making performance depends on these components. Both the morphology and the populations of these constituents must be measured and serve as quality indicators of the pulps. For the hardwood pulps, as it is the case of eucalyptus trees, these constituents are the whole or fragmented fibers, the parenchyma cells and the vessel elements. All of them are elements coming from the xylem. The pulp contamination with cells of bark fed along with the chips ends by introducing also minor amounts of anatomical elements of phloem into the pulps, but these ones are definitively very little representative and hardly ever measured.



Fines, vessel elements, fibers and fiber fragments in a low-consistency pulp suspension
(Photo courtesy: Techpap , CTP Grenoble & Regmed)

The measurements carried out at the vessel elements present in the pulps basically aim to determine their population, their dimensions and the area projected to the plane of these elements. As the vessels are large anatomical components and occur abundantly, to find them and to measure them is not a difficult task. However, there are some peculiarities to know, in order to make no mistakes at these measurements. The most important of them refers to the vessel behaviour in suspensions. When a dry pulp is recently pulped, the vessel elements tend to float in the fiber suspension if the consistency is low enough to allow it. This occurs because they still have some air occluded in their lumen, as well as due to their shape of little rafts or little barrels. In case the vessel population measurement is going to be performed based on a sample collected from this suspension, non-representative samples may be collected if this floating detail of the vessel elements is not taken into consideration. Therefore, the analyst should stir the suspension very well prior to pipetting in the samples to be analyzed in the microscope. Otherwise he runs the risk of underestimating his measurements.

At present, the vessel element dimensional measurements can be carried out by projecting them, by using the microscope or binocular adapted to a micrometric ocular, by using scanners adapted to image analyzers, as well as by using specialized fiber analyzers (Morphi, Kajaani, FQA, etc).

The vessel elements, as they are large and appear to the microscope in the form of a rectangle, have as characteristic measurements the following dimensions:

- Diameter or width,
- Length,
- Surface area (measured as though it were a rectangle by the product between length and width),
- Cell wall thickness.

Based on these values, some fundamental relationships are established between them, such as:

- Wall fraction (wall thickness to vessel radius - percentage ratio),
- Felting index (vessel element length to width or diameter ratio).

The most characteristic values for these dimensions and ratios in eucalyptus vessel elements are as follows:

- Diameter or width: 60 to 250 μm
- Length: 150 to 600 μm
- Surface area: 0.01 to 0.15 $mm^2$
- Vessel cell wall thickness: 2.5 to 5 μm
- Wall fraction: 3 to 15%
- Felting index: 2 to 10

It was already mentioned that the fibers represent from 65 to 70% and the vessels from 10 to 30% of the eucalyptus wood volume. In weight, the vessels correspond to 3 to 5% of the weight of the wood, or by extension of the pulps. Therefore, another important characteristic is the knowledge of the ratio between the amounts of vessel and fiber in a pulp. The vessel element population in a eucalyptus pulp ranges from 25,000 to 150,000 elements per gram of oven dry pulp, whereas the fiber population is far higher, ranging from 12 to 30 million fibers per gram of oven dry pulp. Considering these dry pulp based populations, as well as the vessel and fiber weight ratios, it is possible to establish the average weight of an individual eucalyptus pulp fiber or vessel element:

- Approximate eucalyptus fiber weight: 0.02 to 0.06 µg
- Approximate vessel element weight: 0.25 to 0.7 µg

In numbers, the fiber to vessel ratio in eucalyptus pulps is one vessel element corresponding to an amount of 70 to 350 fibers. The most usual values are 1:100 to 1:250. When a selective fractionation is caused in order to remove vessels from the pulp, the fiber rich fraction presents a ratio of 1:2,500 to 1:5,000, while the vessel rich pulp fraction presents a ratio of 1:15 to 1:25.

The fiber and vessel populations of a pulp are easily counted by the fiber analyzers existing at present on the market. However, these measurements can be carried out even in labs having no such equipment. It is enough to have conventional pulp evaluation lab equipment such as: TAPPI type sheet former, drying stove or furnace, preferably 2 cm wide Scotch type transparent tape, microscope slides, magnifying lens or binocular or optical microscope. The methodology consists in the following:

- Get a representative sample of the pulp to be evaluated.
- Disintegrate the stock in water, so as to produce a well-diluted suspension of 0.2% consistency.
- Keep this suspension under strong vortex stirring.
- Optionally, dye this diluted pulp with safranine.
- Collect a sample of this suspension which is enough to form a web of 1 g/m$^2$ of basis weight. Obviously this web does not exist as a web, but as a network of anatomical elements well-distributed on the web former wire. Is it impossible to take it off in the form of web.
- Remove the wire from the former and take it to a drying stove, to dry the 1 g/m$^2$ web.
- After drying, firmly stick 2 cm wide Scotch tapes to this web, so that the anatomical elements adhere well to the tapes, without leaving anything on the wire when these tapes are removed.

- Cut 5 cm long tapes and glue each of them on a microscope slide. Each 2 cm x 5 cm piece measures 10 cm² in area. As the web basis weight was 1 g/m² or 1,000 mg/10,000 cm², every 10 cm² of tape contain a weight of 1 mg of dry pulp retained.
- With the aid of 10X magnifying lens or a microscope, count all vessel elements present on each slide. Count several slides (repetitions). Let’s consider as N the average number of vessel elements counted in 1 mg of pulp.
- The vessel element population per pulp gram is calculated by Vessel Population = 1,000 x N

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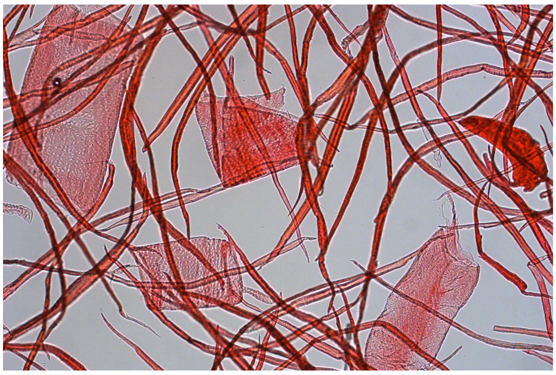
## PROPERTIES OF PULPS RICH ON VESSEL ELEMENTS

Quality evaluation of pulps containing just vessel elements is rare in literature. The great difficulty is the suitable vessel and fiber fractionation. To separate fibers and vessels is something difficult, but it is feasible. The great difficulty associated with it is that when fractionating them from each other according to the technique used the fines are also lost. This will affect the results, as the fines are very important for the fiber bonding processes in the pulps, whether they consist of fibers or vessels, or else contain both of them.

There are several ways of separating fibers and vessels. Some of them work well with a pulp type and not so well with other ones. It is the case of using hydrocyclones, which are rather viable for pulps with large and little barrel-shaped vessels, as it is the case of eucalyptus pulps. The best way of separating vessels from a pulp is by flotation of a suspension recently formed from a previously dried pulp. This suspension should have very low consistency (about 0.5% or less). The vessels tend to float under such conditions, as they endure the action of some occluded air, which favors the little barrel floating, while the thicker fibers sink in the suspension. Then, it is enough to remove the vessel elements from the surface and to create a vessel element rich pulp. To further purify this pulp, it is possible to pass the pulp thus produced through a fiber classifier with a 65 mesh wire (opening of 212 µm). The vessels are retained on this wire and the fines and fiber fragments that possibly floated are also eliminated, passing through the wire. The greatest difficulty is to separate some fibers still present together with the vessels. Therefore, to evaluate vessel rich pulps is already a feat. With this type of methodology 70% vessel purity or more can be reached in vessel rich pulps (vessel to fiber ratio of 1:10).



*E.globulus* pulp – vessel element rich fraction, obtained by hydrocyclone fractionation (Source: Panula-Ontto, 2007)

It is evident that time is required to obtain a reasonable amount of pulp to evaluate refining and quality of this pulp. The continued repetition of the flotation procedure may provide the amount of pulp required for the laboratory evaluations. The hydrocyclone process may be also effective and is quicker, but does not work as well with all types of pulps.

The major characteristics of the pulp containing almost 100% of vessel elements (or rich in them) are approximately as follows:

- Fast refining, since the vessels collapse and fragment very quickly by applying power at refining.
- Quick loss of the paper bulk and fast increase in air resistance, which is due to the vessel element collapse. The vessel rich pulp is so sensitive to this collapse that even the non-refined webs lose paper bulk only by the wet web pressing action.
- Relative tensile and burst strengths and stretch .
- Low tear strength.

The vessel rich pulp quality depends to a reasonable extent on the characteristics of these vessels, as e.g.: shape, size, length to diameter ratio, cell wall thickness, chemical vessel composition, amount of pits, etc. There are hardwood species having narrow and long vessels, very similar to the fiber shape. It is the case of *Betula* and *Populus*. These vessels end by having behaviors very similar to those of hardwood fibers. As to the eucalyptus vessels, which are short and wide, their flattening is inevitable and the strengths of these vessel pulps are not high.

The greatest surprise when evaluating pulps of almost 100% of vessels is precisely the analysis of the pulps of almost 100% of fibers.

Curiously, refining these pulps without vessel elements is more difficult and development of their bonding properties is slower. The vessels, when flattening and fragmenting into debris in refining, develop bonding and bridges between pulp constituents. It is curious that in spite of complaints about the vessel elements, they end by proving their importance in hardwood pulp refining. Nature shows its wisdom once more. Nothing exists by chance, vessels are important for the tree physiology, but also play their part for the hardwood kraft pulp production and quality.

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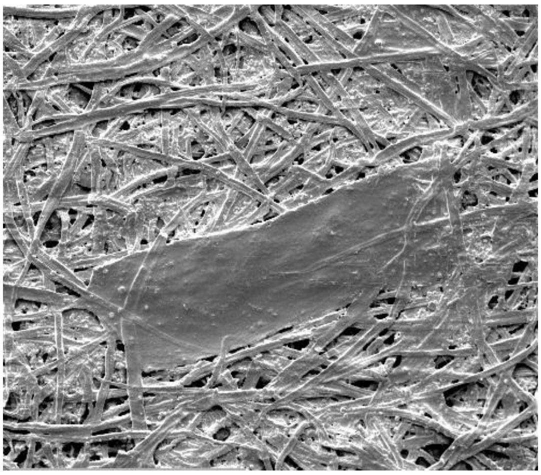
## THE PHENOMENON OF VESSEL PICKING

We already know that the phenomenon known as vessel picking is common in printing papers containing hardwood pulps. As a function of their bulky shape, the vessel elements are not very well retained in the paper web network. In paper grades of low pulp refining level the vessel elements that are on the web surface may be picked from it. This occurs especially in printing papers, at the very moment they are being printed.

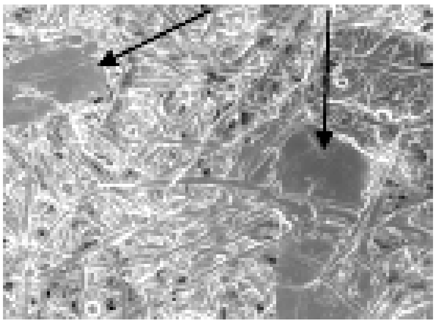
The pickings or pick-outs can be defined as printing interference's or defects resulting in an unprinted area on the paper and dirt in the printing machines. The fibrous materials (vessels, slack fibers, paper sheet dust, fiber aggregates etc.) adhere either to the blanket or to the printing plates. There, as they are hydrophilic, they accept water from the fountain solution in the printing machine. Thus, they do not impregnate with ink, as they become oleophobic. This causes repetitive flaws when printing the following sheets. The interference is characterized by the repeated printing of the same defect on hundreds of sheets, always in the same sheet location.

Not always the vessel element picking is complete. Sometimes the vessel gets slightly loose but is not picked. This is enough for the ink to differently penetrate into the paper surface at that point. There will appear an area with "halftone" printing, not so well-printed at that point.



Huge vessel element on the printing paper surface
(Photo kindness: S. Y. Kaneco)

At other times, the vessels are rather large. When coated with starch at surface sizing and after enduring a calendering process, they become smooth as a plate grafted onto the paper surface. The printing may adhere well to them, but the printed area becomes filled up with small brighter spots, which correspond exactly to the vessel elements. This defect is called "star ground", precisely because of the gloss imparted by the vessels in a dispersed way on the sheet. As the vessels are rich on pits, the ink easily penetrates into them. Then, there is an optimum ink acceptance by the vessels in the paper. In addition, the morphology differences between vessels and fibers highlight the vessel elements well enough. For these reasons the "star ground" defect is relatively common in printing.



Printed sheet showing vessels covered with inks and therefore more glossy
(Source: Alves, 2005)

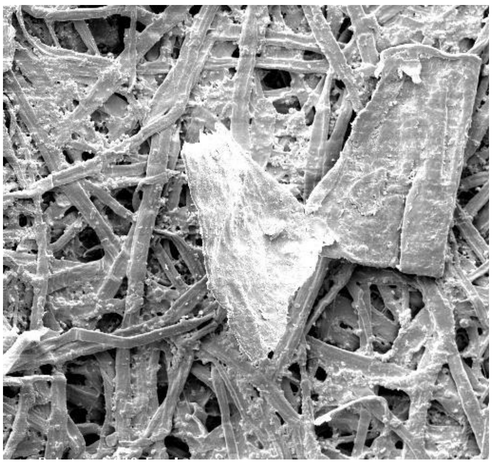
The vessel pick-outs are visible with the naked eye, as well as their contaminations on the printing house blankets. Therefore, using a little 10X magnifying glass or lens are very useful, both for the paper maker and the printer.

The vessel picking and the vessel adhesion to the blanket will depend very much on the ink tack. If the tack exceeds the vessel element bonding strength in the sheet, these vessel elements will be picked out of this surface, each of them leaving a little spot or hole in that place or causing a printing defect corresponding exactly to its shape. At that point there was a lack of ink to cover the lower part of the place where the vessel got loose. Picking is higher for papers with low surface strength and low wet strength, for this reason the problem is more common at wet offset printings.

Then the picked out vessels may stick to the printing machine plates and to contaminate these plates as dirt, causing the printing process additional troubles. The dirtier the blanket, the worse and more abundant will be the defects left by it in printing. The problem will become worse up to the moment the operation will have to be stopped for blanket cleaning. Thus, the printer will lose time, production and productivity, and his costs will increase. Also his temper will not be absolutely favorable at that moment, especially if cleaning is often required.

It must be clearly understood that picking does not occur only when the vessel gets loose, leaving that area without printing because of that loosening. This is the initial step of the problem. The picked out vessel, when it sticks to the offset printing machine blanket, triggers a continued series of defects in the following sheets of the printing process. This repetitive defect is as though the vessel would be stamping blank its shape on the next sheets being printed.

When the vessel is picked out, the fibrous nature of the paper, without any covering, appears right below it on the paper sheet.

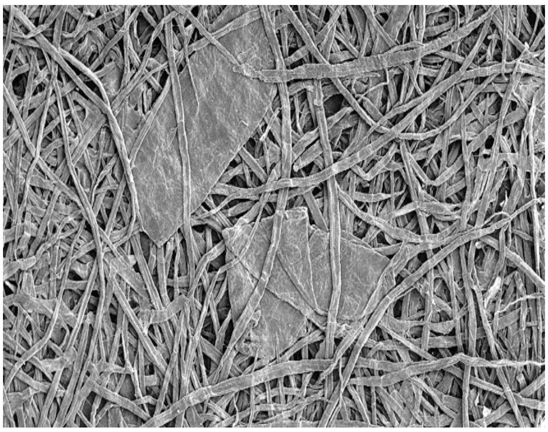


Clearly collapsed, fragmented and weakly adhered vessel elements on a printing paper surface (Photo kindness: S. Y. Kaneco)

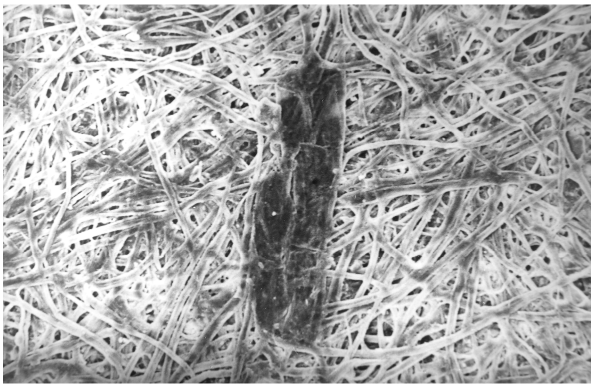
In coated printing papers often the coating itself gets loose instead of the vessel element. In case the coated paper surface strength shows weak points at the coating adhesion, pick-outs may occur because of coating points getting loose. This may be due either to the low surface strength of the paper or to binder insufficiency in the coating formulation. These little coating pieces stick to the blankets in the same way as the vessels, causing the same type of defects. This coating defect can be differentiated from the vessel defect in the following manners:

- By collecting blanket dirt samples and analyzing them with the microscope.
- By the more irregular shape that is printed as defect. The vessels are usually rectangular and these coating pick-outs present an irregular form.
- By observing the printed paper. When the coating is picked out, the fibrous matrix below the picked area appears still with coating, contrary to the vessel picking. In the paper coating the vessels become only impregnated on their upper surface. The lower portion connected to the fibrous matrix does not show coated with the coating ink.

The best way of identifying these problems is using a microscope or stereoscope with low angle lighting.



Vessel elements in the paper web, interacting with fibers, but equally easy to be picked out of the web



Vessel element on a printing paper surface

Besides the vessel and coating pickings there are also the dust and fiber or fiber aggregate picking. All of them end by occurring in the paper, this is almost inevitable. The dust occurs on the paper sheets, as it is generated at the very moment the sheets are cut. However, even when advanced are the cutters, a small environmental dust release always occurs in the paper conversion areas. The paper maker should do his utmost to minimize this dust presence on the paper surface. When the paper is dusty it will also dirty the blankets and give rise to the picking defect. It is always interesting that both the printer and the paper maker have recourse to a black flannel to be passed on the paper at random, to see whether it has dust. It is like a simple but effective quality control.

Fiber aggregates or bundles may come with the stock during paper manufacturing. They are small pieces of pulp that have not been completely pulped or defibered in the pulper. There are also fiber aggregates getting loose from the paper machine dryer cylinders. Fibers getting loose from the web may stick to the smooth dryer cylinder surface. Eventually, they get loose from the dryers and adhere to the paper surface. At the subsequent calendering operation these aggregates are strongly flattened on the paper surface and connect weakly to it. In the printing process they may get loose, as it happens with the vessels.

Since the vessel elements are rectangular and suggest a flattened plate in its collapsed form, the vessel pick-outs are easier to be identified than the remaining ones. It is very important to understand the actual cause of the problem in order to be able to deal with it or to prevent it more suitably.

Most defects known as vessel pick-outs are as a matter of fact repetitive and due to the refusal to receive ink and to transfer it to the paper by the vessel picked from the web at a previous moment. A single picked out vessel dirtying the blanket may leave its marking on some hundreds of sheets printed thereafter. This defect will continue until:

- The vessel gets loose from the blanket and comes back to the paper.
- The vessel becomes oleophilic by getting in contact with the printing ink so many times. Thus, little by little it will absorb ink and the defect will weaken until disappearing, even if the vessel still remains on the blanket and in the same position.
- The printing machine is stopped by the printer for cleaning. The dirtier the blanket becomes, the worse grows the problem, so that it may come to a point at which the only solution to the problem is cleaning the blanket.

It is very common to use a Scotch type transparent tape to remove the printing machine blanket dirt for observation purposes. Although this is not always possible, it is a tool used by the printers to control cleanliness and to identify the causes of the contamination. The tape always brings fibers, vessel elements, pigments, coating particles, ink etc. The vessel elements, as soon as they are picked out, appear as white particles on the blanket. Evidently, when the paper color is white.

The problem of surface vessels picked out of the paper is more usual for papers manufactured on ancient Fourdrinier machines with open low turbulence headboxes and less efficient wet press sections. Pressing itself is very useful to achieve better vessel adhesion to the paper sheet and higher vessel flattening on it. As the vessels can float in these ancient headboxes and paper machines, they may be rather located on paper felt side, which is even worse. It should be reminded that this is the paper side with lower surface strength. On the more modern forming machines, with twin wires and pressurized headboxes with good turbulence, this preferential vessel distribution on one paper side has no longer occurred.

A great question remains at present: how does the vessel distribution occur on the surface and in Z direction (thickness) of the paper? Is it left just to chance? Or is there a hydrodynamic model orienting a preferential distribution? As the vessels are elements definitively different from the fibers and the pigments used for paper manufacturing, there is no doubt that they should behave in a different way with regard to the forces applied at this type of manufacturing. However, very little is known on this matter to date.

Knowing the vessel population per gram of paper, the number of vessel elements present in a given paper area is easy to estimate. What we do not succeed in estimating is how these vessels are distributed in Z direction of the paper, or in its thickness.

Let's assume for instance an eucalyptus pulp with a population of 100,000 vessel elements per o.d. gram of pulp. An offset paper of 75 g/m² has about 30% fillers plus other chemical additives and moisture in its composition. Therefore, the pulp amount is approximately 52.5 o.d.g/m². Then these 52.5 dry grams of pulp contain 5.25 million vessel elements, which represents this vessel amount per square meter of paper. The fiber population, in case it were 25 millions per gram, would cause this paper to contain 1.31 billion fibers per square meter. Then the vessel to fiber ratio would be 1:250. The average thickness of a paper like that is about 100 µm. The vessel walls are on average 4 µm thick. Let's consider that when the vessel collapses its average thickness (vessel) may be equal to 10 µm. Therefore, in Z direction of the paper there will be 100 µm of thickness to place 10 µm thick lying elements. Space enough for these 5.25 million vessel elements to locate and to arrange themselves within the square meter of paper.

In Brazil, a great producer of pulp and printing paper from eucalyptus fibers, the refining degree for manufacturing these papers is high, ranging from 35 to 45º Schopper Riegler, because the practice in the country is to use 100% eucalyptus pulp, without softwood mixture. To impart the necessary strength to the paper web during its traveling through the paper machine, the pulp is refined at these levels. For this reason, the vessel elements become rather damaged and collapsed, thus minimizing the vessel picking phenomenon. In case refining degrees are lower, as it is practiced in Europe or in the United States of America, the picking problem would be greater.

It is only with much refining, vessel fragmentation and their collapsing that the printing paper surface quality can be homogenized. In an optimized situation for vessel picking, the sheet smoothness is higher, the roughness imparted by the vessels is minimized, the vessel fragment is better bonded to the fibers, and the picking problem is reduced. Unfortunately this cannot be carried out for most printing papers. An excess refining impairs paper opacity, porosity, dimensional stability and bulk. Alternative ways of minimizing the vessel element problem will be discussed later on in this chapter.

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## FACTORS CAUSING VESSEL PICKING VARIATION

We know that eucalyptus fibers are very similar to each other. Their diameters and lengths are very close, even in very distinct species of the *Eucalyptus* genus. These fibers form excellent paper webs. They fit well together and provide good paper web consolidation and formation. This allows the eucalyptus printing paper sheets to produce rather uniform and contrasting printing points with good ink retention. This occurs when they are printed in the places containing only fibers and fillers. In the places where there are vessel elements the ink changes the way of adhesion and spreading and the printing points become more irregular and distinct. Thus the printing quality worsens. It is a usual phenomenon with hardwood pulps. But this is no sound reason for banishing hardwoods from the printing paper manufacturing; on the contrary, they are loved for this utilization, as the other advantages they offer are far more important: formation, opacity, porosity, bulk, surface smoothness and purchasing price.

The vessel elements, which are large and short, have many pits in their walls. For this reason the pits provide easy access both to ink and water at wet offset printing. The water promotes a hydro-expansion in the vessels, which is different from that occurring in the fibers. This begins already to contribute to vessel slackening on the paper sheet surface. On the other hand, as fiber walls have much less pits than vessel walls, ink and water penetrate differently into the paper sheet, in the proportion as they are wetting one or the other of these anatomical elements. In case the printer will look for a quick drying ink he will reduce this ink penetration difference, but will cause another one, which is the easier vessel picking by quick drying inks. Picking is favored by quick drying inks, as well as by very tacky inks.

Therefore, there are several important factors governing pick-out occurrence to a higher or lower extent. Summarizing, they would be the following ones:

- Vessel element dimensions and morphology: length, diameter or width, surface area.
- Vessel element population in the pulp.
- Vessel to fiber ratio.
- Types of fibers: high or low coarseness, for instance.
- Vessel element refining stage.
- Paper manufacturing technologies: headboxes, paper machine, surface sizing, coating, wet pressing, calendering, paper cleanliness, converting etc.

- Paper quality: surface smoothness, fiber bonding and vessel bonding, strength in Z direction of the paper, surface strength, superficial ionic charge etc.
- Printing machine characteristics: speed, temperature, fountain solution and ink supply, ink type, equipment cleanliness etc.
- Vessel to ink ratio.

The vessel dimensions and morphology depend much on the eucalyptus wood being used. There are species with larger and abundant vessel elements *(E.grandis* and *E.deglupta*). *E.grandis* fibers have lower coarseness, which causes quick raise of strengths and fiber bonding with the stock refining. This contributes to the reduction of the problem with regard to its pulps, as the large vessels end by being well-grasped by the fibers in the web. Sometimes, even a large and short little barrel type vessel pulp ends by having less problems than another pulp having smaller and less abundant vessels. This may occur if the wood is a high-density one and the pulp of higher coarseness, with thick-walled fibers. Such pulps have a lower fibrous population and in itself, each fiber is heavier than the corresponding ones of the low coarseness pulps. Thus, some undesirable situations may occur:

- the fiber to fiber and fiber to vessel bonding is lower and more difficult to achieve;
- the vessel to fiber ratio shows smaller numbers of fibers for each vessel element;
- the paper surface is rougher and weaker, which favors pick-outs.

Older trees, with higher wood density and thick-walled fiber proportion cause these situations, since their pulps have higher coarseness. It is recognized by literature that vessel picking problems are greater when woods of older forests are used. It is also well-known that the problem occurs more frequently when the pulp mills use old, semi-decayed chips. These chips produce weaker pulps, less capable of retaining the vessels by bonding in the paper body.

Anyway, as already seen, improving fiber bonding is good to reduce vessel picking. A good remedy for this problem, but undesirable for paper opacity, bulk and porosity.

The vessel element population of a pulp is a good indicator for its quality in this respect, so that it should be tried to work with pulps of lower vessel populations and vessels of smaller dimensions. This is something the paper makers strive very much for. The vessel to fiber ratio modification may be even artificially obtained by pulp fractionation.

A low vessel population in a pulp (whether occurring naturally or by fractionation) may result in the following qualitative alterations in the characteristics of such a pulp:

- higher average length of the total anatomical elements;
- lower average width of the total anatomical elements;
- higher fines content;
- higher pulp coarseness;
- higher pulp viscosity, since the vessels are in general much more degraded by the action of cooking liquor penetration itself;
- lower xylan content;
- lower hexenuronic acid content;
- lower content of amorphous hemicelluloses in the pulp, since the vessel elements have a higher proportional hemicellulose content in regard to the holocellulose. This affects the pulp hydration and its ionic charge. With lower hemicellulose content the pulps hydrate less and have a lower ionic charge due to the lower proportion of carboxyl and carbonyl groups.
- higher porosity of the formed paper web, due the fact that the vessels collapse and increase the web resistance to air passage.
- higher absolute value of negative superficial ionic charge, probably because the vessel removal removes a certain quantity of lipophilic extractives contained in the vessels.
- smaller specific vessel surface in relation to the specific fiber surface;
- less difficulties to remove the water present in the paper web, which requires a lower steam consumption;
- lower reactivity with the printing ink and lower ink pigment adhesion. The vessels in themselves do not have any problem to accept the printing inks. They are more reactive in respect to the inks. For this reason they adhere more intensely with the high tack inks.

Consequently the fibers/vessels/inks/water relationships are very important. They must be understood, monitored and optimized. This is very valid for each paper grade and ink and printing machine type.

On the other hand, printers know very well which are the main control points to minimize pick-out problems:

- Printing machine speed: there is a critical speed after which the problem increases. It is typical for each printing machine and for each paper grade. It is the main source of printers' complaints with regard to the paper. If the paper being used requires a lower speed the printer will certainly not like it.
- Ink tack, which can be dealt with by the printer by using solvents and diluents.

- Ink drying speed, which can be also corrected by the printer.
- Fountain solution quality and quantity.
- Blanket cleanliness.
- Number of sheets printed per run, between two blanket cleaning operations.
- Environmental conditions. It is well-known that the problems become more evident in winter, when inks become tackier and temperature differences between paper and printing machine are higher.

Vessel picking problems were initially deeply felt by the printers in their graphic houses. The solutions searched by the paper makers in refining and in the surface sizing helped to reduce this problem to tolerable levels. More recently, new offset machines, faster and printing more colors at the same time, have made their appearance. Thus, the problem has reappeared more deeply. Fortuitously there are new mechanisms the pulp and paper manufacturer can have recourse to in order to minimize the problems.

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## MEASURING THE VESSEL PICKING

Pick-outs can be measured on the papers after printing by observation and counting either with the naked eye or with magnifying lens. The results can be presented in numbers per paper area. The printing quality evaluation must be always based on using large printed areas and on industrial printing machines. It is also interesting to work with an evaluating panel of persons to avoid subjectivity. Some printing companies have special printing machines for testing purposes, in order to check the quality of the papers purchased by them.

Since pick-outs have different causes, it is important to supplement the count by microscopic evaluation. It is also important for the printer to know what is causing the problem and how intensely. It is important as well to separate the pick-outs types, so as to allow him to take actions instead of just complaining.

At present the use of scanners with resolutions ranging from 600 to 4,800 dpi has become very popular to measure the pick-out area and shapes. Scanners with very high resolution (4,800 dpi) are more precise, but generate too heavy files, which makes the trial operation slow. The use of scanners of 1,200 dpi can be adapted and calibrated without any quality problems to the results. They make possible using normal PCs, as file sizes and processing speed are suitable for them. There exist softwares to analyze and to interpret the scanned images. One of these softwares is Image J, which can be downloaded by the Internet, free of charge. It is a software in the public domain of no cost for everyone who makes use of it (http://rsb.info.nih.gov/ij/index.html).

The printer is also interested in evaluating material adhered to the blanket and to the printing machine presses. To remove that dirt he may use a Scotch type transparent tape. If this is not possible, he can collect the dirt with a cloth with solvent, separate it and thereafter take it to the microscope for evaluation. Although these vessel elements represent from 3 to 5% in eucalyptus pulps, when this material is collected from the blankets the vessel element proportion reaches from 40 to 50% of the total weight of the contaminated dirt. This shows the vessel element preferential adhesion to the printing machine blankets.

Besides the printer, the paper maker must also evaluate the picking potential of the paper grades he manufactures. He also needs some quality indicators to orient his corrective actions as required. The most usual equipment for these tests by the paper makers is the traditional IGT measuring lab instrument.


IGT measuring instrument for printing and vessel picking tests

The instrument has been developed for a great number of measuring situations, among which are the pickings. It is possible to perfectly count the picked vessel elements in a given paper area submitted to the IGT printing test. Sometimes the apparatus is used with a smaller amount of ink, to make easy the observation and the counts. The most usual procedure is to carry out the test with 20 mm wide paper strips. In general the vessel counting is referred to an area which can range from 2 to 20 $cm^2$, depending much on the numbers of counts. If this number is too high, a smaller area is used. There are cases where the results are reported for 20 $mm^2$ of area. The most important thing is that the counted number is comprised between 10 and 200, to render the test more practical and impart a higher quality to it.

The strips tested by the IGT may be dried in a stove and thereafter carefully brushed with a brush, in order to further improve the vessel visibility for counting purposes.

The IGT instrument measures small areas. It is very useful for the quality control by the paper maker, but for the printer what really counts is testing with industrial or semi-industrial printing machines.

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## MINIMIZING VESSEL PROBLEMS BY PULP AND PAPER MANUFACTURERS’ ACTION

There are several ways proposed for minimizing the vessel picking problem. When manufacturing their products the pulp and paper manufacturers are timidly adopting some of them.

The solution of the problem depends on a good interaction between some sciences such as:

- Paper physics;
- Paper surface chemistry;
- Technological paper manufacturing processes;
- Fiber and vessel hydrodynamics;
- Separation of solids in a liquid medium.

Pulp manufacturers have other alternatives to deal with the problem, that starts in the forests. In partnership with the forest area, the forest breeding programs may perfectly include this kind of selection parameter. They must search for trees with smaller dimension vessels, with a lower population and a lower proportion in relation to the fibers (vessel to fiber population ratio). The pulp manufacturer can also better select his woods for supplying the production process based on separation criteria of vessel element richer or poorer woods.

As far as paper manufacturers are concerned, they have more options. Let’s mention the following among the most effective ones:

- Paper surface sizing;
- Pulp refining;
- Using special adhesives for the paper surface;
- Vessel element fractionation;
- Vessel element passivation.

In any of these situations, one will be always trying to improve the vessel element bonding on the paper sheet surface, so as to make their removal more difficult. All these actions represent costs for the paper manufacturer, so that he must balance well what to do and compare his options. As a function of this, and within a logical coherence, the paper maker has been trying to deal with the surface sizing of the paper and the pulp refining, in order to enhance the surface strength of the paper without losing other properties desired for the printing paper.

The printing paper surface strength is a function of some fundamental aspects in paper engineering:

- Stock refining;
- Surface sizing (quality and quantity);
- Quality and quantity of the starch used in the stock;
- Starch preparation quality;
- Pulp quality;
- Applied proportion of fillers affecting the fiber bonding;
- Coating quality of coated papers (types of binders, coating amounts in grams of coating ink per square meter of paper etc.);
- Coating base paper surface quality.

## SURFACE SIZING

Suitable paper surface sizing is very important. By applying surface starch to fibers and vessel elements, they get better bound and their removal becomes more difficult. The starch solution penetrates a little from the surface into the paper thickness. It does this through the paper porosity and by the fiber and vessel pits. Within certain limits, the larger the application of this starch solution, the better the penetration and the more bound the paper surface becomes. However, an excess of starch application reduces opacity and renders the paper too rigid.

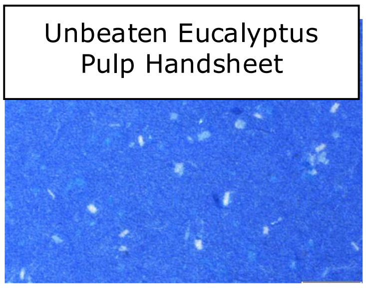
Not only the quantity, but also the quality of the starch and of its preparation is important. Tests carried out with manioc, corn and potato starches, as well as cationic starches, show that depending on the situation one or other type is favored. The associated use of CMC – carboxymethylcellulose – of low viscosity has been also successful. The binder improvement in coated papers also deserves a special attention. The purpose must be always to enhance the surface strength of the paper.

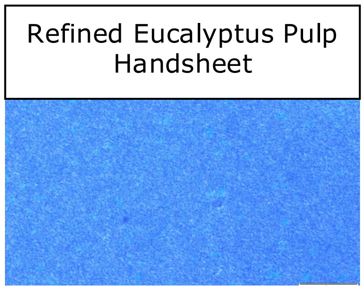
There are some companies applying a starch mist to the wet web surface in the couch roll neighborhood. Thus the paper surface strength is also further improved.

## PULP REFINING

When the paper maker uses hardwood and softwood mixtures, the first measure to be taken is the separate refining of these two types of fibers. Thus, he will be able to provide optimum conditions to each of them and to achieve the best refining for each pulp. Not only strength development is expected by refining the pulp. Among other things, it is also desired to further bind the vessel elements to the paper web.

Refining has definitively an important effect on picking reduction. The more refined the pulp, the more the vessels are fragmented and collapsed and the better they get bound to the fibrous paper network.




Papers manufactured from unrefined and refined eucalyptus pulps, showing pick-out differences (Source: Panula-Ontto, 2007)

The eucalyptus pulp refining promotes the following beneficial changes, as far as vessel picking problems are concerned:

- Vessels fragmentation, which decrease in size, collapse and further adhere to the paper web body;
- Increase in bonding between fibers and vessels, allowing the vessel element to be “captured” by the fibrous network;
- Increase in fiber and vessel flexibility;
- Web consolidation improvement;
- Increase in bonding points and fiber to vessel contact surface;
- Reduction in web surface roughness, improving vessel adhesion to this surface.

The eucalyptus pulp refining has deserved much attention and many developments were recorded in the last and recent years, which have been also oriented toward vessel problem minimization in hardwood pulps. As a function of this, the most suitable refining conditions for refining these pulps, degrading the vessels and preserving the desired fiber qualities are relatively well-known.

It is well-accepted for instance that the power required for vessel element collapse is relatively low, whereas that required for vessel fragmentation and the almost complete picking problem solution is high, amounting to approximately 100 kWh/adt of net refining energy. In case conventional refiners are used, beating degree will increase too much, which is not interesting. Values from 60 to 80 kWh/adt lead already to a good improvement, but then the picking problem may still persist to some extent.

Therefore, the best condition is to work with refiners with an extremely low specific cutting or edge load - which is also called refining intensity – between 0.2 and 0.5 Ws/m. In order to be able to achieve this, the effective length (km/rotation) and specific cutting length (km/s) must be reasonably increased, twice the value that could be reached of late. There are very good disks being manufactured at present, with very narrow bars (about 1.5 mm) and approximately 2.2 to 2.5 mm spaces between the bars, which provides a good refining space and a much higher number of impacts.

Refining disks with highly effective cutting length (www.finebar.com)

Another condition favoring vessel fragmentation is the higher refining consistency. The fiber cushion becomes thicker, with consistencies near to or higher than 10%, the fibers rub more intensely against each other, as well as against the vessel elements, helping to fragment and to flatten them. With a higher consistency for a same dry stock flow through the refiner the pulp remains a longer time between the disks. These actions cause a greater number of impacts on the vessels. Moreover, the net energy applied dilutes further to the blades and each impact is softer on the pulp constituents. Thus the pulp hydrates and fibrils better, while the vessels are fragmented in a softer way. Refining at low refining intensities means favoring fiber bonding without damaging the fibers.

When working at higher consistencies and low refining intensities, it is possible and it is interesting to open the refining space a little further. It is well-known that the more intense refining work occurs on the refiner blade edges. By increasing a little the refining space the forces applied to the fibers by the edges of the bars and to every impact are weaker. Then, the fibers can better endure these forces without being damaged. As to the vessels, which are more fragile due to their low wall fraction, they are fragmented, they open or break to pieces. Under these conditions the refiners will work better and refining will be less aggressive and more selective.

Excess refining on the fibers is not indicated for printing papers. The papers become hard, losing dimensional stability, bulk, porosity and opacity.

Another possibility for the refining to become more effective is to work with refiners in series, or even in a single pass, but at a high recirculation rate. With a single passage through the refining zone, it is very probable that many vessel elements will not even get in contact with the refiner blades. Therefore, refining in series or at high recirculation rates are very indicated.

## VESSEL ELEMENT FRACTIONATION

It is estimated that at vessel to fiber ratios of 1:1,500 or more fibers, the vessel element problems in printing papers are practically eradicated when using eucalyptus pulps. They only persist if the vessel elements are too large.

Among all available ways of fractionating the vessel elements from fibers and thus obtaining a vessel element rich and a vessel element poor pulp, the most practical one is that using a group of accordingly adapted hydrocyclones. These hydrocyclones are sensitive units, working at very low consistencies (0.3% at most) and capable of separating the large and heavy vessels from the long and lighter fibers.

The vessel hydrocyclone separation is not safe for all pulps, only for those having short and wide, little barrel-shaped vessels. When the operation is successful, approximately 60 to 90% of the vessel elements can be separated from the fibers. However, a significant fiber portion still follows along with the vessels: about 20% from the original pulp. To achieve a good separation it is important that the specific surface and the vessel density are rather distinct from those of the fibers.

A good fractionation can result in an accepted pulp with a vessel to fiber ratio of approximately 1:2,500 or higher, and in a rejected, vessel rich pulp, with a vessel to fiber ratio of 1:20.

These rejected, vessel rich pulps, can be separately refined, applying the best refining conditions to fragment the vessels. Later the refined pulps can be incorporated again into the accepted stock that had fewer vessels. The resulting stock may be composed of different dosages of these two stocks. They may be also separately refined and optimally dosed for the paper grade being manufactured. This procedure definitively improves the printing quality of the manufactured papers.

There exist other vessel fractionating processes, but they rather apply to laboratory testing:

- Flotation and screening;
- Screening in distinct meshes (35 to 65 mesh);
- Fiber flocculation and separation of the vessels remaining in the residual non-flocculated suspension (Jacquelin's method).

Jacquelin's method is rather efficient to separate vessel elements for laboratory testing, although it is very slow. It consists in putting the pulp suspension adjusted to approximately 2.7% consistency to revolve in a rotary balloon at a certain angle. This position is favorable for causing the fibers to roll up or to flocculate with one another, but not the vessels. The flocks formed by the fibers can be separated and the vessels will be collected in the residual suspension.

One thing is certain, both for the laboratory and the mills: to separate and clean a pulp up from all its vessel elements is an almost impossible mission. Even if the total separation were viable, about 3 to 5% of the initial pulp weight would be removed. To get rid of vessel elements is an expensive and unjustifiable, absolutely uneconomical procedure. It is better to remove them as much as possible, even in a pulp still containing many fibers, and treat them adequately by refining or passivation, using them thereafter in another paper grade or else returning them to the process, but modified as desired.

## VESSEL ELEMENT PASSIVATION

There are important differences between vessel element and fiber surface chemistry, which is due to the surface differences themselves, as well as to the chemical compositions of these anatomical elements.

To separate most vessels by fractionation, to treat them chemically to passivate them and thereafter to bring them back to the stock is a dream in pursuit of becoming reality. This kind of passivation is little studied and still little known. The idea is to separate the vessel elements and to change their surface chemistry so that they can be better printed and better grasped to the paper network. As the vessels are richer in carboxyl and carbonyl groups, perhaps they can receive more selectively some chemical product which may adhere thereto and achieve the expected solution to the vessel picking problem. The separated vessels themselves may be altered as to their ionic charge, their hydrophilicity, their oleophobicity etc. However, as the difficulties to fractionate the vessels still persist, the passivation has been left to be studied later, although it is interesting.

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## MINIMIZING VESSEL PROBLEMS BY PRINTERS' ACTION

Printers have some actions to minimize the pick-out problem, as already seen above. When purchasing a new paper grade, a new ink or a new printing machine, the problem often reappears. The main actions taken by the printing companies in general are as follows:

- To test both paper sides, to see whether one or both of them present the problem;
- To lower the ink tack by using solvent or diluent;
- To lower the printing machine speed;
- To clean more frequently the blanket;
- To change the fountain solution supply at the wet offset printing operation;
- To increase the ambient temperature, as when the temperature is low. In such cases, the ink tack is higher, besides being higher the temperature differences between paper and ink.
- To use slower drying inks, as when the ink dries quickly the picking likelihood increases;
- To change the paper for another one.

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## CONCLUSIONS

Based on all technical arguments presented in this special chapter of the **Eucalyptus Online Book**, it becomes clear that the vessel elements deserve further attention, more studies and more evaluations. This may occur starting from the forest growth, the tree and wood selection and the pulp and paper manufacturing processes, as well as at the printing houses and other paper users.

We hope that this comprehensive revision we tried to present didactically may have contributed towards a more intensive vessel element study by many of those involved with them, who have not yet realized their great importance for paper manufacturing.

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