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THE PRESENCE AND PROPERTIES OF KNOTS IN FINNISH SPRUCE

INVESTIGATIONS CONCERNING THE ORIGIN AND CHARACTERISTICS OF BRANCH AND KNOT WOOD IN FINNISH SPRUCE WITH PARTICULAR CONSIDERATION GIVEN TO THE RAW MATERIAL NEEDS OF THE PAPER INDUSTRY

TH. WEGELIUS

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Contents.

TO MY FATHER

Preface.

For the origin of this work I am very much obliged to the Society of Forestry in Suomi. At the beginning of the work in the spring 1935, the Board of the Society granted a scholarship of Fmks. 10 000: — for collection and arrangement of the research material. I wish further to express my respectful gratitude towards the Society of Forestry for including the work in the Society's publication series »Acta Forestalia Fennica».

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To Baron L. von Hellens who has translated the work into English and read the proofs I express my best of thanks.

I conclude by expressing my most sincere thanks to all those, whom I have troubled with this volume and who have helped me with good advice and valuable assistance.

Th. Wegelius.

CHAPTER I.

Introduction.

The extraordinary and multifarious use made of coniferous woods during the past century has hardly been attained by any other of nature's raw materials. Through the introduction of steam power, sawmill production developed from a petty industry and a handicraft to a giant industry of international significance. The abundant supply of waste arising from sawmill cuttings, such as sawdust, trimming ends and slabs, solved the power problem regardless of the geographical location of sources of power such as rapids, and shipping facilities as well as the availability of raw materials could be taken into consideration in the erection of new sawmills. The technical gains made in transportation facilities in our times have opened up unforeseen prospects for international trade in products of the woodworking industries.

The methods of producing paper out of wood — the grinding process was discovered in the beginning of the 1840's and cellulose cooking a decade later — must be regarded as particularly valuable advances in technic. It can be maintained without exaggeration that the general dissemination of knowledge and the high standard of living which we are experiencing at present would have been unthinkable if these epochal discoveries had not made possible an expansive diffusion of printed matter at low cost.

The further development of the cellulose industry in the form of rayon production, the manufacture of cellophane, shatter-proof glass, explosives, et cetera, as well as the possibilities opened up by the latest advances in wood chemistry — the extraction of gasoline, lubricating oils, sugar and so forth from wood — have extended prospects furthermore. The limits of human endeavor cannot of course be established, but it can nevertheless be surmised that the possibilities in this branch have not as yet been at all exhausted and that development will be able for a long time to come to show the same upward tendency.

Although the increased application of concrete and iron and steel in building activities has given rise to a continually keener competition in the trade in building materials, the coniferous woods of the northern countries have nevertheless been able, due to their excellent qualities, to maintain their position in international markets and have found a secure source of consumption. Even in the paper and artificial silk industries it has been attempted to find by means of research and numerous experiments new raw materials such as esparto grass, straw, bamboo and the casein matter in milk. For the time being however none of these substitutes has appeared to be the equal of coniferous woods. Because of its plain and regular structure, its good and even fiber qualities, its advantageous chemical properties and its light color, spruce in particular has proven to be an especially valuable and suitable raw material in the manufacture of both mechanical ground wood and chemical pulp.

With the abounding forests in Finland the woodworking industries have been developed at a particularly fast pace, and the question of continually satisfying the increasing need for timber has evolved into a critical problem for the economic life of the country. By means of forceful public enlightenment and expansive work for the improvement of forests and land, action has been taken on the initiative of the Government, the woodworking industries and the private organizations of forest owners for the purpose of bringing the yield of spruce into balance with the increased demands of the future.

At the same time that this requirement of greater quantity has been asserted, demands for quality have likewise increased. This has been principally brought about as a result of the increased competition in world markets and of the more varied and more advanced methods of refinement.

Sawn coniferous woods have for a long time been priced on the basis of definite standards for various classes of value. This segregation has been based partly on the appearance of the wood and partly on its strength properties. The quality of sawn goods has consequently been dependent upon the quality of the timber as well as the manner of handling the wood. In sorting sawn goods, attention is given in practice principally to the visible imperfections of the merchantable goods. The most important of these are the presence of knots, the occurrence of cracks and cant, the deterioration in quality caused by blue stain and decay, and damage by insects in the form of larva crevices and so forth.

Imperfections arising from milling, loading and shipping can be reduced to a minimum by rational and appropriate measures; they can theoretically be completely eliminated. The problem of quality is however appreciably more complicated since it is a question of depreciation in value arising as a result of the imperfections in the raw material, ie., the logs.

The most significant characteristic of round wood is indisputably in this respect the presence of knots. The occurrence of knots as well as the size and kind of knots constitute the most decisive basis for sorting sawn goods. Groups of knots such as knot clusters as well as large knots reduce the strength properties and the qualitative value of sawn goods. Scattered knots of small dimensions are on the other hand of lesser significance.

Living knots which up to the time of felling the tree form a part of its activity of growth and are accordingly anatomically associated with the surrounding stem wood are of course of lesser significance as regards quality and strength than dead, dried up knots which have become separated from the surrounding wood. The latter loosen easily from the sawn product and cause knots holes. Knots affected by decay, so-called decayed knots, as well as knots surrounded by ingrown bark and bark knots also reduce the merchantable value of sawn goods to an appreciable degree. Of less importance than the presence of knots and more uncommon are imperfections resulting from abnormities in the anatomical structure of wood such as the formation of compression wood, resin pockets, distorted growth and so forth.

Statistics show that products of the sawmill industry have tended toward a deterioration in quality during the past decade and that the lower classes of value, especially the percentage of fifths, have been substantially increased. The reason for this is surely to be found in the greater requirements of foreign buyers as regards appearance and the properties of the goods and in the stricter standards resulting therefrom in sorting. Nevertheless, the reason must to a great extent be traced to a deterioration in the quality of sawn goods. The technical improvements that have been made in sawmill production and increased rationalizing and research activity guarantee that this deterioration could not have arisen in connection with the handling and the manufacture of wood products. It can therefore be assumed, based on sound principles, that the quality of the timber in our forests has depreciated. An increased demand for sawn timber has likewise brought about extensive cuttings. These have principally occurred in the form of thinning by removing the large sizes and thereby causing the stands to be uneven and scattered.

A division of logs into classes of value lies in the interest of both forest owners and lumber producers, as has become apparent from the foregoing.

At the same time that such a classification from the forest owners' point of view leads to more rational methods of caring for forests and increases the quality of the timber and the selling price of lumber, it has the effect of increasing the value of the production of the sawmill industry and accordingly improves the competitive strength of this important branch of industry in the international market.

The manufacturing process of the sawmill industry is entirely mechanical, and sawn goods are distinguished from the raw material, logs, only in form. Their consistency and anatomical structure remain unchanged. In the paper industry, particularly in ground wood and cellulose production, the form of the raw material and the cells are changed; fibers are separated by a mechanical or chemical process. In practice it has however become apparent that the quality of wood for these branches of the woodworking industry can also be of great importance as regards the properties and the value of the products.

During the earlier phases of groundwood and cellulose production, when technic was still comparatively undeveloped, it was considered that the properties of wood played only a secondary part, and little interest was given to the question of quality. With increased output and keen competition in the world market, requirements as to the qualitative characteristics of manufactured products have however become more exacting. A general endeavor to obtain higher qualities in, and a better use of, raw material resources has become prevalent and resulted among other things in extensive research activity. Particular interest in this connection has been given to the various properties of the raw material and their effect on the manufacturing process and the quality of the products.

As regards both the quantitative and the qualitative yield in the grinding of woodpulp and in cellulose cooking, the anatomical structure of wood is naturally of basic importance. In this connection the density of the wood, the percentage of summerwood, the presence of knots as well as the characteristics of the fiber and the uniformity of the wood play a decisive role.

In the sawmill industry the cubic content of the goods forms the base in setting the price for both the raw material and the manufactured product. Pulpwood on the other hand is valued on the basis of the cubic measure while the finished product is sold by weight. When it is considered that the weight of the raw material based on volume can vary within particularly wide limits — in dense wood it can be up to double of what it is in rapidly grown wood — it is found that the density of wood is of the

greatest importance as to quantity of pulp yield. The denser the wood, the greater is the percentage of dry substance and the higher the number of fibers per cubic unit.

Although the density and the weight of wood are decisive as regards the quantitative yield of pulp, this is not always the case as to the quality of the pulp. The slow growing and heavy timber of northern Finland, for example, is as regards composition extremely heterogeneous. The dimensions of the fibers usually vary appreciably. In addition, a large percentage of the mass is often composed of compression wood having short fibers, reducing the strength properties of the substance. The presence of knots in the wood, like the content of compression wood, raises the weight for a given volume but likewise effects a reduction in quality. Dry weight in itself constitutes accordingly no reliable characteristic as regards the quality of pulp wood. This is due to the fact that the wood is not homogeneous as to its structure but is composed of numerous fibers having various dimensions and strength. In addition to the variations of the fiber dimensions in various parts of the stem, springwood and summerwood fibers are distinguished in many respects by differences in both chemical and physical properties, with the result that the percentage of summerwood decisively affects the properties of both the wood and the pulp.

The presence of knots in pulpwood is in many respects a hindrance in production. Knot wood makes the manufacturing process more difficult and more expensive, and is furthermore detrimental to the quality of the product. Knot wood differs appreciably as regards structure from the surrounding stem and is considerably heavier and harder than normal wood. In addition, knot fibers, composed to a great extent of compression wood fibers, show dimensions and properties that vary from the normal. The wood around the part of the knot inside the stem is in many respects different from the wood in the stem and is recognized by its particular formation of compression wood and high percentage of lignin and incrustations.

Due to the difference in the direction of the fibers and its extreme hardness, knot wood causes a loss of both power and time in grinding mills. The high percentage of resin in knots, the quantity of fiber unfit for production as well as the presence of ingrown bark and other impurities around the knot give rise furthermore to considerable irregularity in the quality of the pulp. In grinding, knot wood becomes a pulverized mass unfit for paper production, which makes manufacturing difficult and causes resin spots in the pulp and on the sheet of paper because of the abundance of resin.

Knot wood is also detrimental in many respects in chemical pulp production. Because of its great density and weight and its high percentage of lignin and incrustations, it aggravates and delays cooking and increases the amount of chemicals required. It produces spots, impurities and irregularities in the pulp and accordingly makes necessary careful sorting and inspection. The knot substance removed in this respect can constitute an appreciable portion of production and is as regards its properties considerably inferior to the pulp obtained from normal stem wood. The principal use that can be made of this knot substance is in the production of wrapping paper and other inferior products. In spite of careful sorting, decayed knots cannot on the other hand be segregated from the pulp due to dissolving rapidly, and produce ugly spots which decrease the value of the pulp to an appreciable degree.

The chemical composition of wood plays an important role particularly in the production of chemical woodpulp. In this connection especially the percentage of cellulose, lignin and resin merits particular interest. Numerous investigations have shown that the percentages of cellulose and of lignin are inversely proportional to each other, and that a high percentage of lignin shows a low percentage of cellulose. Also the percentage of cellulose appears generally speaking to be in proportion to the dry weight of the wood. Knot wood and compression wood are conspicuous for their high percentage of lignin, as has previously been mentioned. The content of resin and fats varies considerably in different parts of the stem and decreases rapidly when the wood has been stored. The percentage of pentosans in wood is also subject to wide variations. A high percentage of pentosans makes for difficulty in the cooking of cellulose to a certain extent and delays absorption.

The method of measurement at present applied in Finland, which provides that pulp wood is bought on the basis of the cubic contents, pile measure, is both antiquated and impractical when considering the great importance of quality. In actual practice it leads to the production of bulky, rapidly grown and knotted wood of inferior quality. In order to prevent a deterioration in the characteristics of pulpwood, there should be every reason for striving toward an applicable and practical basis for judging the quality of timber.

* * *

Different kinds of manufactured products place of course different demands on the raw material. The presumption that a tree is healthy, straight, as free of knots as possible and that the trunk has a good form should however to able to be laid down as a general rule for both the sawmill and the paper industries. Likewise it is of significance that the wood be homogeneous throughout its structure and be conspicuous for its even growth.

Since the qualitative value of a log is directly dependent upon the characteristics of the sawn product, a valuation of the log must be based on the sorting principles for finished sawn goods. In this connection there should be taken into consideration not only the characteristics of quality in the individual tree but also the characteristics of the wood in the various parts of the stem. The part of the stem that is free of knots and the part supporting the branches constitute different classes of value. Such a method of valuation has already in practice been arrived at in Finland. At Government auctions, for example, sales of the lower portions and the tops of trees are made separately.

Extensive investigations as to the qualitative value of trees have been made by Vuoristo (1931, 1932a and b, 1934a and b, 1935 and 1937). On the basis of the plentiful supply of material that he has accumulated for these investigations, Vuoristo proposes a division of quality into three classes for pine logs and two classes for spruce logs. One of the main principles for this judging of quality constitutes the presence of knots in the wood. Spruce logs are accordingly classified in accordance with the following principles:

Class I. Logs taken from trees having a normal or sparse amount of knots are placed in this class. The maximum diameter of the knots permitted is 2″. The maximum bend of the log permitted is 2/3 of the diameter of the top.

Class II. Living and dried knots are permitted to an unlimited extent. Decayed knots are on the other hand permitted only in case they are small. The shape of the log should be suitable for cutting.

Judging the quality of pulpwood has heretofore been considered to only a very limited extent. In Finland a valuation of pulpwood on the basis of its suitability as a raw material has not up to the present time met with any activity in practice, nor has this question been subject to particularly close study. It is true that Burgman (1930) has undertaken investigations at the Kangas paper mill in Jyväskylä concerning the quality of pulp wood and has made sample grindings of wood having various densities. These investigations show that pulpwood produces a better yield both quantitatively and qualitatively in case it is of dense growth. However, density cannot generally be laid down as a basis for judging quality for reasons which will be mentioned hereinafter, and since numerous other factors are also influential in this connection, of which the presence of knots must doubtless be regarded as of the greatest importance.

In Norway Gustav Klem (1930, 1932 and 1934) has proved by means of extensive investigations based on a plentiful supply of material that the weight of wood, the length of the fibers and the presence of knots in wood are dependent upon the form of the stem. The better the form of the trunk, the better are the properties possessed by the wood as raw material and the less the presence of knots. On the basis of these studies Klem proposes a division of pulpwood into three classes of quality and presents the tapering of the tree as a basis for this division.

Tapering and the presence of knots are however two characteristics which, although showing in themselves a clear relationship to each other, stand however in relation to each other in different regions and under different circumstances in accordance with principles which digress to a certain extent.

The presence of knots in wood appears on the other hand to constitute a characteristic of quality that is not influenced to a like degree by geographical and biological conditions. Knot wood is equally detrimental to production in all kinds of spruce wood regardless of its origin. The same situation is found in secondary phenomena caused by the presence of knots in wood, such as the formation of compression wood, exceptionally high percentage of resin and so forth.

The presence of knots in pulpwood constitutes one characteristic of quality independent of production methods and, as such, is suitable as a basis for evaluating pulpwood. Even for the sawmill industry the abundance of knots, as already previously mentioned, is the most significant basis for judging the suitability of the raw material. Therefore, the presence of knots in wood seems to be able to constitute a desirable basis that is easily applicable and practical for evaluating the quality of both logs and pulpwood.

The purpose of the present study is to contribute toward an understanding of the origin, development and characteristics of knot and branch wood, and the effect of knot wood on manufacturing processes in the production of ground wood and chemical pulp and on the quantitative and qualitative yield in production.

CHAPTER II.

Survey as to the significance of the presence of knots in logging and in the transport of timber.

As has previously been mentioned, the presence of knots in wood is of decisive significance in the handling of timber in the forest, in the transport of the timber and in the preparatory treatment of the wood at the place of manufacture. In forest work, that is, in the felling, limbing and barking of trees, the dimensions of a tree and the extent of its branches constitute the bases which determine the difficulty of the work. There is therefore reason to attach sufficient importance to the size and presence of knots in the trees to be felled when formulating a scale of wages for forest work.

Forest work in Finland and the efficiency thereof have been the subject of interest particularly for Vuoristo. His investigations (1936) show that the presence of knots in timber causes the consumption on the average of 12 % to 13 % of the total time required for preparing growing spruce into partially barked, ready piled pulpwood. The division of work requiring the greatest expenditure of time is barking, which amounts to 36.6 %, on the average, of the total time expended. The trimming of timber into one-meter lengths requires 20 % of the working time, while piling amounts to 16 %. The time spent in transferring work from one tree to another, in felling and in resting during working hours is on the other hand surprisingly insignificant, and comprises only 8 % of the total working time.

The difficulty of the work of limbing is dependent upon the number and thickness of the branches. The relative time required for limbing decreases as the thickness of the tree increases. This situation has previously been thoroughly analyzed by Lassila (1930). He states that when the diameters of trees vary within definite limits and when the trees are of a similar species, age, type of forest and form of stand, working difficulties in limbing are directly dependent upon the length of the crown in relation to the length of the stem.

In order to facilitate the performance of the subsequent stage of work, that is, barking, limbing should be done carefully and effectively. Large branches in particular should be removed carefully since they, as contrasted with small branches, cannot be scraped off by a barker or spud. Vuoristo's investigations show that the difference in time required for limbing can vary within particularly wide limits, rising up to 100 % above normal.

The stage of work termed barking of pulpwood is relatively time-consuming, as has been previously stated, and calls for about one third of the time required for producing piled pulpwood. The characteristics of the tree which in this connection are the factors exerting the greatest importance are the dimensions of the tree, the quality and thickness of the bark, the extent of knots in the tree and the quality of the branches. In connection with limbing, it often happens that the branch is not cut away so carefully that the surface of the cut is level with the surface of the wood. If this is not done, there remains of course a bulb on the trunk which makes barking difficult and slows up the operation of the barker or the spud as the case may be. Vuoristo has proved that the time required for barking is influenced by knots to such an extent that an excessive occurrence of knots can increase the time by up to 15 % above normal.

The presence of knots in timber is an important factor also in the floating of pulpwood. Floated logs absorb water principally through the surfaces where the tree and its branches have been cut by mechanical operations and where the grain of the timber accordingly ends on the surface of the log or bolt. A log or pulpwood bolt free of knots accordingly absorbs water only through the two ends, while a limby one can have a water-absorbing area that is many times greater. It is believed that no investigation has as yet been made as to the effect of the presence of knots on the buoyancy of logs. However, on the basis of the investigations that have been made as to the capacity of timber to absorb water, it can be concluded that the presence of knots in timber is of distinctive significance in floating.

The presence of knots plays also an important part at the place of production in the preparatory handling of the wood in the wood room and in chipping machinery. In using rotary knife-barking machines, the presence of knots in wood increases the amount of power required, makes great demands on the strength and quality of the knives and necessitates

frequent sharpening. In using friction-barking methods such as drum barking and Thorne's system, the presence of knots makes work difficult in many respects. Bark around the knot is often only partly removed and accordingly necessitates re-barking or cleaning by hand. Because of their extreme hardness, knots cause an increase in the amount of power and time consumed by the chipping machines and place great demands on structural strength and the quality of the blades.

CHAPTER III.

The terms »Branch» and »Knot».

Coniferous wood occupies for several reasons a special status among the raw materials which lignified vegetation places at the disposal of industrial life. Because of straight stem formation, regular anatomical structure and highly valuable fiber characteristics conifers offer many possibilities for manufacture under conditions in which hardwoods, although being more abundant but likewise more heterogeneous as to composition, provide quantitatively a less satisfactory raw material.

The homogeneous and regular structure of coniferous wood is the result of its particularly bounded process of increment. This is reflected in an even and regular course in the formation of wood as well as in the development of the outer architectonical structure of the tree; ie., in the relative position of the stem and its branches to each other.

The architecture of a tree constitutes one of the most characteristic signs in distinguishing various species of trees. Particularly the angle of the branches with relation to the vertical axis of the stem as well as the relationship between the dimensions of the branches and the stem are in this connection characteristics of decisive significance.

As a general rule coniferous trees display a more symmetrical and bounded architecture than hardwood trees, and the relationship between the main axis, the stem, and the lateral axes, the branches, is more pronounced.

Jost (1936) states that a tree differs from bushes and shrubs not only due to its greater mass and greater abundance of branches but primarily due to the system of branches in the portion of the individual plant above ground. This consists of so-called increment axes of various thicknesses and position in space. The main axis, the vertical trunk, supports a system of lateral axes, branches, which stand at an angle to the direction of the stem. The latter in turn support the side branches. Depending on their relationship to the main axis, the lateral axes on the other hand can be distinguished through various categories of branches. Branches of the first category, or primary branches, emanate from the stem; branches of the second category, or secondary branches, on the other hand from branchings of branches of the first category, et cetera.

Velenovsky (1905) has defined the axes of phanerogamian plants in the following manner:

»Die Achse ist die Zusammenfliessung der unteren Teile der Anaphyten, welche sich an der erwachsenen Pflanze als ein, durch den mehrzelligen Vegetationsgipfel nachwechsendes, morphologisch und anatomisch einheitliches Ganzes darstellt, durch dessen Tätigkeiten an den Seiten Blätter und in ihren Achseln Knospen in regelmässiger Stellung hervorkommen. Die blattragende Achse nennen wir Spross.»

The object of the present work is to aid in explaining the presence of knots in spruce and the characteristics and significance of knot wood with particular reference to the raw material needs of the paper industry. The term »branch» is in this connection defined as follows:

A branch is understood to be every offshoot of a lignified plant which deviates in direction from the vertical, main axis or stem and emerges from the stem. While the trunk is in its nature orthotropic and aims toward a vertical position, branches on the other hand are plagiotropic, lateral axes.

A branch can be divided into an outer and an inner part, ie., limb and knot, depending upon its relative position with regard to the stem. The inner branch (knot), ie., the part of the branch situated within the stem, is difficult to separate from the surrounding stem wood. It consists of the original ingrown knot which merges through a layer of compressed wood of irregular structure into normal stem wood. On the other hand the outer branch consists entirely of branch wood and constitutes a detached and separate geometrical body.

As a rule a branch is smaller in thickness than the stem at a corresponding height. This difference in size can be regarded as a prevalent characteristic of spruce.

As regards its organographic structure, the stem of spruce is radially symmetrical. Its geometrical form constitutes generally speaking a rotation body to which the plagiotropic axes, the branches, are attached in radially extending knot clusters. Between these there appear scattered intermediary branches varying in number. On the other hand the organographic structure of a branch in spruce is bilaterally symmetrical or dorsiventral, and the lateral branches generally extend horizontally to each side of the main branch. The reason for this branching structure is found in the task of the branch as a retainer of the organs of assimilation for the tree, making the branch suited for intercepting the sun's rays to the greatest possible extent.

Branch wood and stem wood are anatomically of identical basic composition. The growth process takes place in both of them in accordance with like principles, and cell bands arise according to identical biological laws.

Since a branch can attain an appreciable length, up to 5 or 6 meters, and be comparatively heavy when including the lateral branches and needles, the demands made on the strength properties of the base of a branch are great. This part of the branch is subjected to a noticeable lever effect. In order to withstand this load there is formed tension wood (Zugholz) on the upper side of the branch and compression wood (Druckholz) on the lower side. The anatomical structure of the branch becomes eccentric as a result thereof. The pith is as a rule located above the center of the cross-section area, and the lower part of the branch has an appreciable quantity of compression wood. By compression wood is meant the dark, compact and short-fibered wood which is found as supporting textures in specially loaded parts of the stem. (This wood is called in German »Rotholz», in French »bois rouge», in Norwegian »tennar», in Swedish »tjurved» and in Finnish »lyly» or »janhus».) The breadth of the growth rings is insignificant and the precentage of summerwood high.

As has appeared from the foregoing, branch wood differs cytologically from stem wood. Fiber dimensions are generally smaller in the branch than in stem wood and vary to a greater extent.

Branch and knot wood and stem wood are on the other hand extremely similar phytonomically. The principal differences arise partly from the more pronounced task of the branch as the supporting element for the organs of evaporation, respiration and assimilation, and partly, as previously mentioned, from the mechanical reasons caused by dissimilar load conditions.

* * *

In milling as well as in the manufacture of chemical and ground wood pulp in the woodworking industry knots are in many respects impediments to production and effect a lowering in the quality of the wood.

In the lumber industry the occurrence of knots is the most deciding factor in sorting and evaluating the sawn product, as has already been mentioned. This is due partly to the fact that knots impair the appearance of the product and partly on the other hand to their lowering the strength characteristics of the sawn goods. Since knots are principally composed of compression wood, they shrink to an appreciably greater extent than the surrounding stem wood when the sawn product dries out. This leads both to the formation of checks within the knot along its lengthwise axis and to transversal fiber breaks parallel to the knot in the surrounding wood. Since the knot fibers as well as the fibers in the section of the stem adjoining the inner knot are very irregular in direction, the sawn product is weakened to a high degree at these places. Furthermore, the knot adversely affects the cleavability of the wood and planing is made more difficult.

In view of the foregoing, a classification of different knots has been made in the sawmill industry. Knots in the raw material are segregated, depending upon the condition in which they are found at the time of felling the stem, into two main groups; that is, growing and dead knots. These knots on the other hand are called tight or dried knots in sawn goods.

The living or sound knot has continued to perform its complete function during the life of the tree up to the time of felling. It has supported the assimilating organs as well as served as the conveying link to and from these sections. It is therefore anatomically attached directly to the surrounding wood and does not become detached therefrom in the drying process. On the other hand, a dead or dried knot is practically separated from the surrounding stem wood. It has come into existence when a dried up or dead branch has remained in place and is thereupon surrounded like something entirely foreign by the adjoining and growing stem wood (»Fremdkörper»). A dead knot has given off its resin and a large portion of its fats into the layer between the knot wood and stem. Furthermore, it has upon drying shrunk considerably more than the stem wood. It therefore becomes easily detached and is particularly damaging because it is apt to fall out of the plank after milling and drying and leave an empty knot hole.

A knot is called a bark knot or barking knot when it is surrounded by a ring of bark which has been covered by wood. Such bark knots are particularly common in old spruce forests, especially in the eastern and northern parts of Finland. It decreases the quality and value of the product in both the milling and paper industry.

The most damaging kinds of knots are so-called decayed knots, the wood of which has been dissolved and destroyed by fungus infections. They are soft and accordingly contain no strength properties. Furthermore, they constitute a contagious pocket for the surrounding sound wood.

Various kinds of knots are classified as to types depending upon the exposure of the knot in the sawn product. A knot that has been sawn more or less in its crosswise direction is termed a round knot. If the knot on the other hand is sawn in its lengthwise direction so that its portion of the surface of the sawn product becomes the maximum, it is called a horn knot. If the sawing has however been made through a knot cluster and two or more knots have been sawn in their lengthwise direction, there arises a group of knots extending over the whole breadth of the plank or board. This lends itself very much to decreasing strength properties. Small, scattered knots are called pin knots. These are of little significance.

Likewise in the paper industry, as has been previously mentioned, knots are obstructive and annoying in production. In ground wood pulp mills they cause a great loss of time and power due to the dissimilar directions of their fibers. In the ground wood process the knot is often pulverized into a meal worthless in the production of paper, which plugs the screen perforations and appreciably lowers the quality of the pulp. Large knots can cause such great friction against the surface of the grinding stone as to severely damage it. The losses of material which may in this manner be brought upon a factory can be very great. The presence of knots in timber plays a still greater role in the chemical pulp industry than in the production of groundwood pulp. Because of its compact structure a knot contains very few cavities into which chemicals can enter. As a result the defibration of the pulp is not complete. In so-called knotty pulp, which arises in this manner, the fibers are usually bunched into groups, and the pulp is coarse and sticky. Furthermore, knotty pulp appears darker in color than prime cellulose, reducing to a high degree the value and quality of the cellulose. Because of the foregoing imperfections, knotty pulp gives rise to additional work and expenditures. Due to its stickiness and comparatively great weight, it can be separated to an appreciable extent from prime cellulose in the knot screens and the cellulose factory's sand extracting apparatus. The situation is however worse as regards pulp which has originated from decayed knots. Such pulp dissolves more or less completely and causes ugly spots and streaks on the finished sheet of

paper. Furthermore, it can often constitute infectious pockets upon warehousing over an extended period of time.

Ingrown knots, which are extensively found in timber of northern Finland, have particularly appeared damaging in the production of cellulose. They cause a considerable amount of extra labor in the barking and wood cleaning plants, and effect in addition appreciable losses of timber. In this connection the knots must be removed by bark cutters and axes. The loss of wood in this knot-cleaning process can amount to 10 percent or more of the total. In order to reduce such losses it has even been attempted to use various kinds of knot boring machines, but these have not won general acceptance due to their limited working capacity.

Both the sawmill and the groundwood and cellulose industries use as yet only limbed trunks, logs and bolts as raw material for manufacture. Accordingly, it is only the part of the branch situated within the periphery of the trunk, the knot, which has been of practical significance and has been used, while the limb has been left in the forest. The proportion of knots in spruce of northern Finland can amount to a considerable figure compared to the total quantity of woodpulp. A large portion consists of ingrown knots, ie., dead knots, which are seldom observed upon an ocular inspection of the surface of the wood. These are in many respects noxious and annoying, and lower to a great extent the favorable characteristics which are otherwise found in spruce of northern Finland. These ingrown, dead knots are usually surrounded by remains of bark which defile the woodpulp. They are in addition often infected with decay.

It should however be observed that the so-called knotty pulp which appears in manufacture is derived only to a slight extent from actual knot wood, when regarded from the botanical point of view. Even the wood of the stem surrounding a knot is in many respects different from normal wood in knot-free portions of the stem and presents many of the characteristics similar to actual knot wood, such as greater weight, hardness and percentage of lignin and incrustations as well as fiber properties inferior in many respects in paper production. This compressed wood termed »knot root, radix» by Brax (1936) can appreciably exceed in volume the quantity of actual inner knot, and should therefore be accorded due consideration in research concerning the presence of knots and their significance in the technic of woodworking.

The branches of spruce and the wood contained therein have not up to the present been the subject of noticeable interest. They were previously used as litter in barns and manure piles. According to data obtained from actual practice, it is possible to obtain 2 to 3 loads of such litter from a rather large spruce tree. Spruce branches are in addition used in road construction, particularly in forest roads, where they have been shown to be a material for the road base that is both good and binding. Spruce branches are also used in the construction of protection against snowdrifts on open winter roads. Spruce branches have lately met with an increasingly greater use as fuel, and are accordingly used in more densely populated districts even in very small sizes due to their relatively high value as fuel.

In spite of the fact that spruce branches are relatively thin, and are seldom more than 20 % of the diameter of the trunk at a corresponding height, the branches of spruce contain not an insignificant cubical content. According to the investigations of A. G. Blomqvist (1883), branches comprise up to 12 % of the total cubic contents of a tree. However, in applying present day woodworking methods, many difficulties are run up against in being able to use the branches of spruce for industrial purposes. Because of their insignificant thickness there is found for readily appreciable reasons no use for them in sawmills. Their great hardness and high percentage of lignin, resin and incrustations make spruce branches furthermore an unacceptable raw material for ground wood pulp mills and sulphite cellulose factories. It is however theoretically possible to consider the manufacture of branch wood of spruce into sulphate cellulose. A number of difficulties as regards transportation speak against such a procedure. In addition, many practical complications are run up against in the forests and in barking plants.

CHAPTER IV.

Research material.

The problem of the quality of wood and its effect on the quantitative and qualitative yield of the manufactured product are a comparatively new study in the paper industry, as has already previously been mentioned. The significance of the quality of wood varies of course within particularly wide limits depending upon the processes of manufacture and the producing machinery in the various mills. It is likewise an accepted fact that the geographical location of producing mills as well as the sources of supply are of decisive importance. A mill in northern Finland using in production fine-grained timber containing compression wood cannot apply the same standards of quality as a mill in southern Finland working with coarse-grained timber. Ground wood pulp mills and sulphite cellulose mills furthermore make different demands of the raw material. In the former the physical and mechanical properties of wood are primarily of significance while the latter on the other hand are to a great extent dependent upon the chemical composition of the wood and its resistance to different chemicals.

In order to obtain an understanding of the significance of these factors and to procure material as illustrative as possible and representative of the variations in the qualities of the raw materials of the country, visits for the purpose of study were made in 1935 to the majority of the more important ground wood pulp, cellulose and paper mills of Finland. In this connection the quality of timber at the various places of production, the manner of handling the timber and the methods of production were given primary consideration. The travel included the following manufacturing plants:

The ground wood pulp, sulphite cellulose and paper mills of Kymmene Aktiebolag at Kuusankoski, Kymmene and Voikka; Yhtyneet Paperitehtaat Osakeyhtiö's ground wood pulp and paper mills at Myllykoski, sulphite and sulphate cellulose and paper mills at Valkeakoski, sulphite and paper mills at Jämsänkoski, and ground wood pulp and paper mills and carton factory at Simpele; the ground wood pulp mill and carton factory of Tammerfors Linne- och Jernmanufaktur Aktiebolag on the Anjala Rapids at Inkeroinen; Karhula Osakeyhtiö's ground wood pulp mill and carton factory at Karhula; Stockfors Aktiebolag's ground wood pulp mill at Pyhtää; Kaukas Fabriks Aktiebolag's sulphite cellulose mill at Lauritsala; the sulphite and sulphate cellulose mills and carton factory of Enso-Gutzeit Osakeyhtiö at Enso; Hackmann & Co. Aktiebolag's sulphite cellulose mill at Johannes; A.B. Waldhof Osakeyhtiö's sulphite cellulose mill at Käkisalmi; Diesen Wood Co. Aktiebolag's sulphate cellulose mill at Pitkäranta; the ground wood pulp, sulphite and paper mills of Kajaanin Puutavara Osakeyhtiö at Kajaani; Toppila Osakeyhtiö's sulphite cellulose mill near Oulu; Raahe Osakeyhtiö's ground wood pulp mill on Martinniemi at Haukipudas; the sulphite and sulphate cellulose mills of A.B. Kemi O.Y. at Kemi; Veitsiluoto Osakeyhtiö's sulphite cellulose mill near Kemi; Rauma Wood Osakeyhtiö's sulphite cellulose mill at Rauma; the ground wood pulp and paper mills of Äänekoski Aktiebolag at Äänekoski; the ground wood pulp and paper mills of Kangas Pappersbruk Aktiebolag near Jyväskylä; and Aug. Eklöf Aktiebolag's sulphite cellulose mill at Tolkis, near Porvoo. Furthermore, it was possible to supplement these studies in Sweden at the ground wood pulp, sulphite cellulose and paper mills of Holmens Bruk Aktiebolag at Hallstavik and the company's ground wood pulp and paper mills at Norrköping.

At all of the foregoing mills there were discussed with the plant management and the experts of the forestry divisions the prevailing situation as regards the kinds of raw materials used by the plant, their origin and the process of handling, and the methods of production. Particular attention was given to the difficulties which arise because of the quality of the timber and to the observations which were made, and the experiences encountered, in connection with eliminating such complications.

After consultation with the plant management and the forestry divisions of the respective mills, there was then chosen the material for analysis which appeared particularly to illustrate the qualities of timber and their deviations within the districts of the main watersheds of Finland. Special consideration was given in this connection to the presence of knots in pulpwood.

In order to obtain a perspicuous and clear picture of the quality of timber in the stocks of a manufacturing plant, it is necessary to perform a comparatively extensive series of investigations. In practice it is of course not feasible to take a qualitative inventory of the complete stock since the supply of timber usually comprises many hundreds of thousand cubic meters of pulpwood. It is therefore necessary to be satisfied with a series of samplings taken at random but in accordance with certain basic principles. A plant's supply of timber is as a rule composed of stems taken from districts having often extremely divergent possibilities for the growth and development of trees. Timber from various districts can be accumulated in separate piles in the wood yard, but particularly if the timber has been floated a rather great distance or if the mill maintains its raw material accumulated in piles in accordance with the American »pulpwood storage» system, the groups of timber are easily mixed together and it then becomes a difficult problem to ascertain the district of origin of the logs.

The following method was carried out in making the selection of timber as effective and representative and at the same time as practicable as possible.

The selection of timber was made from the conveyor transporting pulpwood from stock to the barking plant. All timber to be used by the mill in production must of course pass on such a conveyor. In large plants such as for example Kymmene, Myllykoski, Kemi and others, the belt or chain conveyor transports more than 1,000 cubic meters of pulpwood per 24 hours, ie., 1/360 of the annual requirement. Accordingly, with such a means of transport it is particularly convenient to carry out studies as to the quality of timber and its variations. The bolts pass by at such a rate that they can be advantageously observed, and a good, general view is obtained. Observations for the work at hand were made in this manner during an extended period of time, as a rule during an entire period of 24 hours (three eight-hour shifts), and careful notes were made in the form of tables as regards the quality of the wood. In this connection the presence as well as the kinds of knots were observations of primary interest. In addition, notes were made concerning variations in the dimensions, shape and taper of the bolts, the width of the annual rings and the presence of compression wood and decay. Furthermore, the method of trimming and the loss of timber arising in the cleaning of the wood were studied in the barking plant. Series of ocular observations as to the quantity of knot pulp and the degree of defibration were also carried out in the shaker screens and refiners of ground wood pulp mills and in the chip conveyors, knotter screens and rifflers in the chemical pulp mills.

On the basis of the foregoing observations and studies, materials which were considered representative of the general run of the product were chosen for analysis and transported to Helsinki for thorough examination.

The characteristics in pulpwood which were most apparent in such ocular investigations were the following:

1. The presence and size of knots in pulpwood;
2. The dimensions of the pulpwood;
3. The shape of the stems, particularly their excentricities;
4. The percentage of compression wood (this was particularly evidenced by the spiral grain of the tree); and
5. The width of the annual rings.

In examining the supply of timber at the various mills, the wood appeared to be classifiable to advantage into five classes of timber easily distinguishable to the eye. The outward signs of these groups are evident in the following presentation:

I. Timber free of knots having an insignificant taper, a maximum of one centimeter per linear meter. Cross-section area practically circular. Small knots are nevertheless permitted but their diameter shall not exceed one centimeter on the surface. Spiral grain and apparent formation of compression wood not permitted.

II. Tapering such as in class I. Cross-section area may however in this class be somewhat elliptical, nevertheless not so much that the difference between the maximum and minimum diameter exceeds 1.5 centimeters. Up to four living knots per linear meter with a diameter of less than two centimeters each are allowed. Noticeable formations of compression wood and marked spiral grain not permitted.

III. Up to six knots per linear meter are permitted. The wood may nevertheless be more oval in shape than in class II so that the difference between the maximum and minimum diameters of the cross-section area varies up to two centimeters. The taper permitted is two centimeters per linear meter. Noticeable spiral grain is allowed, but a marked percentage of compression wood is not allowed.

IV. Pulpwood having both coarse and an abundance of knots is entered in this class. The number of knots is unlimited. The difference in the diameters of the cross-section area can be as much as 3 centimeters. Unlimited tapering is permitted. The timber may be spiral grained but a noticeable formation of compression wood is allowed at only one end of the bolt.

V. Spiral grained timber having an abundance of compression wood and a marked, oval shape is entered in this class. The difference in the diameters of the cross-section area exceeded almost without exception 3 centimeters. The taper varied in particular. This timber was found principally in the most northerly districts of Finland, contained many ingrown knots, remnants of bark and pitch pockets, and was very heavy based on volume. After barking it was usually sorted out for firewood or wood for sulphate pulp.

The wood that was chosen from the stocks at the various wood working plants could be examined only as regards its anatomical structure and its various characteristics such as physical quality, chemical consistency, strength and so forth. It was on the other hand impossible to ascertain the biological circumstances during the growing period and their effect on giving shape to the structure of the tree, primarily on the presence of knots and on the various qualitative features of the wood. Under the prevailing circumstances this series of investigations was able to give only a view of the variations in the quality of pulpwood in the floating districts of the main waterways.

In order to show the biological circumstances such as site quality and the effect of the form of the stand and of the method of silviculture on the suitability and qualitative value of pulpwood, it is however necessary to perform investigations using material from test stems whose habitat, possibilities of development and history of growth can be accurately ascertained. Just as numerous authors (see Laitakari 1935) have maintained, the technical quality of a tree and its usefulness for various purposes constitute a result of the conditions prevailing during the growing period. In this connection the type of forest, the form of the stand and the measures of forest protection which have been undertaken within the stand play a decisive role. It is therefore necessary that also these matters should be given full consideration.

In order to supplement the series of investigations made in the foregoing manner with material taken from mills, the author undertook also a parallel series of investigations based on test material taken from the forests of the Forestry Research Institute at the Ruotsinkylä experimental station in Tuusula.

In conducting this series of biological observations attention was given to the botanical development of branches, their structure and various characteristics, and their technical value for production.

The origin and development of branches were studied in test trees of various ages and representing various types of forests and forms of stand. The material accordingly included young spruce plants (0—20 years), test trees from young stand (20—40 years) in various types of forests and stems suitable for cutting into pulpwood taken from various forms of stand in the most important types of forests. There were accordingly examined in all 100 spruce plants (10—20 years), 20 young trees (20—40 years) and 20 test trees of sizes ready for cutting. The division of the material as to types of forests and age classes appears in the following table:

Table I. — *Taulukko I.*

Ageclass *Ikäluokka*	Type of forests *Metsätyyppi* OT	MT	VT	Spruce swamps *Kuusikorvet*	Sum *Yhteensä*
0—20 years *vuotta*	25	25	25	25	100
20—40 »	5	5	5	5	20
40+ »	5	5	5	5	20
Sum — *yhteensä*	35	35	35	35	140

Each test tree was first examined as a standing tree at its place of growth. Accurate notations were made concerning the type of forest and the composition and condition of the surrounding stand. The ground cover was accordingly investigated carefully and recorded according to the Norrlin system (Cajander 1909). As regards the stand there were noted the percentage of various kinds of trees, and the crown projections surrounding each test tree were charted. Lighting conditions around each test tree were also taken into consideration.

Necessary measurements and complete stem analyses were made of each test tree felled. For the sake of certainty the taper curve was drawn at the place of felling. The trees were thereupon transported by automobile to Helsinki, where the origin, development and anatomical structure of the knots as well as the compression wood surrounding the knots were examined by means of cross and lengthwise cutting of samples, microscopic analyses and fiber maceration. Investigations were furthermore made of the physical, chemical, technical and other properties of the samples. Suitable parts of the material were tested by test grinding and cellulose cooking in the laboratories of the Institute of Technology for the purpose of ascertaining the usefulness of the wood in manufacturing in the paper industry.

1. Geographical origin of the material.

As will doubtlessly appear from the foregoing, the material was grouped partly with regard to the quality of the wood and its variations within various districts of Finland and partly with consideration to the biological factors affecting the development and growth of trees. Material for the first type of investigation was procured from woodworking plants representing the timber floating districts of the most important of the main waterways in Finland. The floating districts of the main waterways, the location of the respective mills and the districts from which their raw materials are obtained appear in the following map.

The material for the more thorough series of analyses to be made in Helsinki was chosen on the basis of the preparatory studies made at paper and pulp mills in such a manner that two cubic meters of pulpwood, pile measure, for each of the five classes of quality were taken from a mill in each district of quality wood. The following tables treat of the results of the ocular determination of quality at the various mills. Although these series are calculations based only on ocular measurements and errors can of course appear, the tables nevertheless give a relatively clear understanding of the variations of the quality of wood in different parts of the country.

Table II. — *Taulukko II.*

Name of the factory *Tehtaan nimi*	Number of knots per linear meter *Oksien lukumäärä juoksumetriä kohti*	Middle width of the annual rings mm *Keskimääräinen vuosilustoleveys mm*	Variations in the dimensions *Läpimittavaihtelut cm*	Middle dimension *Keskimääräinen läpimitta cm*
A.B. Kemi O.Y., Kemi	14	0.78	9.4—23.3	15.83
Toppila O.Y., Oulu	16	1.50	8.8—25.2	14.88
Kajaanin Puutavara O.Y., Kajaani.	15	1.04	9.3—24.7	15.09
Hackmann & Co., Johannes	22	1.65	8.9—22.9	16.05
Yhtyneet Paperitehtaat O.Y., Walkiakoski	17	2.01	7.9—26.2	15.24
Myllykoski	18	1.90	8.0—27.1	14.11
Rauma Wood O.Y., Rauma	15	1.97	8.1—25.6	15.00
Aug. Eklöf A.B., Tolkis	21	2.27	7.5—26.0	13.92

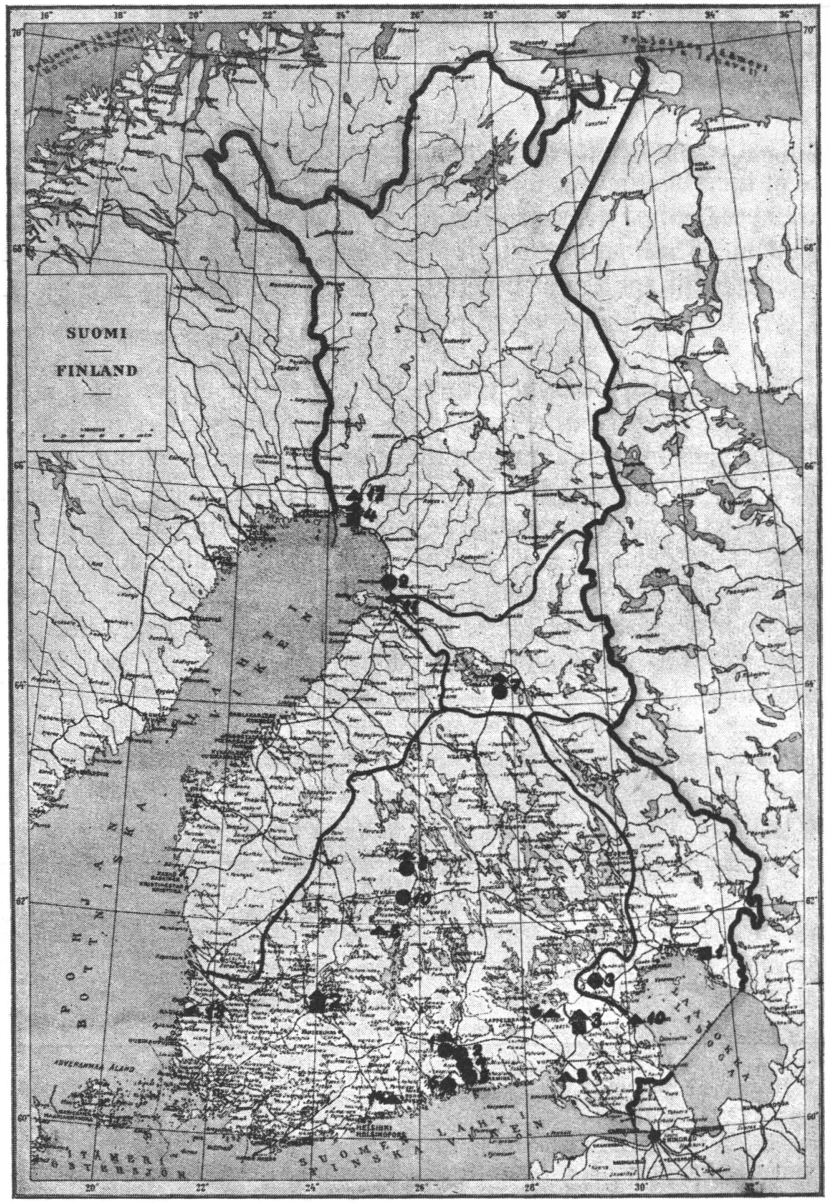


Fig. 1. The districts of the main waterways and the location of the mills from which test material was brought. — *Kuva 1. Päävesistöalueet ja tehtaat, joiden puuvarastosta tutkimusaineistoa hankittiin.*

Mechanical woodpulp mills.

1. Kymmene Aktiebolag, Kuusankoski, Kymmene, Voikka.
2. Yhtyneet Paperitehtaat O.Y., Myllykoski.
3. » » » Simpele.
4. Tammerfors Linne & Jernmanufaktur A.B., Inkeroinen.
5. Karhula Osakeyhtiö, Karhula.
6. Stockfors Aktiebolag, Pyhtää.
7. Kajaanin Puutavara O.Y., Kajaani.
8. Äänekoski. A.B., Äänekoski.
9. Raahe Osakeyhtiö, Haukipudas.
10. Kangas Pappersbruk, A.B., Jyväskylä.

Sulphite pulp mills.

1. Kymmene Aktiebolag, Kuusankoski, Kymmene, Voikka.
2. Yhtyneet Paperitehtaat O.Y., Valkeakoski.
3. Enso Gutzeit Osakeyhtiö, Enso.
4. A.B. Kemi O.Y., Kemi.
5. Yhtyneet Paperitehtaat O.Y., Jämsänkoski.
6. Kaukas Fabriks Aktiebolag, Lauritsala.
7. Kajaanin Puutavara O.Y., Kajaani.
8. Äänekoski Aktiebolag, Äänekoski.
9. Hackmann & Co., Johannes.
10. A.B. Waldhof O.Y., Käkisalmi.
11. Toppila Osakeyhtiö, Oulu.
12. Veitsiluoto Osakeyhtiö, Kemi.
13. Rauma Wood O.Y., Rauma.
14. Aug. Eklöf Aktiebolag, Tolkis.

Sulphate pulp mills.

1. Diesen Wood Co. A.B., Pitkäranta.
2. Yhtyneet Paperitehtaat O.Y., Valkeakoski.
3. Enso Gutzeit Osakeyhtiö, Enso.
4. A.B. Kemi O.Y., Kemi.

It will be immediately observed that northern Finland, ie., Lapland and the northern part of East Bothnia with the River Ii as the southern boundary, constitute a decidedly limited quality district. Wood from these parts is particularly full of knots and compression wood. The investigations of Blomqvist have already shown with particular clarity that spruce of northern Finland is conspicuous for a very slowly occurring pruning process. These studies have later been verified by Cajander, Wahlgren, Enander, Lakari, Klem and others. The stems are covered with living and dead knots down to the very base. Wood of northern Finland is furthermore distinguished by the cross-section of the stem often being oval as to its shape and the trees also showing as a rule a clearly visible spiral grain.

The quality of wood changes clearly south of the River Ii. In districts around the Gulf of Bothnia as far south as Kristiinankaupunki the forests have been subjected for a long time to extensive cuttings primarily for the export of round wood (Kalm 1771) and the stands as a result thereof are open and bunched. Trees therefore have thick branches and present evidence of fast growth with wide annual rings, particularly when considering the rather rigorous climate. The taper of the stems is great and the form class according to Jonson's system is comparatively low.

Wood in the Kainuu districts, ie., in the vicinity of Kajaani, Sotkamo, the Hyrynsalmi watershed and northern Carelia, comes principally from marshy spruce forests. The increment is rather insignificant but the wood has grown in close stand and the stem form is good. Pulpwood from the districts of the more northerly sources of the Saimaa basin is very much like Kainuu wood but the trees are somewhat more coarse grained.

Carelian spruce wood is conspicuous for its qualitatively high properties, with the exception of assortments from the Isthmus of Carelia. The stem form is good and the occurrence of knots insignificant.

Spruce forests around the great inland lake basins are seldom composed of clear stands, as is well known, but consist mostly of mixed forests. When spruce has grown in broad-leaf and pine forests, where the supply of light is greater than in clear stand, it assumes a more branchy form and develops into less compact wood. It can therefore be maintained that wood obtained from Savo is as a rule qualitatively inferior to spruce wood in Carelia and in the district of Häme, which originates principally from clear spruce stands.

As has appeared both from Vuoristo's investigations of 1936 and from the author's observations, spruce wood in the district of Häme is particularly similar to that of southern Finland. Quality varies greatly due to the irregularity in the condition of the forests from the silvicultural point of view, but the growth rate as well as the possibilities for development are on the whole the same. On the basis of the preliminary studies which were made when considering the main waterways leading to the various manufacturing plants, the country has been divided into five zones for the purpose of comparing quality. These are as follows:

1. Lapland and northern East Bothnia;
2. The coastal region of East Bothnia and northern Satakunta;
3. Kainuu, northern Carelia and the most northerly district of Savo;
4. Central and eastern Carelia; and
5. Southwestern Carelia, Uusimaa, Häme, Finland Proper and southern Savo.

The geographical division of the zones of quality appears in the attached map. In making a study thereof it should however be observed that the boundaries are approximate and have been based only on the ocular studies of the raw material stocks made at the various manufacturing plants.

Since the cellulose mill of the Kemi Company is the largest manufacturing plant in northern Finland both as regards production capacity and the size of the district from which raw materials are procured, the author considered this company's supply of timber to be suitable for illustrating the variations in the quality of northern Finnish wood.

The sulphite pulp mill of A.B. Kemi O.Y. uses as raw material for manufacture spruce pulpwood which is floated or transported by truck from the forests around Kemi, the watersheds of the Ii rivers, Kuolajärvi and Kuusamo. The sulphate mill on the other hand uses as raw material edgings and other sawmill waste from the company's 12-frame sawmill in Karihaara and the 4-frame sawmill on the island of Laitakari and pine pulpwood. Since the quality of wood in northern Finnish spruce timber is particularly heterogeneous and pulpwood contains both a large percentage of knot wood with a large amount of ingrown knots and bark and also considerable compression wood and decay, spruce pulpwood is sorted in the large barking drum of the mill so that timber which is damaged by decay, is particularly full of knots and contains considerable compression wood is segregated for the use of the sulphate mill while the sulphite mill uses only the better grades of spruce.

The division of the various ocular quality classes of Kemi wood appears in the following table. This shows the variations in the quality of Kemi

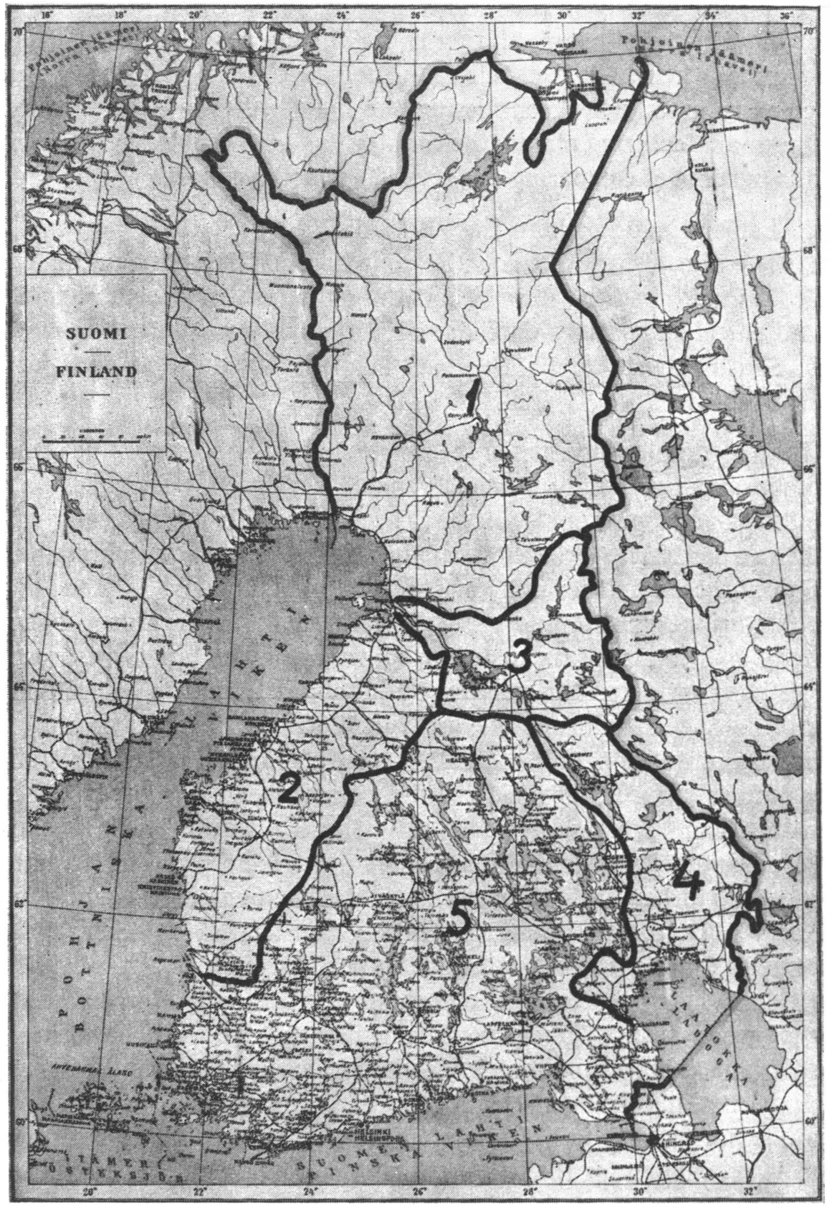


Fig. 2. The geographical division of the zones of quality. — *Kuva 2. Laatuvyöhykkeiden maantieteellinen sijainti.*

pulpwood during three working shifts. There were chosen from this material two cubic meters, pile measure, for each quality class, or 200 bolts in all, which were transported by steamer to Helsinki for further investigation. The timber originated in the districts around Kemijärvi and Pelkosenniemi, and was floated during 1935 to Kemi after having been felled and hauled out of the woods during the autumn of 1934.

Table III. — *Taulukko III.*

The division of ocular quality classes for »Kemi» wood.
Kemin piirin paperipuun jakaantuminen laatuluokkiin.

Quality class *Laatuluokka*	I	II	III	IV	V	Sum *Yhteensä*
Number of bolts.... *Pölkkyjen lukumäärä.*	430	648	162	231	129	1 600
%	27.	40.	10.	15.	8.	100.

The quality of spruce pulpwood in the Kainuu district is best illustrated by the Kajaanin Puutavara Osakeyhtiö's wood stocks at the mills in Kajaani. This industrial establishment produces from timber obtained only in this region. The major portion of its pulpwood is acquired from forests around the Hyrynsalmi, Suomussalmi, Sotkamo and Kuhmoniemi basins. Variations in quality in Kajaani timber appear from the attached table. Since the fifth ocular quality class was so insignificantly represented and furthermore resembled to such an extent the bolts of compression wood from Kemi, there appeared to be no reason for choosing wood representing this class. There were however transported to Helsinki two cubic meters of wood of each of the remaining quality classes. The length of the bolts was two meters and their number 160 in all. The timber originated in the district of Kuhmoniemi. It was felled during the winter of 1934—1935 and floated to Kajaani during the summer of 1935. Transportation to Helsinki was made by railway.

As will be observed, the breadth of the annual rings in Kajaani wood is only slightly greater than in Kemi timber. Kajaani wood is also very dense as regards growth. The greatest difference appears in the occurrence of knots and in the form of the stems. Kajaani timber is in all respects clearer of knots, has a straighter grain and contains less formation of compression wood than Kemi wood.

Table IV. — *Taulukko IV.*

The division of ocular quality classes for »Kajaani» wood.
Kajaanin piirin paperipuun jakaantuminen laatuluokkiin.

Quality class *Laatuluokka*	I	II	III	IV	V	Sum *Yhteensä*
Number of bolts .... *Pölkkyjen lukumäärä.*	211	447	225	193	74	1 150
%	18.	39.	20.	17.	6.	100.

Timber from East Bothnia and northern Satakunta is extensively exported in the form of pulpwood and pit props. The most important consumers of spruce wood of lesser dimensions are the two sulphite pulp mills in the district; Toppila O.Y. located in Oulu and Jakobstads Cellulosa A.B. in Pietarsaari. The paper industries in Pori also consume timber obtained from this region. Toppila Osakeyhtiö procures timber for its sulphite pulp mill in Oulu partly from the forests around the river Oulu, partly from the district of the Ii watershed and partly from delivery points in the district of the East Bothnia rivers. A very considerable portion is made up of timber from Siikajoki, Pyhäjoki and Kalajoki. While wood from Iijoki resembles Kemi wood to a great extent, timber from the rivers south of Oulu is as regards its characteristics quite similar to that of southern Finland. For that reason it is placed separately in wood yards. The annual rings are wider and knots have greater dimensions although the number of knots per linear meter is less than in the Kainuu and Kemi regions. A total of 160 bolts of two meters each in length, representing the various classes of quality except the fifth, which was practically speaking not represented, were chosen as characteristic of the quality of wood in these more southerly districts. The timber originated in the buying districts around the river Siikajoki. It had been felled during the autumn of 1934, floated in 1935 to the Ruukki station and then transported by rail to Toppila. Variations in quality of wood obtained from Siikajoki and Pyhäjoki appear in the table below, based on ocular observations made while transporting to the barking drum. The timber was transported by steamer to Helsinki for more accurate analysis.

Table V. — *Taulukko V.*

The division of ocular quality classes for »Toppila» wood.
Toppilan piirin paperipuun jakaantuminen laatuluokkiin.

Quality class *Laatuluokka*	I	II	III	IV	V	Sum *Yhteensä*
Number of bolts.... *Pölkkyjen lukumäärä.*	162	556	290	179	13	1 200
%	14.	46.	24.	15.	1.	100.

Timber from the Saimaa floating districts, from the Isthmus of Carelia and from the coastal regions along the Gulf of Finland as far as Virolahti is used in the sulphite pulp mill of Hackmann & Co. Aktiebolag at Johannes. The region from which the mill obtains its material is accordingly particularly extensive. It extends as far north as Sotkamo and the northern sources of Pielisjärvi. The wood yard of the mill at Johannes has accordingly all the possibilities of being able to present a clear picture as to the quality of timber and its variations in Carelia and Savo. The studies as to the qualitative characteristics of pulpwood which were made at the mill showed the timber from northern Savo greatly to resemble that of Carelia. On the other hand timber from the southern section of Saimaa had a considerably greater rapidity of growth and contained a greater number of knots. The material for analysis was segregated into four classes just as in Toppila and Kajaani so that it represented the slow grown timber from the northern and eastern parts of the district of delivery and illustrated the conditions of quality in Saimaa wood. The timber was felled during the winters of 1933—34 and 1934—35 and floated to the mill. The material for analysis originated in the Kallavesi and Joensuu purchasing districts and was transported by rail to Helsinki. It comprised in all six cubic meters, pile measure, or 240 bolts.

The variations in quality in the wood yards of Hackmann & Co. at Johannes are illustrated in the attached table.

Table VI. — *Taulukko VI.*

The division of ocular quality classes for »Hackman» wood.
Johanneksen piirin paperipuun jakaantuminen laatuluokkiin.

Quality class *Laatuluokka*	I	II	III	IV	V	Sum *Yhteensä*
Number of bolts.... *Pölkkyjen lukumäärä.*	119	693	231	111	6	1 160
%	10.	60.	20.	10.	0.	100.

The quality of timber in southern, central and southwestern Finland is illustrated partly by the ocular studies made of pulpwood at the Valkeakoski paper and sulphite pulp mills and Eklöf's pulp mill and partly by the test trees taken from Ruotsinkylä. Since Ruotsinkylä timber could not be directly compared as regards its technical properties for manufacturing to the qualities of pulpwood of the mills because of its having been recently felled and not floated, the material for investigation was furthermore supplemented by samples of sulphite timber chips obtained at the pulp mill of Eklöf A.B. at Tolkis.

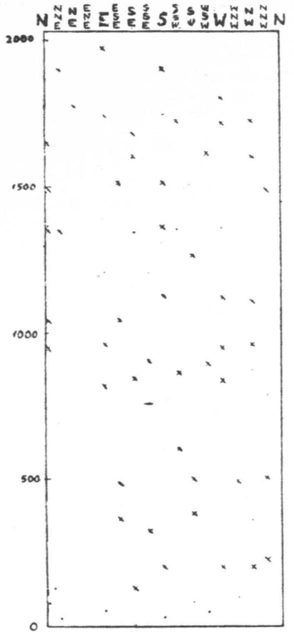
2. The habitat of the material. Possibilities of development during the growth period.

The material for investigation acquired at the Forestry Research Institute's experimental station in Ruotsinkylä provided the basis for the studies covering the effectiveness of the place of growth and the form of the stand on the occurrence of branches in spruce. As has previously been mentioned, this material comprised fully grown trees, young trees and plants representative of the most important types of forests and forms of stand. Table m (page n) shows the division of the various test trees into types of forests, forms of stand and age classes. The analyses which were made as to the occurrence of branches and their development during various conditions of growth appear in detail in the following tables. Calculations covering locations within the stand, the relationship of the crown projections to each other, the dimensions of the trees, the occurrence of branches and their sizes were made for each tree and the graphic analysis covering each stem was drawn.

The results are more apparent when scrutinizing separately each of the various types of forests and age classes.

a. *Spruce stands in localities of the Oxalis type.*

The large trees chosen to represent the quality of wood and the occurrence of branches in forest stand on Oxalis type of ground (OT) were felled in spruce stand which had recently been thinned. The trees were 50 years old on the average. Considerable felling of the stand was done in 1934 and ash and oak were planted in 1935 to protect the remaining, dominating trees. Because of the slight density of the forest (the combined area covered by the crown projections constituted about 60 % of the ground area), the trees had a low form class, according to Jonson 0.57. The occurrence of branches was also very great, ie., they covered 4 % of the surface of the stems. Upon examining the extent that the occurrence of branches varied in the various parts of a stem, it was found to be very great throughout, and that only about one-fifth of the stem on the average was free of branches.



	2030	1000	0
ø N–S	45	75	95
ø W–E	45	74	93
Medel ø	45	74.5	94
antal års-ringar			

Stam N:o O₁

läge	riktn.	ø vid stam
1970	E	19
1900	NNE	20
1900	S	15
1800	W	15
1770	NE	14
1740	E	15
1720	NW	14
1720	SSW	13
1715	W	6
1675	SE	11
1645	N	4
1610	WSW	13
1600	NW	4
1600	SE	4
1515	S	6
1515	ESE	9
1510	ENE	5
1495	W	4
1490	NNW	4
1485	N	3
1365	N	2
1360	SE	1
1360	S	4
1360	W	3
1355	SSW	2
1345	NNE	2
1345	N	6
1345	SE	4
1345	SE	2
1265	SW	21
1205	E	4
1205	SSE	2
1195	SE	3
1125	S	20
1120	W	11
1105	NW	15
1045	ESE	18
1040	N	12
960	E	14
960	NW	17
950	W	14
945	N	13
905	SSE	10
895	WSW	5
880	N	3
875	NW	3
870	ENE	2
865	SSW	6

Fig. 3. Knot analyse of a stem bolt. —
Kuva 3. Runkokappaleen oksa-analyysi.

The foregoing concerns the older trees in the stand. Upon examining those which represented the middle crown layer, ie., the ages of which varied between 20 and 30 years, it was found that the presence of branches was appreciably less. The reason therefore can be traced partly to the fact that they had grown in much denser formation, with the result that natural

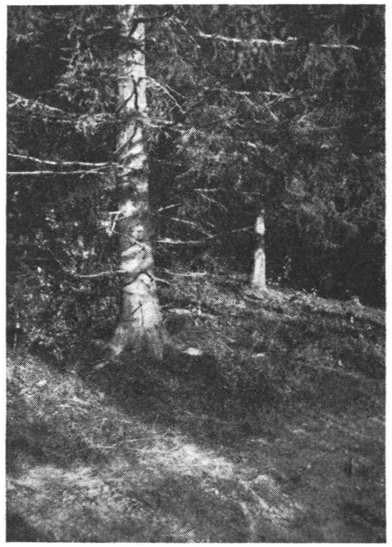


Fig. 4. Branches in forest stand on Oxalis type. — *Kuva 4. OT-metsikön oksaisuutta.*

Fig. 5. Branches in forest stand on Myrtillus type. — *Kuva 5. MT-metsikön oksaisuutta.*

Table VII. — *Taulukko VII.*

OT stand.
OT-metsikkö.

	Age y. *Ikä v.*	Length *Pituus*	D 1.3 *cm*	Form class *Muotoluokka*	Branch free stem part *Oksaton rungonosa*	
		m.			*m.*	%
Dominating crown layer *Vallitseva latvuskerros*	50	16.5	42.5	0.575	1.9	12
Middle crown layer *Keskimm. latvuskerros*	20—30	6.5	10.5	0.625	1.5	23
Plant stand *Taimisto*	0—10	0—1.2	—	—	—	—

limbing had also been much more effective. Even in plant stands of less of 10 years of age, it could be observed that great density had reduced the occurrence of branches. A factor contributing to this situation was furthermore the thriving vegetation on the ground, causing the branches to exert themselves to the greatest extent in order that longitudinal increment would become as great as possible and the plant would be able to subdue the herbs in the hard struggle for sunlight and the possibility of existence.

b. *Spruce stands in localities of the Myrtillus type.*

Trees from stand that had grown on Myrtillus type of ground (MT) were chosen from a rather dense and closed forest (the crown projections covered 85 % of the surface of the ground). The average age of the forest was 75 years for the dominating trees, 30 years for the middle crown layer and 0—10 years for plants.

Table VIII. — *Taulukko VIII.*

MT stand.
MT-metsikkö.

	Age y. *Ikä v.*	Length *Pituus*	D 1.3 *cm*	Form class *Muotoluokka*	Branch free stem part *Oksaton rungonosa*	
		m.			*m.*	%
Dominating crown layer *Vallitseva latvuskerros*	75	22.5	33.0	0.725	4.5	20
Middle crown layer *Keskimm. latvuskerros*	30	6	10	0.70	2	20
Plant stand *Taimisto*	0—10	0—1	—	—	—	—

Table IX. — *Taulukko IX.*

VT stand.
VT-metsikkö.

	Age y. *Ikä v.*	Length *Pituus*	D 1.3 *cm*	Form class *Muotoluokka*	Branch free stem part *Oksaton rungonosa*	
		m.			*m.*	%
Dominating crown layer *Vallitseva latvuskerros*	85	19.5	26.5	0.75	6.0	31
Middle crown layer *Keskimm. latvuskerros*	35	6	10	0.70	2	20
Plant stand *Taimisto*	0—15	0—1	—	—	—	—

Fig. 6. Branches in forest stand on Vaccinium type. — *Kuva 6. VT-metsikön oksaisuutta.*

The occurrence of branches was consequently less on Myrtillus type of ground than in Oxalis stand. The reason therefor lies partly in the fact that the Oxalis stand was more open. But this was also due to a series of physiological factors. As a consequence of the limitation in the afflux of nutrition, the process of life in the form of activity in the increment of the tree is less extensive when the site quality of the forest decreases. This in turn leads to the fact that the need for assimilating organs is lessened.

As will appear from the attached tables, the occurrence of branches in plant stands on Oxalis type of ground is less than in plants on Myrtillus type. This is caused by the fact that the ground in an MT forest is less covered with grass. The plants can therefore develop a stem form having an increased number of branches and need not strive toward maximum longitudinal increment in the same manner as OT plants.

c. *Spruce stands in localities of the Vaccinium type.*

The stands from which trees in Vaccinium stands (VT) were chosen were very much similar as regards structure to the Myrtillus stands. The principal difference was that the trees were somewhat more scattered, a natural consequence of the fact that natural limbing occurs more extensively on poorer qualities of sites. As is apparent from the tables, the occurrence of branches was less in spite of the more open forest than in the MT forest.

d. *Spruce stands grown in spruce swamps.*

The trees representing the conditions of increment, the forms of the stems and the occurrence of branches in spruce which had grown in swamps showed clearly that the process of increment in such wood is much slower than what it would have been if the physiological circumstances of nutrition were of a more favorable nature. The occurrence of branches is also therefore much more limited than in the remaining types of forests.

Fig. 7. Branches in forest stand on spruce swamps. — *Kuva 7. Korpikuusikon oksaisuutta.*

Table X. — *Taulukko X.*

Spruce swamp stand.
Korpikuusikko.

	Age y. *Ikä v.*	Length *Pituus*	D 1.3 *cm*	Form class *Muoto-luokka*	Branch free stem part *Oksaton rungonosa*	
		m.			*m.*	%
Dominating crown layer *Vallitseva latvuskerros*	105	18.6	22.5	0.725	6.2	33
Middle crown layer *Keskimm. latvuskerros*	55	6.5	9.5	0.675	2.5	26
Plant stand *Taimisto*	0—20	0—1	—	—	—	—

It is naturally of the greatest interest to know how the density of a stand affects the occurrence of branches in stands of various ages and types. In order to be able to draw reliable conclusions with sufficient exactitude and certainty, there is however required a very extensive supply of material. Since the present study in such a case would have become altogether too extensive, this part has had to be treated with the greatest brevity. There exists as is known a clear and close relationship between the stem form of a tree and the occurrence of branches. It can likewise be ascertained that there is a clear connection between the form of a stem and the length of the portion of the stem which is free of branches.

If it is a question of determining the occurrence of branches and the relative length of the portion of the stem free of knots in a growing forest, Jonson's method of ascertaining the relative height of the form point constitutes a very suitable and practical manner of procedure. If such a series of investigations is furthermore supplemented by tests made at random covering the thickness of branches and the distances between them, there is obtained a rather clear picture of the fluctuations in the occurrence of branches as resultants of the type of the forest and the form of the stand. The foregoing theory gave the author the thought of investigating the variations in the occurrence of branches in stand of varying density and on forest lands of differing site quality through studies covering the height of the form point. The results which were thus obtained appear in the following table.

Table XI. — *Taulukko XI.*

Type of forest *Metsätyyppi*	OMT			MT & VT			Spruce swamps *Kuusikorvet*		
Closeness of the forest *Metsikön tiheys*	very closed *tiheä*	normal *tav.*	not closed *harva*	very closed *tiheä*	normal *tav.*	not closed *harva*	very closed *tiheä*	normal *tav.*	not closed *harva*
Anjala	0.70	0.65	0.55	0.70	0.625	0.55	0.70	0.625	0.55
Sotkamo	0.675	0.625	0.55	0.65	0.625	0.55	0.65	0.60	0.525
	Branch free stem part %. — *Oksaton rungonosa* %.								
Anjala	25	20	15	27	22	15	26	22	17
Sotkamo	22	18	14	25	21	15	23	20	16

3. The occurrence and kinds of branches in the research material.

The distribution of branches and their ocularly typical properties in the various groups of the research material appear in the following tables and diagrams. In this connection the living and dead branches have been segregated, as also the scattered branches and the branches located in clusters. The analyses of branches made concerning the individual stems show furthermore how the occurrence of branches is distributed at various heights above the ground.

Upon examining the foregoing tables and diagrams it is found that there is no set relationship between site quality and the type of forest on the one hand and the number of branches on the other. The diameter of

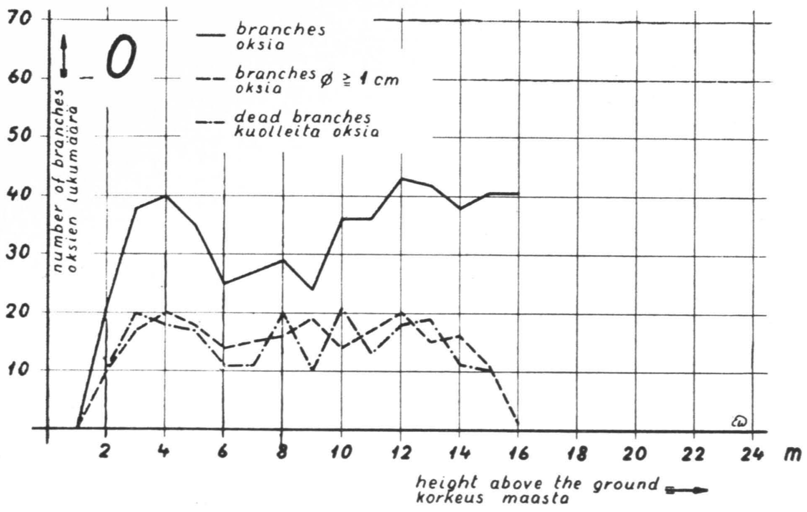


Fig. 8. Diagram showing the division of branches at various heights above the ground on a test tree from Oxalis type. — *Kuva 8. OT-koepuun oksaisuuden jakaantumista osoittava diagramma.*

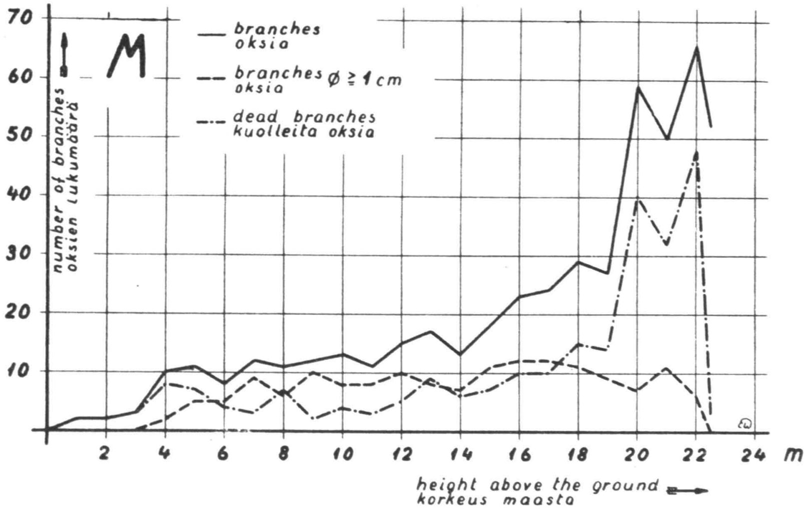


Fig. 9. Diagram showing the division of branches at various heights above the ground on a test tree from Myrtillus type. — *Kuva 9. MT-koepuun oksaisuuden jakaantumista osoittava diagramma.*

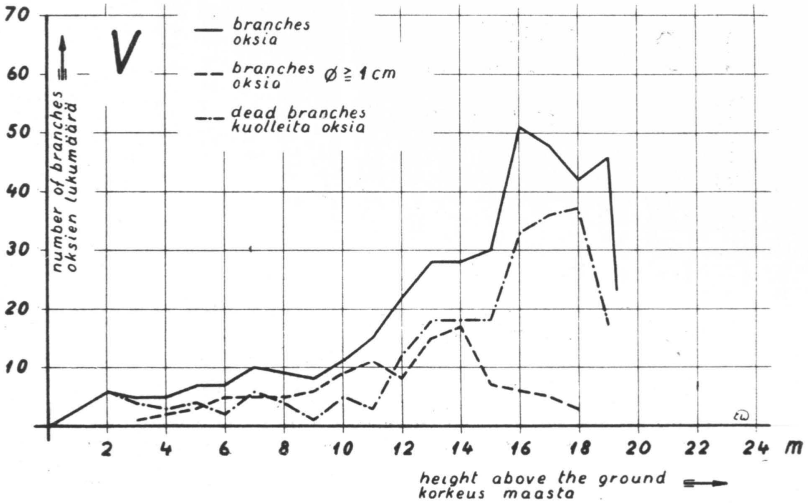


Fig. 10. Diagram showing the division of branches at various heights above the ground on a test tree from Vaccinium type. — *Kuva 10. VT-koepuun oksaisuuden jakaantumista osoittava diagramma.*

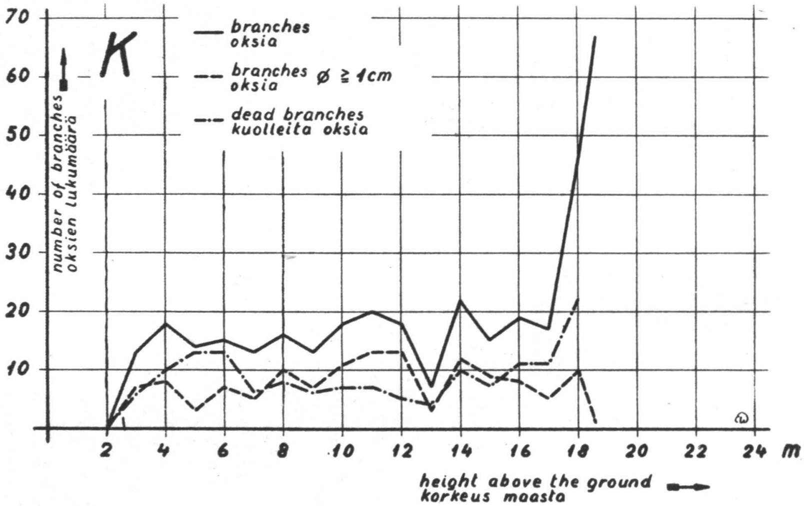


Fig. 11. Diagram showing the division of branches at various heights above the ground on a test tree from spruce swamp. — *Kuva 11. Kuusikorpi-koepuun oksaisuuden jakaantumista osoittava diagramma.*

the branches appears however to stand in a direct relationship to site quality, and the trees having the thickest branches are found as a rule in the better qualities of sites while swamp spruce has the thinnest branches. It is however difficult to state whether this situation can be regarded to depend upon the quality of the site or whether it is a result of the form of stand and the degree of density.

As regards the occurrence of dry and dead stubs, it appears as if this stands in relation to the number of living branches. Natural pruning was best on Vaccinium type (VT), but it was also considered good on Myrtillus type (MT). Spruce on Oxalis type pruned the least, while swamp spruce showed the greatest number of dry branches.

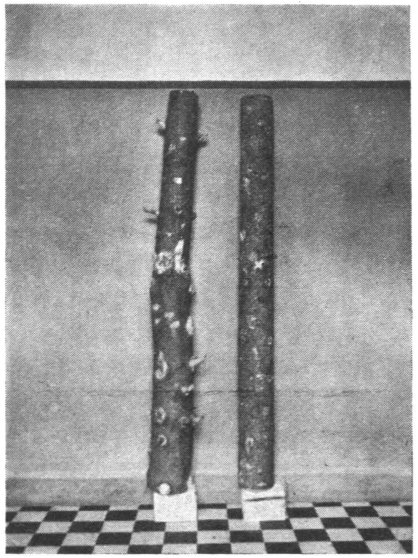


Fig. 12. Stem bolts from Oxalis and Myrtillus forests. — *Kuva 12. OT- ja MT-metsiköiden koepuukappaleita.*

The ocular studies of quality which were undertaken in various spruce stands based on Jonson's form classes showed also a similar tendency. It is possible to draw the conclusion therefrom that natural pruning occurs as a rule most effectively in spruce forests on MT and VT types of stands. Although swamp spruce often has the living crown located very high up, the proportion of dead branches is however as a rule great and shows an expansive spread downward toward the base of the stem.

As a generally applicable rule it can consequently be established that the occurrence of branches is primarily the result of the density of the stand during the early growth period. Natural pruning occurs in general more slowly on the most thriving and most barren quality sites than on those of average quality.

CHAPTER V.

Origin and development of branches.

The statement that the occurrence of branches and knots constitutes a significant factor decreasing quality in practically all activity where wood is used is both well-known and unquestionable. This applies to all uses made of wood where demand is placed in its strength properties, on the quality of its fibers and on the evenness of its chemical consistency. The most notable exception is the use made of wood as fuel. Because of its greater density and higher content of incrustations, branch and knot wood has per cubic unit a higher fuel value than normal stem wood. It should nevertheless be observed that working difficulties, particularly in splitting, are greater where the wood contains knots.

In view of the foregoing, quality wood is therefore understood to be wood which has attained a structure as free of knots as possible by means of various methods of care of stand such as raising in dense stand and pruning. In this connection it is principally a case of endeavoring to obtain as long a stem free of knots as possible and to advance the crown as high up toward the top of the tree as possible.

In order to understand the biological possibilities of obtaining quality timber free of knots, it however becomes necessary to understand the conditions which affect the structure of branch wood. Only by means of a knowledge of these biological, primary factors is it possible to judge the possibilities of being able to improve, with regard to the presence of knots, both the quality of timber and the methods of manufacture. The following points come to the fore in this connection:

1. The origin of branches;
2. The process of increment in and around knot wood; and
3. The decay of branches and the healing over of knots.

1. The origin of branches.

It can be observed everywhere in nature that living organisms strive during their development to consume the available materials for their growth in as economic a manner as possible so that demands on mechanical stability are satisfied to the greatest extent possible while at the same time taking into consideration the physiological factors. The more advanced stage of development that the plant represents in the botanical scheme, the greater is also the degree of the division of labor that has occurred as between its various organs. The orthotropic, main axle has no longer been able to satisfy all the requirements it has had to fulfill. The support of the organs of assimilation and evaporation has therefore been transferred to the lateral axles, which vary in number and size. This division of labor is particularly accomplished to an advanced stage in various kinds of trees. Coniferous trees, principally abietacans, are distinguished in this connection by a developed regularity in axillary structure.

The fundamental reasons for the branching of plants are as yet entirely uncertain, just as Goebel (1928) and others have stated. It can perhaps be maintained however that these are of a physiological nature and are the expression of irritations in the embryonic portions.

The organographic and cytological origin of branching is on the other hand a question that has already been completely analyzed in botanical science. It has been ascertained that the development of new organs in each anaphyte occurs in the apical point of vegetation which is found at the extreme end of each growth axis capable of life. The cytological structure of the vegetative point has been thoroughly analyzed by Nägeli, Hanstein, Sachs, Dingler, Korschelt, Haberland, Schwendener, Karsten, Goebel, Jost and others.

The descriptive term »vegetative point» originated in K. Fr. Wolff's work Theoria Generationis (Halle 1759), which laid the foundation for the history of botanical development. The longitudinal growth of the main axle is continued exogently out of the embryonic portions of this growing point, from which the respective branching clusters also arise in plants of the higher order, such as Picea exelsa.

Karsten (1886) maintains on the basis of numerous microscopic analyses of various Abietinae-kinds of growing points that the medial lengthwise section through the growing point in plants of this family within the botanical scheme always produces in the main an identical configuration.

In the middle there is found a texture lacking in protoplasm but highly resinous, which consists of lengthened, lamellar attached rows of cells, the so-called plerome.

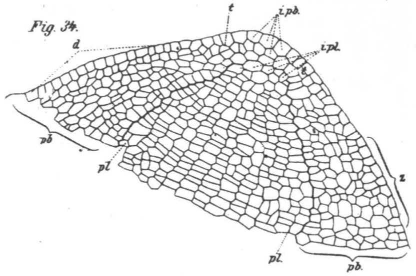


Fig. 13. The growing point in Picea-excelsa (according to Karsten).— *Kuva 13. Kuusen kasvupiste (Karsten'in mukaan).*

These cell tissues can always be-traced back to a narrower limited zone of primary cells (ipl, fig. n.). The plerome texture is surrounded by a cell tissue having a particular abundance of protoplasm called periblem (pb, fig. n). The primary cells in this layer of texture areto befound in the two uppermost groups of cells closest to the top of the growing point (Karsten 1886).

In phanerogamic plants the primarycells correspond to the one-cell growing point of cryptogams. (»Scheitelzelle»), (Eltving 1930).

Karsten (1886) maintains that the outermost layer of cells in the vegetative growth bud, which is characteristic of phanerogamic plants, the so-called dermatogen in Abietacans as well as also in Lycopodiaceae, is almost completely missing; the dermatogen is discernible only as four or two cells which cover the growing points.

During the further development of the plant there come later into existence:

a. the pith and the medullary rays, ie., the parenchymatous cell tissues, out of the plerome;
b. the cambial textures out of the periblem, which continue the growth formation of the plant in thickness and of the assimilating portions of the plant. The lateral buds from which the plagiotropic, lateral axes originate are also formed out of the periblem and accordingly originate exogenously at the growing point;
c. the dermatogen which gives rise to the outermost cell layer.

The branching process takes place in all coniferous trees in accordance with the monopodial system, ie., the increment originates from the one

and the same growing point, so that the orthotropic main stem continues in the same direction (Müller 1888). The increment occurs furthermore acropetally; the older the parts of the stem and branches, the more distant are they from the growing point. In addition, it may be mentioned that the increment occurs periodically through the influence of climatic periods. The bud is formed at the end of a growing period. During the following period of rest it develops further, although at a very slow rate. And finally, during the succeeding growing period, the bud opens. There accordingly occurs a rather long period of time, varying from six to ten months of development, between formation and opening (Benecke-Jost 1923).

As has previously been mentioned, both the leaves and the lateral branching are formed in acropetal sequence out of the periblem layer of the growing point. In phanerogamic plants the point having the tendency to branching always takes in this connection the form of a lateral bud in the leaf axil between a leaf or source of leafing and the stem (Fitting 1936, Goebel 1923). This source of branching undergoes little by little the same development as the orthotropic growing point, the terminal bud.

In coniferous trees of the gymnospermous class the leaves appear exogenously acropetally in spiral-like, cyclic sequence out of the periblem of the growing point. In this connection the plagiotropic source having the tendency to branching appears in the leaf axil above the leaf and between it and the stem. It should however be observed that the points having a tendency to branching actually become developed in only a few of the leaf axils (Schwartz 1892, Fitting 1936, Benecke-Jost 1923).

A spruce plant makes its appearance, as is well-known (Blomqvist 1883 and others), after germinating three to five weeks. Its tender stem an inch in length supports at the top six to nine star-like cotyledons which in the beginning are held together by the thin seed coat. In addition to these cotyledons the plant develops still during the first year a little shoot, the length of which is dependent upon the fertility of the soil and the supply of light in the forest stand. There is also developed a little terminal bud on the top.

During the second year the terminal bud sends out a little annual shoot which is densely covered with needles and which sends forth, in addition to its own terminal bud, two to four buds lying in a circle immediately thereunder. One or several irregularly placed buds also appear on the small, annual shoot (Blomqvist 1883).

Tubeuf (1891) maintains that cotyledons in spruce have one toothed

Fig. 14. One-year-old spruce plant (according to Blomqvist) scale 1 : 2. — *Kuva 14. 1-vuotinen kuusentaimi (Blomqvistin mukaan) m. 1 : 2.*

edge while primary needles present two toothed edges. It is only in the third year that needles have smooth edges and show a rhombic crosssection area.

The first branches appear at the base of the third year's shoot. They are located in a whorl-like position and are usually still indefinite in number. Even under favorable growing conditions it is not until the fourth or fifth year that spruce develops regular knot whorls consisting of three or more branches. Furthermore, small branches appear indiscriminately in the uppermost shoot, particularly in the vicinity of the top. These small, intermediary branches, which often by chance appear to be in whorl-like groups, do not develop on the whole as actively as the branches in whorl-like position. The majority of them attain only an insignificant length and soon dry aaway. Because of this irregularity in the formation of branches it is not possible on the basis of the number of whorls of branches to determine the age of spruce with as great certainty as that of pine (Blomqvist 1883).

The whorls of branches in spruce develops symmetrically so that there are annually formed at the base of the uppermost shoot three or more radially grouped branches. The reason for this condition is to be found in the regularity which controls the acropetal origin of the places for leaf formation around the growing point. The places for the formation of leaves as well as branches occur spirally in this connection from the base toward the top. The geometric placing of the branch buds is accordingly directly dependent upon the location of the places for leaf formation with relation to each other. These positions of leaves have been ascertained by Schwendener in a mechanical-geometrical manner. He gives primary consideration to the reciprocal pressure between the places for leaf formation in the growing point. This is in turn dependent upon the increment and the change in the volume of the axle.

The spiral position of the places for leaf formation can be expressed simply as a fraction (Schwarz 1892) in which the numerator expresses the number of times the spiral has circled around the main axle before a place for leaf formation has reached the »ortho» or vertical position above the previous one. The denominator indicates the sequence of the lateral organ calculated from the previous branching which is radially in a similar position. This fraction accordingly indicates the angle of divergence between the places for leaf formation.

In a particular conifer higher values of divergence (1/2, 1/3, 2/5, 3/8, 5/13 et cetera) prevail in the terminal buds, which are larger and more capable of development, than in the weaker lateral buds out of which the branches originate. In other words the axles of increment of a different order in a tree present a spiral position of the leaves and branchings with differing steepness and density (Müller 1888). It can therefore be maintained that the rule that the angle of divergence is constant for each species of trees is not accurate. The abundance of branching in each knot whorl accordingly varies also in spruce. Lateral branches of a number dependent npon outside circumstances develop in the axils of only a few places for leaf formation. The number of branche is influenced not only by the grow-ing ability of the plant but also by lighting conditions and the form of the stand.

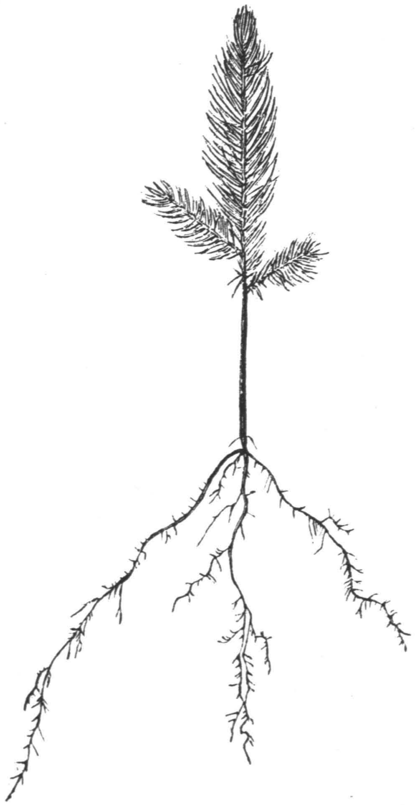


Fig. 15. Two-year-old spruce plant (according to Blomqvist) scale 1 : 2. — *Kuva 15. 2-vuotinen kuusentaimi (Blomqvistin mukaan) m. 1 : 2.*

With regard to the branching of spruce it may furthermore be stated as always occurring racemosely both from the radially symmetrical stem as well as from the dorsiventral, lateral branches of the lower order (Schwarz 1892, Fitting 1936). The main axle is developed more actively than the lateral axles of the first order; these in turn more actively than the subsidiary branches of the second originating therefrom, et cetera.

With the increase in the age of the axles and shoots, their length and the number of further branchings, calculated of course from the youngest and outermost, increase basipetally. It is this monopodially racemost branching structure which gives spruce its typical habitus. As regards a tree as a whole, this is reflected in its pyramid or cone-like architectonics. The plagiotropic, dorsiventrally symmetrical systems of axles present on the other hand a similarity to isosceles triangles more or less turned down on each side of the highest plane having the longest axis, ie., its axis of the highest, plagiotropic order.

2. The process of increment in knot and branch wood.

In his extensive treatise »Dickenwachstum und Holzqualität von Pinus silvestris», Schwarz (1899) emphasizes in part as follows: »Die Physiologie hat nicht nur die Funktionen der einzelnen Organe und Gewebe festzustellen, sondern auch die Abhängigkeit der Pflanzenform und der Ausbildung der Gewebe von den wirksamen Faktoren zu untersuchen. Einer derartigen Untersuchung sind hauptsächlich nur die quantitativen Unterschiede in der Ausbildung der Gewebe und in der Grösse des Wachstums zugänglich, während die durch Vererbung gegebenen, qualitativen Unterschiede einer physiologischen Begründung entzogen sind. Es gibt jedoch auch qualitative Unterschiede, wie z.B. zwischen Frühholz und Spätholz, welche sich bei genauerer Betrachtung nur als graduelle Differenzen in der Grösse der Zellen und in der Dicke der Wandung darstellen und deshalb ebenfalls einer physiologischen Untersuchung unterworfen werden können.»

The noticeable differences in spruce between normal stem wood and knot wood on the one hand and the compression wood surrounding the knot on the other hand can be traced in part to various physiological reasons of nutriment and are presupposed by the tasks to which the separate axes of growth are entrusted. It must however be regarded in the main that differences in anatomical structure are to be found in the various, purely mechanical stresses to which the vertical, orthotropic stem and the more or less horizontally situated plagiotropic lateral axes are subjected. In order to understand these circumstances correctly, attention in the study of wood anatomy should accordingly be given to both the physiological demands made on cellular tissues and the mechanical requirements of the strength properties of wood. Kny (1882) states in part as follows: »Die der physiologischen Forschung im Gebiete der Pflanzen-Morphologie gestellte Aufgabe wird darin bestehen, zu untersuchen, wie die äusseren Kräfte — Schwerkraft, Licht, Wärme etc. — den durch Erblichkeit überkommenen Entwicklungsgang im Einzelnen abändern, nicht aber wie sie ihn unabhängig gestalten.» Branches originate from lateral buds of the growing point in the same manner as the orthotropic terminal shoot from the terminal bud, and the process of increment takes place in the branch in accordance with absolutely similar principles as in the terminal shoot. The new cell tissues, the youngest annual rings, are separated from the branch cambium in a similar manner as the stem cambium, and the wood formation process of the tissues is completely homogeneous. But while it can as a rule be maintained that stem wood is distinguished by an even growth with annual rings concentrically arranged around the pith, the branch on the other hand is usually distinguished by a noticeably eccentric increment in diameter.

This eccentricity in the increment of thickness has already in early times been the subject of interest. Plant physiologists such as A. P. De Candolle (1833) and Treviranus (1835) already gave attention to these phenomena. Schimper and Braun (1854) analyzed these circumstances more thoroughly and explained the different phrases for eccentric increment in thickness; hyponasty, epinasty and diplonasty. They maintained as a general rule that most coniferous trees are hyponastic while the majority of broad-leaf trees show an epinastic character.

H. Noerdlinger (1860) had likewise observed the eccentric grouping of annual rings in branch wood. He states that the Netherlander Muschenbroeck had already given attention to this question in the 18th century. Noerdlinger makes the following statement: »Auch schiefstehende Stämme sowie Aeste tragen das Mark der obern Seite stark genähert, d.h. sie haben auf den untern, dem Boden zugekehrten Seite breitere Jahresringe». It accordingly appears as if Noerdlinger regarded all kinds of wood as hyponastic.

Particularly extensive investigations concerning the eccentric increment in thickness of the trunks of trees have been undertaken by Kny (1882). In the same manner as Noerdlinger, he was able to ascertain that knot wood differs in many respects from stem wood and constitutes from the anatomical-structural point of view a mean between stem and root wood. He has also proved that knots and branches close to the top, the young branches, appreciably resemble stem wood at a corresponding height. This matter is self-evident, since the branch in the top has the same orthotropic position as the stem and therefore also presents a concentric grouping of annual rings similar to the terminal shoot of stem wood. H. Noerdlinger had already maintained that the pith center in branches, with the exception of the youngest, is as a rule found to be eccentrically situated. It has been ascertained in particular that this eccentricity has been particularly great in horizontal and drooping branches. H. von Mohl (1862) maintains it can be regarded as a rule that the lateral branches of all lignified plants are hyponastically constructed. He states in part: »Bekanntlich sind die Zweige der Bäume, wenn sie eine mehr oder weniger horizontale Lage besitzen, ebenfalls excentrisch gewachsen. Bei diesen ist es nun sehr leicht, sich davon zu überzeugen, dass die Jahresringe beständig auf der unteren Seite der Zweige dicker sind. Die Erklärung dieser Tatsache liegt in der, meines Wissens zuerst von Knight (published in Philosophical Transactions 1801—1808) ausgesprochenen Annahme, dass der Absteigende Nahrungssaft dem Gesetze der Schwere folgend in horizontal oder schief liegenden Zweigen in grösserer Menge auf der unteren Seite des Zweiges zum Stamme fliesse und diese Seite stärker ernähre, als die nach Oben gewandete.»

Kraus (1867) agrees with von Mohl's understanding to the extent that he also considers the eccentric growth of branches as being the result of the power of gravitation. This is however not caused directly but constitutes an indirect result of the tension caused by gravity on the upper and lower sides of the branch. Kraus states in part: »Die Einwirkung der Schwerkraft auf die Querspannung ist, wie zu erwarten stand, eine der auf die Längsspannung geübten ganz analoge: beim Niederlegen von Stengeln verlängern sich nicht allein die Gewebe und Gewebeszellen der Unterseite stärker, als die der Oberseite, sie wachsen auch stärker in die Breite. Die unterseitigen Gewebe nehmen daher einen stärkeren Umfang an und das Dickenwachstum des Internodiums wird excentrisch, der Querschnitt desselben zeigt nach unten grössere Radien als nach oben. Diese Erscheinung findet man nicht allein an Sprossen, die noch eine Längsspannung besitzen, sondern auch an rein quergespannten alten Aesten, Stämmen, Wurzeln.»

While von Mohl and Kraus have accordingly ascertained only the hyponastic characteristics of wood and speak in all cases of an eccentricity with the pith on the upper side, Hofmeister (1868) brings out the epinastic structure of branches in broad-leaf trees. According to his conception, this is also directly dependent upon gravity. He states: »Bei den meisten Laubhölzern wächst auch das Holz an der nach oben gewendeten Seite seitlicher Zweige stärker in die Dicke, als an der unteren. Das Wachstum, die Tätigkeit des holzbildenden Cambium sind in der Richtung aufwärts gefördert. Das Mark solcher Zweige hat eine excentrische, nach unten gerückte Lage. Die nicht lotrecht gerichteten Achsen einer Anzahl von Pflanzen werden in ihrem Dickenwachstume durch die Schwerkraft in genau umgekehrter Weise beeinflusst. Die dem Erdmittelpunkt zugewendete Längshälfte ihrer geneigt oder horizontal wachsenden Achsen verdickt sich überwiegend. Es besteht somit zwischen verschiedenen Pflanzenformen in Bezug auf die Förderung der Stammverdickung durch eine in Richtung der Lotlinie wirkende Kraft ein ähnlicher Gegensatz, wie in Bezug auf die Förderung des Breitenwachstums der Blätter.»

Wiesner (1868) points out also that only cross-sections of vertical axes are circular, while all plagiotropic axes on the other hand present oval limitation curves. He maintains that the difference between the maximum and minimum diameter of branches is increased the more horizontal the position taken by the branch. The maximum diameter lies in the direction of gravity, ie., in the vertical plane, and the minimum on the other hand in the horizontal plane. Wiesner also points out that the pith in horizontal axes is eccentrically located in relation to the surrounding wood texture and lies on its upper side. The reason given for this situation by Wiesner, who apparently had studied only the hyponastic phenomena in branch wood, is the following: »Die eben angeführte Thatsache ist bemerkenswert, wenn auch aus den angeführten Beobachtungen noch keinen Schluss sich ziehen lässt auf das Zustandekommen der ungleichen Massenentwicklung der Gewebe geneigter Aeste. Am nächsten liegt die Annahme, dass die Zellbildung, wenn sie im Sinne der Schwere erfolgte, beschleunigt ist, hingegen eine Verzögerung erfährt, wenn hierbei die Schwere zu überwinden ist.»

Noerdlinger (1874) considers in his treatise »Deutsche Forstbotanik» the question of epinasty and hyponasty during the process of increment of trees. He points out that a more or less warped position of the stem and branches in relation to the vertical axis affects the breadth of the annual rings. It seems as if Noerdlinger is uncertain as to the difference between these two phenomena. He maintains among other things that a greater growth on the lower side of the branch is very often found in broad-leaf trees and that this is a rule without exception for coniferous trees. He has also made the observation that a contrary situation, ie., a greater growth on the upper side, often presents itself in trees of large dimensions. On this basis he draws the conclusion that the study of this question could offer much of botanical-morphological interest.

Kny emphasizes in an unpublished lecture (1877) that the upper and lower sides of branches during their growth are not only affected by gravity but also in various ways by other, external factors such as heat, light and humidity. He sets forth among other things the influence that transverse tension between the wood portion and bark texture of the branch has on the increment in the diameter of the annual rings. According to Kny even the dorsiventral morphology of the branch ought to be in this connection of significance.

Sachs (1879) has later come to a corresponding result, after having followed a somewhat different method of research, and maintains that the foregoing transverse tension constitutes an important factor. He has ascertained among other things that medullary rays in wood of eccentric growth are more frequent and denser in the thicker portion than in the opposite side of the branch.

Detlefsen (1881) maintains that the tension arising between the wood and the bark texture because of the bend caused by the power of gravitation constitutes the reason for eccentricity in the structure of branches. Peculiarly enough, he gives attention only to the hyponastic phenomena. As a conclusion he sets forth briefly and to the point that a declivous branch is always hyponastically constructed. That broad-leaf trees show an epinastic construction he regards as depending on the other hand upon the fact that their branches are acclivous.

Kny has later on (1882) conducted a thorough investigation of the increment in the various axes of a tree. In this treatise he has given particular attention to the development of branches and roots. In this connection the following basic principles in general have been established for horizontal branches above ground:

1. By far the majority of dicotyledonous tree plants show clear epinasty, with the upper side of the branch having more pronounced development than the lower side.
2. Conifers show practically without exception a hyponastic structure in branch wood. This hyponasty is not regular however but seems to be influenced by a number of factors. The most pronounced thickening of the annual rings does not always occur in the nadir but is often advanced toward the side. This situation ought to be able to be regarded as a result of the effect of the wind.

As has previously been pointed out, Kny considers that the structure of the branch is a result not only of the effect of gravity but also of many other circumstances of a climatological and physiological nature. He maintains among other things that the light of the sun's rays tends to increase on the upper side the diameter increment of the hyponastic branch. Just as Famintzin, he considers that this constitutes a result of the light accelerating cell formation; heat also operates in the same manner stimulatingly upon the upper side of the branch. The moisture percentage is also greater in the upper portion of the branch, and this in turn causes greater evaporation therefrom. Cross tension between the wood and bark textures also plays a significant role according to Kny. He has ascertained a pervading hyponasty in spruce.

Mer (1887), the French plant physiologist, has given much attention to analyzing the question of the origin and causes of compression wood (bois rouge). Similarly as R. Hartig, he also defines this as differentiated wood. According to Mer compression wood is formed in parts of the lignified body of the plant in which an increased afflux of structural matter occurs, irrespective of whether the annual rings in this place are extensively or slightly developed. If the structural matters that have been supplied cannot soon enough be used up for the formation of new cells during unfavorable conditions of increment, the excess is changed to cellulose and stored in the cell walls. Upon an eccentric increment of the stem the annual rings on one side can accordingly be very narrow without however being compressed, while the side with wider rings can be excessively nourished so that the tissues become appreciably thickened. According to Mer such an origin for compression wood can occur in both the springwood and summerwood zones. Compression wood is also found very extensively in branches which have replaced a broken off top, particularly in the portion of the knot which has previously constituted the lower side of the branch. Mer has also ascertained that spruce knots and branches show as a rule an abundance of compression wood on the lower side.

The celebrated botanist of forestry R. Hartig has thoroughly treated in the majority of his works the process of increment in the most important German species of trees, including spruce, and the factors influencing it. In connection with these studies he has also been interested in the eccentric increment in diameter of tree trunks and the hyponastic and epinastic characteristics which branch wood practically always shows. He maintains in his work »das Rothholz der Fichte» (1896) that compression wood constitutes a kind of supporting texture which distinguishes itself from wood of normal structure through its great density, high degree of hardness and extraordinary compressive strength. Similarly as previous investigators, he states that this wood is abundantly found in stems growing in windy places. Compression wood occurs then in the portion of the stem which is subjected to wind pressure. Hartig states furthermore that stems which stand at an oblique angle to the horizontal plane show an extensive formation of compression wood on the inner side of declivity. This situation is clearly found in trees growing on the slopes of hills, river banks, et cetera. Much compression wood is likewise found in parts of stems which for a correlative reason endeavor to attain an orthotropic position from a plagiotropic plane.

According to Hartig branch wood in spruce has a pervading and extensive formation of compression wood on the lower side because of the great demands which gravitation places on its strength. He has ascertained the distribution of this compression wood through making many measurements. Furthermore, he has shown by a series of analyses the extraordinarily great density, the specific gravity and the insignificant percentage of shrinkage in this wood.

Hartig has consequently ascertained that compression wood is always formed in places where pressure in the direction of the longitudinal axis of the organ must be overcome. A branch will accordingly be subjected, on the side that must withstand an increase in pressure, to a constant irritation which periodically will be increased because of the stress of the wind. This pressure on the young living cells is spread out without becoming weakened due to the elastic and thin fiber walls, and the fibers react toward this pressure in various ways. Firstly, the form of the tracheids is affected by the fact that the hydrostatic pressure continually acts on the entire surface of the walls and accordingly causes a rounding out in the shape of the cell. While stem wood seldom forms intercellular spaces except around the parenchymatous cells, compression wood has numerous intercellular spaces. Since the cell walls must withstand a much greater pressure per unit of measure than normal wood, they are strongly thickened. The irritation exerted by high pressure brings about however not only a thickening of the cell walls but also the process of cell division and its intensity so that the portion of the annual ring containing compression wood is as a rule appreciably wider than that not containing compression wood. The cambial mantle accordingly releases faster a new growth and division of cells. The original individual, cambial cell will likewise not be as old as on the side of narrow rings and will not have the same length. It is therefore easily understood that the tracheids of compression wood are appreciably shorter than those in white wood, ie., in the tension wood on the tension side of the tree trunk.

In his final work R. Hartig (1901) expended a great deal of effort through various experiments in ascertaining the factors which affect the origin and development of compression wood in branches. In this connection he came to the conclusion that compression wood is caused by irritations brought on by the power of gravitation and by stress and pressure conditions.

Hartig made the investigation by hanging up vertically or at an angle in a glass house one meter spruce planted in pots so that the tops would point downward. By tying the tops in suitable directions he was able to bring about an irritation of the cambium by means of the power of gravity. In each case that was investigated there arose a strong formation of compression wood only on the lower side of the stem. Another method consisted of subjecting the top to a load which was continually increased until the bent portion attained a position of 90 degrees to the vertical stem. Thereupon the pressure was removed, and then again increased in the same manner. Furthermore, Hartig kept spruce plants rotating for long periods of time so that the tops outlined a circle lying in a vertical plane. The foregoing investigations showed the complete accuracy of his previous assumptions and established the fact that compression wood can be regarded as a supporting texture which is formed in the parts of the tree trunk which are subjected to especially great pressure.

Schwendener (1874 and 1884) has maintained that a branch can be considered as constructed to support constant resistances. Upon bending, the danger of a break is the same at each point along the branch and the cross-breaking strength at any particular point must be proportional to the momentum of the power of the strain. He has also pointed out that the analogies which can be set up for supporting trunks having circular cross-sections and the series of figures which can arise therefrom not only characterize the outer form but also the annual increase in thickness. He states that the wind has the same effect in this connection as a sideward attraction which is concentrated at the center of gravity of the area subject to attack.

Metzger (1893—1894) has developed furthermore Schwendener's theory concerning the construction of tree trunks for withstanding mechanical strain. He has analyzed this mechanical strain mathematically and has shown that branch wood is also constructed according to the same mechanical principles as the stem. If measurements of the diameter or the radii are made at equal intervals, the cubes of such diameters will constitute parts of an arithmetic series and can be fitted graphically into a system of rectangular coordinates.

Metzger (1892) has furthermore presented in a particularly clear and illustrative manner the static fundamentals for the structure of forest trees and stands. As has been stated above, the basic principle in this connection is that both the stem and the branches are formed in accordance with the physical law regarding structures as supporters of a constant resistance. This resistance takes the form of the strain which the wind places on the individual tree. A tree standing by itself must be short and strong in order to be able to withstand these load requirements. On the other hand, in closed stand where the action of the wind cannot be equally as effective, the trees can develop in length. The result thereof is a long and slender form of stem and a process of branching having orthotropic tendencies.

Sonntag (1903) has shown that spruce develops wood subject to tension on the upper side of its branches and wood subject to compression on the lower side. Ursprung (1901) has teleologically explained on the basis of Sonntag's investigations why compression wood must be located on the lower side of branches and tension wood on the upper side.

While all branches were previously considered as a rule as hyponastic (De Candolle, Treviranus, Nördlinger, v. Mohl), later, more thorough-going investigations, particularly those of Kny, have however shown that this characteristic is prevalent only in conifers. Metzger (1908) undertook an interesting experiment for argument's sake in order to ascertain the reasons for the hyponastic structure of the branches of conifers as contrasted with the epinasty in broad-leaf branches. While broad-leaf branches are formed, according to his statements, to withstand the highest possible tension strain and must therefore contain as much tension wood as possible, coniferous branches are on the other hand formed with consideration for maximum compression strength. It can consequently be stated figuratively that the supporting textures in broad-leaf wood lie like a belt subject to tension on the upper side of branches while in conifers it corresponds to a supporting beam subject to compression on the lower side. These phenomena are self-evident when it is borne in mind that broad-leaf wood has relatively greater tensile strength than compressive strength, while in conifers the situation is clearly the opposite. The correctness of this allegation is shown for example by the investigations of Mikolaschek (1879). While branches, according to Metzger, in similarity to the entire tree, are formed on the principle of the greatest possible strength with the least use of structural matter, such an eccentricity is consequently the most advantageous from the point of view of botanical-physiological economy. As a daring conclusion Metzger states that the reason for the difference in the structures of the supporting textures in broad-leaf and coniferous wood is to be found in the history of development of the respective plants. While conifers trace their origin to plants which were already at an early stage isolated and column-like and therefore formed with the view to great compressive strength, he presumes that broad-leaf trees originated from clambering plants which were formed in order to have great tensile strength.

Broad-leaf branches show on the other hand a completely opposite structure. The center of the eccentric annual rings lies in this case on the lower side while the upper side presents a strong texture of connecting fibers.

The hyponastic characteristics in coniferous wood appear particularly clearly in spruce branches, especially in the parts closest to the knot and in inner knots. The greater the age of the branch, the more the center advances proportionately toward the upper side of the branch and the more noticeable become the compression wood formations on the lower side. If a young spruce branch is observed, it will be found that the structure of the wood is somewhat regular. The young plant grows in keen competition with the surrounding vegetation of grass and shrubs on the ground. In order to survive this competition, it is compelled to strive toward the light to the greatest possible extent. The branches are therefore directed as vertically as possible and show on the whole orthotropic characteristics in similarity to the orthotropic, main axis. A cross section of such a branch in the plant stage presents therefore a concentric figuration of the annual rings. A noteworthy formation of compression wood cannot be discerned except in the parts closest to the knot. When the tree increases in age the branches assume by degrees a continually more plagiotropic direction in relation to the vertical stem. The reason therefor is to be found in biological, primarily alimentary-physiological circumstances. The branches assume continually greater and more extensive proportions and must attain a more horizontal direction in order to be able to utilize the sun's rays.

It is believed that the foregoing situation has not been previously considered in literature. Because of the great significance the angle of deviation of the branch from the stem has on the relative cubical content of knot wood in relation to the volume of normal wood, the author has given this question special consideration. This series of studies has been undertaken partly on the basis of the material obtained from growing spruce trees representing various ages and classes of growth in the Forestry Research Institute's forests in Ruotsinkylä, Tuusula, partly on the basis of Herz' material for investigation concerning the development of spruce plants '(Herz 1934) and partly on the basis of the material for investigation-originating from the main waterways of Finland.

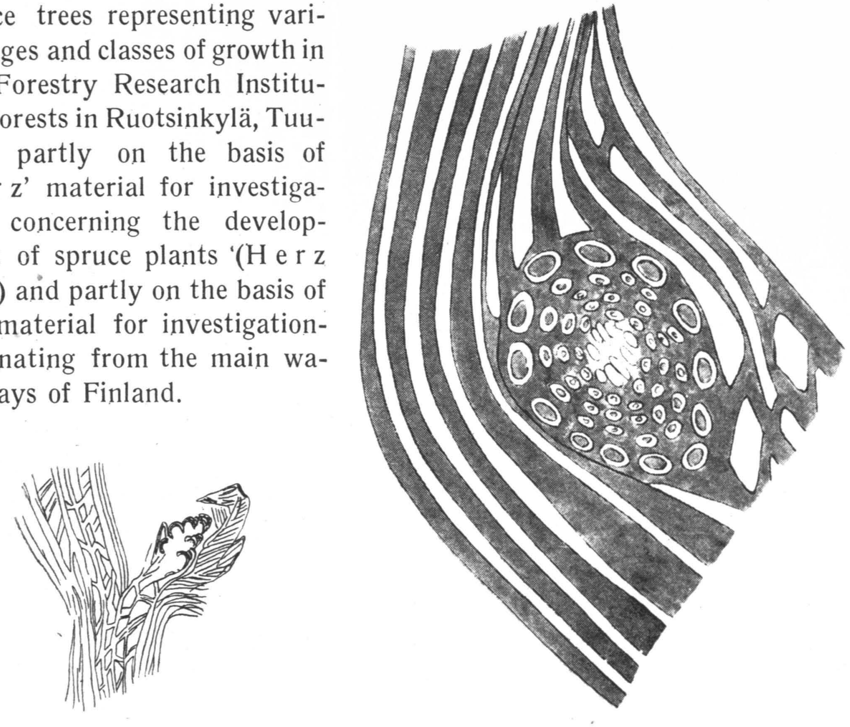


Fig. 16. Branch during formation in a one-year-old spruce. a. Length section. b. Cross section. — *Kuva 16 1-vuotisen kuusentaimen kasvava oksa. a. Pituusleikkaus. b. Poikkileikkaus.*

The figure shows a branch during formation in a one-year-old spruce plant. The flow of resin in the plerome has not yet ceased and cell formation is not yet completed. Among other things will be observed the incompleted cell walls in the center of the figure. It can only be ascertained that a break in the vertical direction of the fibers is about to occur.

The following figure illustrates how the development of the knot and branch has advanced when the spruce plant has attained the age of two years.

A new axis of growth has originated. It forms a very small angle to the vertical one, ie., the vertical plane. On the lower side of the base of the branch will be observed a knot-like support of hardened compression wood. The cross-section of the branch perpendicular to the surface is circular and the pith is centrally located.

It is self-evident that development in each individual plant does not follow exactly similar lines. The clearer the ground is fo vegetation, primarily of shrubs and grass, and the less the plant is bothered by nearby competitors, the more horizontal is the angle of deviation of the branch. In particularly closed stand the branches of spruce still show orthotropic tendencies to a very advanced stage. On the other hand, the yare more or lessplagiotropic in open stand.

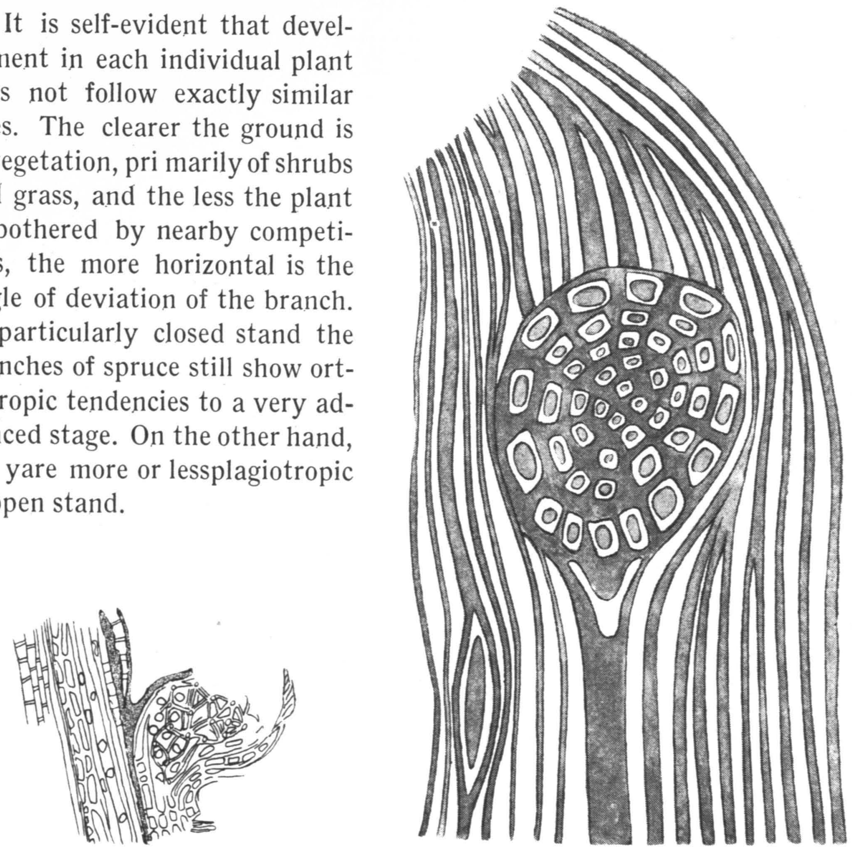


Fig. 17. Branch during formation in a two-year-old spruce. a. Length section. b. Cross section. — *Kuva 17. 2-vuotisen kuusentaimen kasvava oksa. a. Pituusleikkaus. b. Poikkileikkaus.*

A series of investigations covering branch material at the Ruotsinkylä research station shows that the angle of deviation of branches stands in proportion both to the age of the tree and to its rapidity of growth. The following diagram shows graphically the relationship between the angle of deviation of the branch and the age of the tree. The test trees of the most important types of forests are each drawn separately. This series is particularly clear as regards trees growing on Oxalis type of ground. The branches are rather steeply pointed upward where the ground is covered by grass. In 10-year-old plants it is still found that the angle has not exceeded 90 degrees. Thereafter the curve in the diagram rises slowly, and at an angle of about 110 degrees it remains horizontal constantly. As regards the direction of the branches on Myrtillus type of ground, the graphic curve shows a much more inclined rise in the beginning. Ninety degrees is already attained at an age of 7 to 8 years. Thereafter the branches tend toward a downward angle. The older the tree becomes, the greater is the angle of deviation for the branch. The result thereof is that the curve shows a direction aiming toward infinity and rises uninterruptedly. Its mathematical formula appears to be easily calculated. The curves for Vaccinium and swamp types of spruce forests are of the same kind as the Myrtillus curve but show a still more inclined rise. In swamp spruce the angle of deviation is less than 90 degrees only in so far as the smallest and youngest plants are concerned.

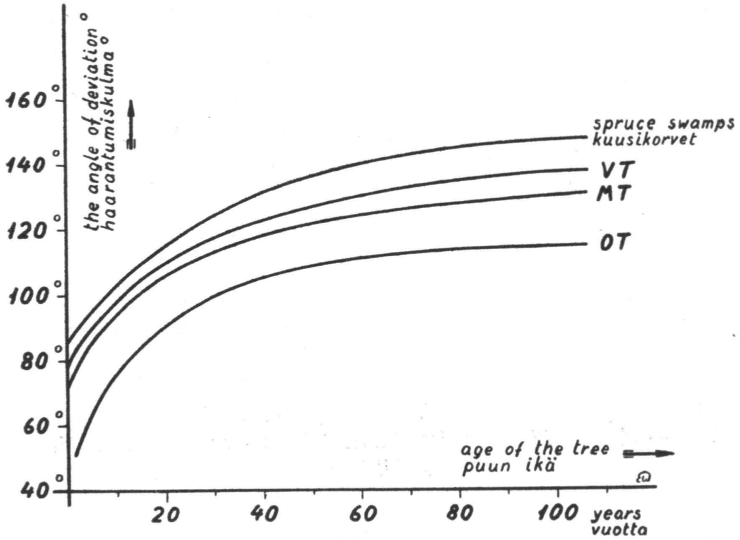


Fig. 18. The angles for branch deviation different forest types at Ruotsinkylä. — *Kuva 18. Oksan haaraantumiskulmat eri metsätyypeillä Ruotsinkylän kokeilualueella.*

3. The decay of branches and the healing over of knots.

There is hardly any reason for making extensive investigations concerning the breaking off and the death of branches since this matter has previously been the subject of much interest and thorough-going studies.

Many German men of science have expended a great deal of effort in analyzing these questions in order to be able to conjecture the presumptions and useful possibilities of rational methods of pruning. Because of the fact that there has occurred in Germany since the middle of the 18th century special interest in pruning particularly due to the need of high quality timber for the requirements of the fleet, there has become available extraordinarily valuable, and a plentiful supply of, research material. Various methods of pruning have been tested in Germany practically without interruption for 200 years, and a considerable number of these prunings have been recorded and made the subjects of observation with scientific exactness during long periods of time.

The biological process of natural pruning has previously been extensively examined by von Höhnel (1878—79). He has found among other things that it takes place in broad-leaf and coniferous trees in accordance with norms deviating to a certain extent. In similarity with subsequent men of research, von Höhnel considers that natural pruning comprises both the death of live and assimilating branches as well as their breaking off and incasement in stem wood.

Most kinds of broad-leaf trees as well as some conifers have the faculty of becoming free of dried branches by means of an active process of natural pruning (Höhnel 1879 and Röse 1865). This process of natural pruning, which is of course of great benefit to the qualitative properties of the tree, can be observed in the pine of our conifers. A cross-section of the base portion of such a branch shows that a new texture transversal to the direction of the branch has arisen in this place. This layer is about 1 mm. wide and consists of cells containing a high percentage of cellulose, which have not yet lignified to an appreciable degree. Through the division of the cells there arises in this layer a dividing wall which finally frees the stem of the branch. Spruce as well as the other species of Picea do not however possess this faculty of cell division. Accordingly, this botanical phenomenon does not need to be taken into consideration when treating of the natural pruning of spruce.

Different kinds of trees prune themselves with a rapidity that varies appreciably (Mayer-Wegelin (1934) and Gelinsky (1932). The reason therefor is to be found in the structure of the wood and in its physical and chemical properties. Branch wood of broadleaf trees, being composed epinastically of cellulose contents and relatively soft in structure, decays much more rapidly than the hyponastically composed, appreciably lignified and closely growing branches of conifers.

Mayer-Wegelin (1936) maintains that the pruning of spruce is a clearly passive process in which the dead limbs decay and finally become removed from the stem by their own weight or are detached by outer mechanical forces.

Spruce is distinctive because of its very slow pruning. This circumstance is noticeable upon an inspection of spruce forests. The stem is usually covered down to the roots with a quantity of dried limbs, ie., short stubs on the lower portion and unbroken but decayed branches close to the fresh crown. Mayer-Wegelin (1936) maintains that while the dried up branch of beech for example breaks off at the point of origin when it becomes loose from the stem, a spruce branch on the other hand breaks off a part at a time. If an old spruce stem is observed, there are found stubs of dried limbs far down the portion of the stem which is otherwise free of branches.

The slow pruning of spruce is in many respects a particularly damaging circumstance when it is a question of obtaining wood of a high quality. As has previously been mentioned, the dry, encased parts of branches are not anatomically connected to the surrounding stem wood. In sawn goods they easily loosen and leave a hole which appreciably lowers the strength and quality of the wood. Because of their particularly deviating anatomical and chemical composition the dead knots are in addition a great detriment in the production of ground wood pulp and cellulose. It can therefore be of interest to give attention to the decay of branches and the healing over of knots, and by means of human interference to attempt to moderate the damage to which spruce wood is subjected because of the slow pruning of its branches.

The gradual decline of the branch and the cessation of the function of life therein constitute the first phase in natural pruning. This decline is brought about by a number of concurring factors. Lundegårdh (1916) and Jost (1936) maintain that the stem's clearing itself of its lower branches depends principally upon the fact that they no longer are able to satisfy the requirements of light necessary for assimilation. Due to faulty assimilation, it follows that bud formation gradually discontinues and the living substance of the tree does not any more obtain nutrition to a sufficient degree. A result is that the chemical composition of the tree is changed and strength is decreased until it can no longer withstand the load. When the branch can no longer contribute toward furnishing food to the stem and toward the formation of new stem wood, the stem likewise ceases as a result thereof to feed the branch, since just as in the case of each species of plants there is also applicable for the various parts of the individual plant Metzger's law of economy: »Wer nicht arbeitet stirbt».

Kienitz (1878) has shown that growth material is conducted from the upper branches past dead branches. The dying branch is therefore left to the products of assimilation that its own needles can produce. When the needles can no longer furnish nutriment, the supply of assimilative substances likewise ceases. A study of the changes in the breath of annual rings clearly shows how this changing condition of nourishment in the branch and its ability to develop take place exceedingly slowly. Similar investigations have also been made by Gelinsky (1932) concerning the situation as regards the annual rings in beech branches and lead to corresponding results.

The period for the decline of branches usually occurs in winter or spring.

The supply of light plays the most essential role in the decline of branches. This has been shown by Th. Hartig, R. Hartig (1878, 1901), Kienitz (1876), Schellenberg (1923) and Mayer-Wegelin (1930) and others. Wiesner (1907) has attempted to ascertain by means of photometric investigations what the minimum light requirement is for the growth of branches. Mayer-Wegelin (1929) has ascertained that branches in certain kinds of trees attain a plagiotropic maximum for their angle of deviation from the stem. When this angle is reached the branches decline. Many investigations such as Ratzka's (1859) have shown that the branch never dies exactly at the point of origin in stem wood but always at a point somewhat extended outward therefrom. The knot is accordingly still nourished after the death of the branch. The result of this is a curvature of the annual rings of the stem around the base of the dead branch. The figure alongside shows the length-section of such a branch.

The dead knot is gradually subjected to the destroying effect of decomposing bacteria and fungus diseases. Winkler (1930) states that these fungus diseases have already commenced their work on a living branch. They are comprised principally of tremella, exidia, stereum, various kinds of polyporus and fomes, as well as of wood mold merulius to a great extent; as is apparent principally of fiber destroying fungi. In spruce branches with their abundance of compression wood and abnormally high percentage of lignin, these fungi obtain proper nourishment only with difficulty. The branches therefore break off very slowly. Because of spruce branches being particularly susceptible to climatological effects and dry

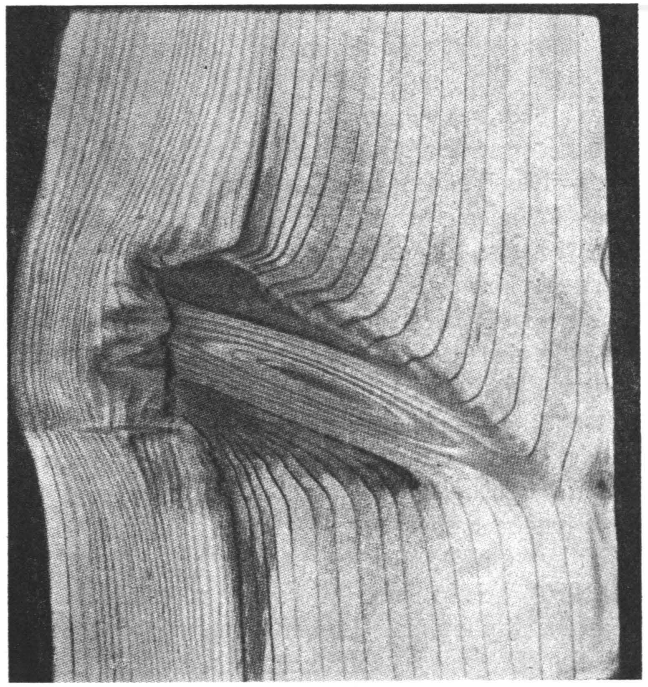


Fig. 19. Curvature of stem wood around a dead branch.
Kuva 19. Kuolleen kuusenoksan kylestyminen.

out very readily, the wood is furthermore only periodically sensitive to fungus increment.

Köster (1934) has devoted a thorough study to the process of the natural pruning of spruce branches. After having explained the reasons for branches ceasing to carry out their functions of life based on R. Hartig (1878) and Schellenberg and Winkler (1930), he goes into the study of the decay of spruce branches. This process begins with the bark loosening on the inner lateral branches. This loosening is caused since the bark is loosest, due to its quality, on these youngest branches and is therefore decomposed on them most easily. The bark is first detached at the forks.

On old branches, ie., branches of the lower order, the bark gradually loosens in the beginning between the forks. However in places such as large knot clusters, the bark still remains long after the decay of branch wood has commenced. As soon as the bark has loosened in places, the occurrence of numerous longitudinal shakes can be observed. In the beginning they are only a couple of millimeters long and a fraction of a millimeter wide, but become larger with the passing of years. These shakes arise as a result of the variations in tension in the compression wood (Druckholz) on the lower side of the branch and the tension wood (Zugholz) of the upper side. The shakes will later extend also through the knot cluster of the branching points. Gradually there will also arise cross-sectional checks in the bark, but only on the lower side of the branch. When the bark has fallen off and the formation of checks has advanced, a process of decay can be observed both alongside the checks and on the top of the branch. The wood continues to become more dark brown in color and the branch is in the beginning decomposed along the checks on the upper edge. Later the chips loosen piecemeal from the whole of the upper side of the branch, which is looser as regards structure.

Branch wood commences to be covered with lichens about two years after its function as a living organism has ceased. They appear in the beginning only on the upper side of the branch but thereupon cover by degrees the entire surface. The branches loosen piecemeal with branches of the higher order first becoming detached after having broken off at the base portion covered with bark. Branches of the second order become detached thereafter either entirely or partially. The main branch or the primary plagiotropic axis also breaks off piece by piece. Only in exceptional cases does it loosen at the stem, but as a rule it remains in the form of a fragment of dried up, dead branch wood which will later grow into the stem. A healing over is consequently not possible within the immediate future.

The strength properties of branch wood are lowered partly as a result of fungus infections, as has previously been mentioned, and partly due to the mechanical formation of shakes and checks. The final process of becoming detached, ie., the breaking off of the branch, is furthermore hurried by outer mechanical factors such as wind and snow. Köster has even given consideration to the moisture content of dead branches and its fluctuations, and their effect on the possibilities of fungi existing in branches. He has likewise studied the physiology of fungi and their relationship in the ability of various species of fungi that brings about destruction. Also the breaking off activity of insects, principally Buprestidae and Cerambycidae, has been considered.

Because of its hardness and the minimum breadth of the annual rings, branch wood has strength properties to a particularly high degree. Its strength in resisting infections and rot caused by them is furthermore increased due to the high content of resin. The author's investigations (see chapter, The Chemical Properties of Branch and Knot Wood) also show clearly that the content of resin in branch wood may be many times greater than in stem wood. In branches the content of resin is greatest in the knot and decreases in the direction of the tip. It is consequently easily understood that the knot, which is strongly impregnated with resin, must show much greater strength properties than branch wood farther up towards the tip. Köster maintains that this particularly pronounced accumulation of resin in a knot constitutes in spruce a measure of protection against infections from decayed branches. This measure of protection nevertheless acts on the other hand to delay the process of pruning and healing over. Köster has also observed that knots loosen principally in the winter and spring.

As will appear from the foregoing, the healing over process for spruce knots differs essentially from that for other species of trees due to the slow pace at which it takes place.

Alers (1879) was the first to give consideration to the healing over process in conifers after pruning. He has shown that an accumulation of resin arises around a dead knot. A flow of resin preserving the wound against outer infections arises gradually. It is only after this impregnation of resin has occurred that healing over can continue, and the surrounding texture then begins by degrees to grow over the old wound.

CHAPTER VI.

The effect of forest management on the quality of wood and on the occurrence of branches and knots.

The added knowledge that has lately been obtained regarding the significance of the quality of wood for the wood working industry has naturally in turn directed the interest of foresters toward the possibilities of obtaining products of the highest possible value as results of their work. In this connection it has been observed that rational and appropriate methods of forest protection have been well able to improve the technical quality of wood and to increase the value of the yield.

Since it is a question of improving the quality of timber in the forests, it has been ascertained that the stem form of trees and the presence of branches are of the greatest importance for not only the sawmill but also the paper industry, and that a uniformly thick stem form having the greatest cubical content is practically always accompanied by a very limited occurrence of branches. It has likewise been found that wood is structurally most homogeneous and most valuable in stems having a good form and slight taper, and wood then shows the most uniform breadth in the annual rings and the most advantageous relationship between springwood and summerwood. As has previously been mentioned, relatively slow grown and heavy wood will as a rule have the best strength properties and can furthermore usually have the greatest abundance of fibers and contain qualitatively good fiber material. This situation has been particularly clearly illustrated in Klem's extensive investigations (Klem 1930 and 1934).

It is found that the quality of the wood is directly affected by the form of the stand. In dense and closed forms of forests, trees develop a slender and uniformly thick stem form and are well cleared of branches. Bühler and Flury (1892) have ascertained, and have proved by an abundance of statistics, that the presence of branches stands in direct relationship to the distance of the trees from each other. The more open the form of forest, the greater is the presence of branches. This is very clearly apparent in planted stand, where it can be found that the presence of branches is greatly increased upon extending the distance between plants. According to the foregoing investigators, pruning furthermore occurs better on forest lands of quality than on poor vegetative land. Schiffel (1904) on the other hand considers that the distance of the plants from each other is of secondary significance and recommends the sparse placing of young stand. Schwappach (1905) presents a diametrically opposite opinion and Janka (1909) points out forcefully that the cultivation of spruce should be made especially densely and then thinned very carefully and by degrees in order that pruning may be encouraged to the greatest extent possible. Busse and Jaehn (1925) as well as Busse and Weissker (1931) have furthermore maintained that planting should occur in the most dense formations possible in order to encourage the pruning process of spruce stems.

The occurrence of branches can be reduced in growing forests not only by raising the plants in dense stand and accordingly endeavoring to promote natural pruning but also by active intervention. This active intervention implies the mechanical pruning of branches already existing. Such pruning can either comprise only the dead branches of the tree or also be extended to embrace live branches. Since spruce is however very receptive to damage by decay, as has previously been pointed out in connection with the breaking off of branches and the healing over of knots, it is necessary to proceed extremely cautiously. Lakari (1920) has accordingly shown that the pruning of live spruce branches leads almost without exception to stem rot, and Wahlgren (1922) has strongly emphasized the fact that the pruning of dead branches only should come into consideration in spruce forests. Even when this is done, great caution should be observed so that the living wood substance in knots is not infected.

Because of the great perils that become involved in pruning spruce stand, the making of scientific tests has as yet been risked only to a very limited extent. The most extensive tests of this kind have been made in Germany, where the question of quality has for some time occupied a position of foremost importance. The most extensive work of analyzing this problem has been done by Mayer-Wegelin. After having thoroughly considered the many risks of infection which appear in the pruning of spruce, Mayer-Wegelin (1936) establishes as a fact that the pruning of live branches of spruce leads almost without expection to rot. This has likewise been shown by the investigations of Lakari (1920), Koehler (1934), Ratzka (1874), Rossmessler (1928), Gerhardt (1932) and others.

Dry pruning of spruce has on the other hand the possibilities of being successful if it is only performed in the correct manner. Mayer-Wegelin has made extensive investigations in stands which have previously been pruned and has in addition continued the investigations commenced by Borggreve (1891) and Alers (1879) in various forest districts in Hesse, Prussia and Braunschweig. He has ascertained that they have turned out particularly well. He states that the reason for their having succeeded so well is due to the strong impregnation of resin which has occurred in the dead knot and made it immune to infections.

As a conclusion to his investigations Mayer-Wegelin maintains that spruce must be pruned since it will not prune naturally at a sufficiently fast rate. He presents as the goal of pruning the obtaining of stems which are free of dead knots. In order to attain this, the pruning of all live branches close to the stem and all pruning during the growing period should be avoided. Pruning should be performed in accordance with a definite plan and be concentrated on the best units in the stands, primarily those having the dominating types of crowns. The work should be confined only to dead branches, should occur at regular intervals and be made with good tools. Planting irons and ladders should be avoided. Pruning occurs most advantageously when using well adjusted pruning saws.

Laitakari (1935) has made studies in Finland concerning stand and the effect of habitat on the fitness of spruce stems. Based on material taken from numerous sample plots, he has drawn the following conclusions:

In closed stand, spruce develops into stems having relatively thin branches and prunes naturally in a satisfactory manner provided the stand has been dense during its earliest stages. Only in cases where the plants are few and far between do spruce stems have thick branches and an abundance of branches in naturally seeded stand. The decisive period as to what the quality of wood will be occurs accordingly in spruce in the plant stage. The form of the stand during the later period of development is of less significance. This situation is most clearly illustrated by a comparison of stands which have arisen in a natural manner through natural seeding and planted, artificial spruce stands. These are noticeably very different as regards the abundance and size of the branches. Although branches in the lower portions of a stem even in artificial stand cease performing their functions of life when the forest has become closed, the breaking off of the branches occurs much more slowly because of their greater diameter. Artificial stand is for this reason conspicuous for its much greater quantity of dead branch stubs. Particularly when the distance between plants exceeds two meters, the process of natural pruning is considerably delayed. If this is supplemented in artificial spruce stand by naturally seeded plants, quality is of course improved appreciably and can be compared with that in naturally seeded, natural stand.

E. Cajander (1933) has maintained that active, mechanical pruning of dead branches is necessary if it is desired in artificial stand to obtain wood which is comparable to that available in naturally seeded stand.

Laitakari's investigations evidence that a naturally rejuvenated forest contains better stems than forests established by artificial regeneration. The denser the plant stand has been, the thinner will be the size of the branches, the better the natural pruning and the earlier the thinning can be commenced. When branches have died up to a height of about 4 meters, the spruce stand can be thinned extensively without increasing the presence of branches or impairing the form of stems. There is no reason for uprooting spruce stand consisting of trees of large dimensions in close stand if it is aimed to obtain quality timber. This will delay dimensional growth, which is determined by the measures of forest management taken during the very first period of development, without increasing quality. By means of rational thinning, the quality of timber can be greatly affected. Even from a forest where there are especially many branches, it is possible to obtain qualitatively valuable stand by removing the large trees having thick branches. Such a system of thinning furthermore decreases root competition.

Since it is a question of obtaining a spruce forest of valuable timber of quality, interest should accordingly be directed already during the plant stage to the density of the stand, as has been pointed out by Laitakari. When material having thin branches and slender stems has in this manner been obtained for working purposes, it is then possible to take action calculated to improve quantity production. The old rule that best results can be attained only by using first-class material accordingly becomes applicable also in forest management.

CHAPTER VII.

Studies concerning the volume of branches and knots in various kinds of spruce wood.

Much has been said about the significance from the technical point of view of the quality of wood for manufacturing, and it can be regarded that the presence of knots constitutes as a known fact one of the most important characteristics which lowers quality. Nevertheless, there is very limited information in literature concerning the extent of the presence of knots, ie., the distribution of knots in a stem and their volume. It may furthermore be mentioned that the available sources of information are to a great extent one-sided and deficient. They treat to a degree of the number of branches, their distances from each other and the proportion of knots, but the absolute volume of knot wood and the changes caused thereby in the structure of wood have on the whole been left completely out of consideration. When attention has been given to this question, it has generally been investigated incompletely; the presence of knots has either been studied on the basis of the relative extent of knots in relation to the surface of the tree trunk or it has been attempted by means of cuts through a stem to conjecture to how great a volume the ingrown portion of a knot occupies in the stem. On the other hand there have very seldom been made measurements covering the quantity of compression wood surrounding knots. Since this wood from the manufacturing point of view has however the same significance as knot wood proper because of its physical and chemical consistency, and since it can furthermore appreciably exceed in volume the occurrence of actual knot wood, it constitutes a characteristic for the suitability of wood, the importance of which should not be underestimated.

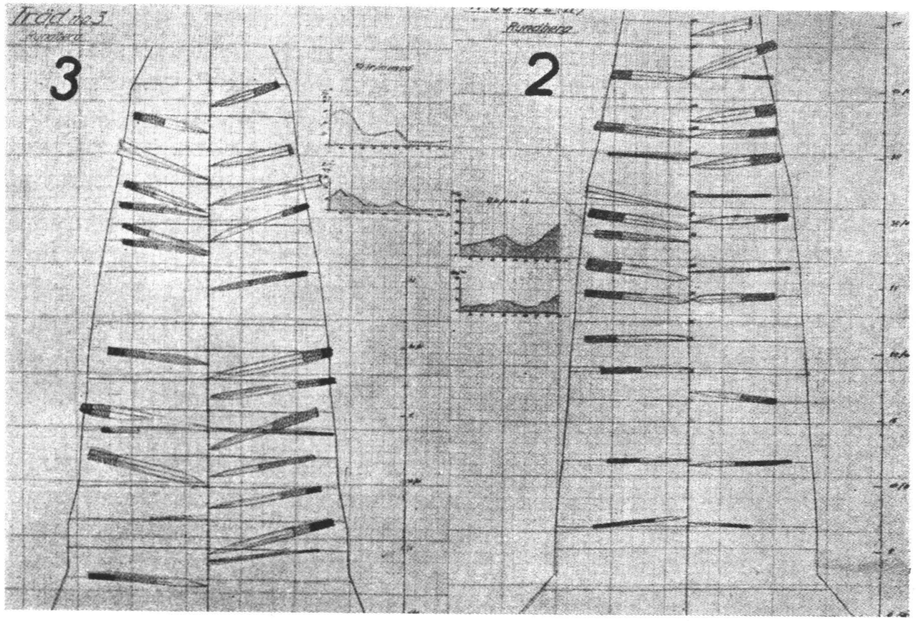
1. The distribution of branches and knots.

It is a generally known fact that the occurrence of branches reaches its maximum in the top of a tree and that it then diminishes upon proceeding downward toward the roots. Because of this circumstance the proportion of knots is relatively high in the upper parts of a stem. But although the base portions appear outwardly to be well limbed, cuts through the stem will however often show an abundant occurrence of ingrown branch stubs. This is particularly the case in trees which have come up in planted stands. This circumstance plays of course an important role as regards the production value of the wood. It has also attracted therefore the interest of forestry. The occurrence of healed over branches is of prime importance in the sawmill industry but its effect on the production of the paper industry should not be overlooked. Wennerholm (1937) in Sweden has investigated these conditions in pine timber and has found a very clear relationship between the uniformity in the increment of a tree, ie., in the breadth of the annual rings, and the proportion of ingrown branch wood. He therefore proposes a determination of quality in which the rapidity of increment during the early age of the stand is of decisive importance. The greater this has been, the more abundant is also the occurrence of knots.

Wennerholm has conducted his investigations in pine timber originating in the upper districts of Norrland. He states that during the very long period of inactive growth which these old forests have gone through before being felled, the dry branches have fallen off so that it is difficult to judge from the exterior whether the knots in a butt log are large or small. It can of course be assumed with certainty that logs having a smooth and not undulated surface contain only small knots. But a large number of logs are of good quality in spite of having an undulated surface. Only on the types having the greatest number of branches are the dry branches on butt logs still visible.

The following figure shows two of Wennerholm's analyses of knots made from two different trees as regards quality in which the branches in butt logs have healed over.

Tree no. 3 shows the appearance of a knot in a tree that had grown rapidly in the early stages and tree no. 2 a branch in a tree which was suppressed in its early stages and then liberated. Both trees came from the same district and the same quality site. In the butt logs of both trees the stubs of branches had healed over. The analyses concerning knots showed a relationship between the increment in a tree in its early stages and the size of the knot. The more slowly the tree had grown in its early stages, the thinner were the ingrown branches. The diameter of the branch increases appreciably when the increment of the tree has been increased. Upon lengthwise cutting of the butt log there is obtained material for judging what portion of the radius of the butt must be slow grown in order that a log of the desired length will have a certain thickness in its branches.



F i g. 20. Figure based on Wennerholm. — *K u v a 20. Oksa-analyysi Wennerholm'in mukaan.*

Wennerholm states furthermore: »Den grovlek på torrkvist, som tolereras i bräderna, bedömes först i brädgården. Denna kvistgrovlek bör bedömas i brädernas kanter, där kvisten inverkar mest kvalitetsnedsättande. Medellängden, som köparna fordra på bräderna, är bestämmande för den längd brädsågningstimret måste hava. För att rotstocken skall kunna uttagas till brädsågning, måste stammen till en höjd, som motsvarar rotstockens längd, sakna grövre torrkvist än vad som tolereras i bräder av god osorterad kvalitet. I stort sett torde man härvidlag kunna utgå ifrån att god osorterad sågvara av 1 tums tjocklek tål 1 cm. grov torrkvist som kantkvist, av 2 tums tjocklek 2 cm:s kvist och av 3 tums tjocklek 3 cm:s kvist. De vanligaste tjocklekarna på bräder för export är $^{3}/_{4}$ till 1 $^{1}/_{2}$ tum.

Den grovlek, som kan tolereras för torr kantkvist, varierar därför mellan $^3/_4$ och 1 $^1/_2$ cm. Den medellängd, som är önskvärd att bräderna hålla, medför att sågtimrets minimilängd ej bör understiga 14 à 15 fot.

»Fordringarna på brädsågningstimret bliva således, att stockarna på minst 14 à 15 fots längd ej få innehålla torrkvist grövre än $^3/_4$—1 $^1/_2$ cm. Vid provsågningar undersökes därför, vilken tillväxthastighet i ungdomen, de stockar haft, vilkas kvist ej är grövre än $^3/_4$—$^1/_2$ cm., och huru länge träden måste hava haft denna långsamma tillväxt för att kvisten upp till 14 à 15 fot ej skall överskrida denna grovlek. Årsringbredden mätes härvid bäst i stubbskäret, för att man skall kunna använda sig av det erhållna måttet vid stockarnas sortering. Genom provsågning kan man således för timmer från en viss trakt utröna, exempelvis att stockar, som i rotcentrum på 5 cm:s radie hava minst 50 årsringar, ej innehålla torrkvist grövre än 1 cm. till 15 fots höjd. Den längd av stockens rotradie, på vilken årsringbredden skall bedömas, motsvarar naturligtvis den grovlek stammen haft vid stubbskäret, när grönkvistrensningen hunnit till den önskade höjden på stammen.

»Sambandet mellan årsringbredderna i rotcentrum och kvistgrovleken i rotstocken varierar troligen för olika tallraser, klimatområden och boniteter. Skall utsortering av brädsågningstimmer inom ett visst område ske med tillhjälp av detta samband, bör därför provsågningar utföras med timmer från området i fråga.

»I detta sammanhang bör påpekas, att det vid företagna provsågningar visat sig vara nödvändigt, att icke blott fästa avseende vid årsringarnas medelbredd på den del av rotradien, där årsringbredden skall bedömas, utan även att taga hänsyn till de variationer i årsringbredden, som förekomma på denna del av rotradien. Om resultatet av en provsågning blivit, att en brädsågningsstock skall hava exempelvis 50 årsringar på 5 cm:s rotradie eller i medeltal 1 mm:s årsringbredd, måste därför denna instruktion kompletteras med en bestämmelse, om vilka variationer i årsringbredden, som kan tolereras på denna del av rotradien, utan att en stock, som håller det bestämda antalet årsringar behöver kasseras. Det kan visa sig att om t.ex. 10 årsringarna på 5 cm:s rotradie hålla 1 $^1/_2$ mm:s bredd bör stocken ej uttagas till brädsågning, trots att medelbredden på årsringarna ej överskrider den önskade.»

If the results obtained by Wennerholm upon studying the occurrence of branches in pine timber of Norrland are compared with those the author ascertained for Finnish spruce upon the basis of the material for the present investigation, it will be found that they show an identical tendency. A close study of the occurrence and kinds of branches and knots in the research material (see chapter IV. 3) clearly indicates that the occurrence of branches is primarily dependent upon the relative intensity of increment during the early development of the stand.

Laitakari (1935) maintains that when the occurrence of branches in a growing forest is mentioned in literature only the living branches are generally taken into consideration, and information concerning dry branches is only seldom to be found. However, since the significance of the dry branches as regards the technical quality of wood is very great in considering the raw material needs of both the paper and the sawmill industries, these should absolutely be taken into consideration when it is a question of valuing the quality of wood.

Laitakari's investigations (1935) show that the occurrence of dead branches and their sizes are great in planted stand and that natural limbing occurs very slowly under such circumstances. He has likewise ascertained that the diameter of branches in large trees increases up to a height of 6 meters above the ground and thereafter decreases as the top is approached, slowly at first and then at a faster rate. He states furthermore that the number of dead branches tends to be proportionate to the number of living branches and that stems having an abundance of living branches also have numerous dead ones. Trees of lesser dimensions, which have been hindered in development, show a greater occurrence of branches than the dominating stems.

As regards the length of stem wood free of branches, Laitakari (1935) has ascertained that this increases as a rule with an increase in the diameter of a tree. The area covered by the crown projections is inversely proportional to the distance of the first living branches from the ground.

There is a particular lack of information concerning the significance of site quality and the type of forest in natural limbing. Bühler and Flury (1932) have ascertained that spruce prunes better on good than on poorer site quality and regard site quality as the most important factor in determining natural pruning. Lönnroth (1925) has ascertained that in natural, normal pine stand the parts of stems free of branches in the best and dominating stems comprise 67 % of the length of the stems 50 years old in stand on MT type of ground, 70 % on VT type and 67 % on CT type having an age of 100 years. It is found however that Lönnroth's figures do not at all show the same tendency as those of Bühler and Flury. Laitakari's investigations (1935) have likewise shown that there is no proof for this contention, and it can finally be maintained that the results obtained by the author (see chapter concerning the occurrence and kinds of branches in the material for investigation) are also entirely different from those of the Swiss men of research. This shows that the history of the development and the density of the stand should be considered as the primary factors for natural pruning. In various types of forests there is found interspersed stand which has an occurrence of branches and that which is well limbed. The reason for this situation has been treated more thoroughly in the preceding chapter.

2. Volume of knot wood.

It is in practice a particularly complicated procedure to determine exactly the volume of knot wood in logs and pulp wood. It is even more difficult to ascertain the quantity of wood of abnormal structure which surrounds the knots and which can often be as obstructive in the manufacturing process as actual knot wood.

The volume of knot wood in a stem can be calculated by means of the following methods:

a. The knot is separated from the surrounding stem wood and the cubical content is obtained stereometrically by a sufficient number of measurements of the length and diameter of the knot in suitable cross-sections.

b. The knot is separated from the surrounding stem wood and the cubical content is obtained in an xylometer.

c. The knot is drilled out and the cavity thus arising in the stem is measured as to its volume.

d. The areas of the cross-sectional surfaces of a knot are determined at definite distances from each other. The sample is sawn into slices of a definite thickness in which the cross-sectional areas of the knot are determined planimetrically with a glass area measuring apparatus or a planimeter.

e. The volume of a knot is determined in accordance with tables compiled on the basis of experience. As bases for the classification of form class there can be used in this connection the diameter of the knot on the surface of the stem, its length from the pith to the surface, the angle of deviation of the branch from the stem and the form of the knot considered as a rotation body.

f. The volume of a knot can also be determined photographically by the use of X-ray photography.

To determine the volume of a knot by separating it from the surrounding stem wood and then measuring its volume after having removed the extraneous wood particles is of course the most exact method. As a method of analysis it is however both slow and impractical and becomes therefore very expensive. Furthermore, it is necessary to destroy the surrounding stem wood more or less by sawing or otherwise in order to remove the knot. Since this method is however regarded as the most accurate theoretically, a series of determinations as to the quantity of knot wood based on this method was made in connection with the present study. The following table shows the results of this work.

There are listed in the table the diameter of the knot horizontally (the minimum diameter), the diameter vertically (the maximum diameter), the length of the knot from the pith to the surface of the stem, the volume of the knot expressed in cubic centimeters and the angle of deviation of

Table XII. — *Taulukko XII.*

Xylometrical volume measurements.
Ksylometriset kuutioimissarjat.

Forest type *Metsätyyppi*	max. diam. cm	min. diam. cm	length *pituus* cm	volume *kuutio* cm^3	angle° *kulma°*
OT	0.5	0.4	10.0	1.92	90
	1.0	0.9	12.0	8.01	97
	1.4	1.2	12.0	15.13	104
	2.1	2.0	14.0	36.71	116
	2.6	2.3	17.0	63.19	120
	3.1	2.9	20.0	111.26	124
MT & VT ...	0.5	0.4	12.0	1.53	110
	1.0	0.8	13.0	7.85	115
	1.5	1.2	14.0	14.00	120
	1.9	1.6	15.0	31.22	121
	2.6	2.2	18.0	61.61	132
Spruce swamps *Kuusikorvet*	0.5	0.4	12.0	1.63	120
	1.0	0.8	12.5	7.20	125
	1.5	1.3	13.0	15.11	130
	1.9	1.6	14.5	42.07	133
	2.4	2.0	16.0	72.22	137

the knot from the vertical direction of the stem. Furthermore, there appear in the table the average breadth of the annual rings of the knot and that of the stem at a corresponding height, the type of forest at the habitat of the tree and the age of the tree at the height of the particular knot. The volume of knot wood has been determined xylometrically with the use of a mercury xylometer (Amsler system).

As is apparent from the table, there is no definite relation between the length, diameter and volume of knots. These show large variations both within various groups of forest types and in knots from the one and the same stem.

The method of drilling a knot out of stem wood and measuring the volume of the cavity thereby arising is very difficult to apply with satisfactory exactitude. It is only with difficulty that the borderline between knot and stem wood can be ascertained when such a drilling method is used. Because of this reason, there has not been found reason for making use of this method.

Methods of measuring the area can on the other hand be considered very practical and produce rather satisfactory results. The log containing a knot is sawn into slices of a definite thickness with a circular saw that is as thin as possible and has only little swaging. The thinner the slices, the more accurate are the results attained. The proportion of knot wood in each slice is determined by calculating the area with a glass area measuring apparatus or planimeter on both sides of the slice. The arithmetic average of the results for the area of knot wood on both sides of the slice is multiplied by the thickness of the slice. The product thereof is the volume of knot wood in the slice. There should of course be carefully taken into consideration the loss of wood through sawing, and the results accordingly corrected.

Since there exist no tables for determining the volume of knot wood, this question has been briefly treated in connection with the present study. The figures for these tables have been calculated on the basis of series of planimetrical measurements of area. The tables have been set up in the same manner as the previous one, the figures for which were obtained xylometrically.

The author has furthermore made photographic investigations as to the volume of knots by the use of X-ray apparatus. However, since this method becomes very expensive and the investigations should preferably be made in the form of stereometric photographs in order to obtain accurate results, this series has been made on only a very limited scale.

Table XIII. — *Taulukko XIII.*

Planimetrical volume measurements.

Planimetriset kuutioimissarjat.

Forest type *Metsätyyppi*	max. diam. cm	min. diam. cm	length *pituus* cm	volume *kuutio* cm³	angle° *kulma°*
OT	0.5	0.4	10.0	1.90	90
	1.0	0.9	12.0	8.00	97
	1.4	1.2	12.0	15.10	104
	2.1	2.0	14.0	36.00	116
	2.6	2.4	17.0	62.50	120
	3.1	2.9	20.0	110.80	124
MT & VT ..	0.5	0.4	12.0	1.50	110
	1.0	1.8	13.0	7.75	115
	1.5	1.2	14.0	14.00	120
	1.9	1.6	15.0	31.20	121
	2.6	2.2	18.0	60.50	132
Spruce swamps *Kuusikorvet*	0.5	0.4	12.0	1.60	120
	1.0	0.8	12.5	7.00	125
	1.6	1.3	13.0	14.90	130
	2.0	1.7	14.5	41.10	133
	2.4	2.0	16.0	69.00	137

As will be observed from all series of analyses, the volume of a knot can fluctuate within particularly wide limits. As an example, the relationship between the diameter of a knot on the surface of a stem and the length of the knot is particularly indefinite. It is absolutely hopeless to attempt a determination of the volume of knot wood in the basis of only one factor, a procedure which has however often been made. There are nevertheless found in literature numerous statements concerning the content of knot wood in timber which are based on a percentage of the area of knots with relation to the entire surface of the stem (Vuoristo 1937 and others). These statements are however misleading and absolutely inaccurate.

In practically all works in which the problem of the volume of knot wood is treated, interest has been attached only to the volume of the actual knot. The volume of the wood having an abnormal structure, which surrounds the knot, has on the other hand been left entirely out of considera-

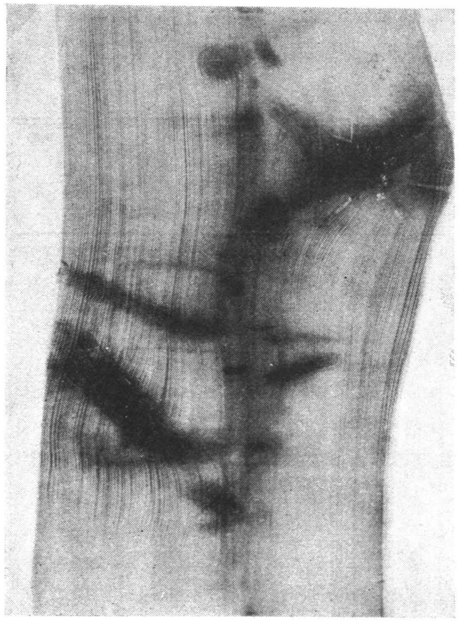


Fig. 21 X-ray photograph of a bolt from Kemi. — *Kuva 18. Kemin piirin pölkyn röntgenkuva.*

(photo Carl Wegelius)

tion. This wood differs from normal stem wood almost to as great an extent as knot wood because of its compact structure with short fibers and because of its dissimilar chemical properties such as a high content of incrustations, resin and lignin. The compression wood around a knot is accordingly a factor in the various branches of the wood working industry which decreases quality as much as actual knot wood. The statements found in literature, and according to which the quantity of knot wood is calculated only on the basis of the volume of the actual knots, have consequently no practical value. In order to obtain an accurate picture of the suitability of wood for various purposes and the significance of the presence of knots in this connection, there should also be understood the extent of compression wood around the knot and its characteristics. However, since knot wood and the surrounding stem wood of abnormal structure are dissimilar in many respects, particularly as regards anatomy, these should each be considered separately.

In practical analyses of the quantity of knot wood (Vuoristo 1937), it is often seen that the volume of knots is calculated as if they were conical in shape. The bottom or base of the cone is the cross-section area of the branch at the surface of the stem while its height is equal to half the diameter of the stem at the position of the knot. In addition to having made the mistake in this method of procedure of not taking into consideration the quantity of adjacent compression wood, there have furthermore been neglected to be considered the biological laws governing the increment of knot wood. A cross-sectional cut of a knot in its longitudinal direction is never triangular in shape but reminds one rather of the form of a parabola. A knot does not become thicker at the same rate as a stem but reaches the culmination in its increment in thickness relatively earlier. It is found in a small spruce plant that the branches are approximately as thick as the orthotropic, main stem. As the plant becomes older, it is clearly discernible that the stem acquires a greater diameter than the branch. In older trees the main stem is many times thicker than the branches. The following figure shows the development in the breadth of the annual rings of stems and branches at a corresponding height above the ground. The cumulative increment clearly reaches its culmination for branches while still increasing in the stem.

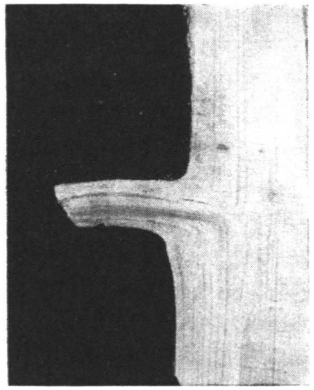


Fig. 22. 20 years old branch. *Kuva 22. 20 v. vanha oksa.*

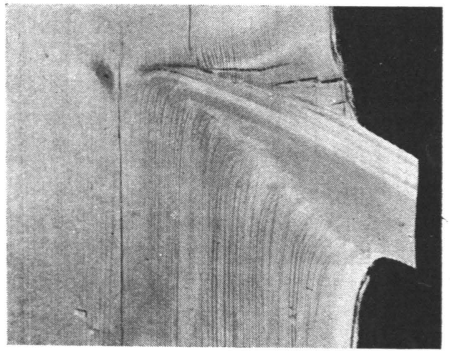


Fig 23 100 years old branch — *Kuva 23. 100 v. vanha oksa.*

In order to obtain a picture of the development of compression wood around a knot and to be able to determine the quantity of such wood which gives rise to so-called knot pulp in the production of cellulose or ground wood pulp, there has been included in the present study a separate series of analyses. This series has been made on the basis of cross-sectional cuts in the vertical plane, and measurements were made in the form of areal determinations with a glass area measuring apparatus. It is found firstly that the quantity of compression wood is particularly indefinite as regards volume. Likewise, the distribution of the compression wood around the knot is subject to great variation. The principal portion of compression wood sometimes appears on the upper side of the knot and sometimes on the lower side. These compressions of the wood are however of a differing nature on the upper and lower sides of knots. Anatomically, the former reminds one more of tension wood while the latter is more identical to the compression wood on the lower side of branches.

Table XIV. — *Taulukko XIV.*

Compressions of wood on the upper and lower sides of knots.
Lylypuumuodostumat oksan ylä- ja alapuolella.

Forest type *Metsätyyppi*	Knot wood *Varsinaista oksapuuta* cm^2	Upper compression wood *Lylyä yläpuolella* cm^2	Lower compression wood *Lylyä alapuolella* cm^2
OT	1.11	0.12	0.67
	1.41	0.41	0.72
	2.32	2.07	1.49
	8.69	4.12	5.30
	12.21	5.00	6.15
	16.72	8.12	7.98
	18.34	10.57	11.09
	28.15	10.81	16.99
	34.91	12.71	15.32
	43.33	23.15	36.06
MT & VT	1.07	0.06	0.32
	1.98	0.41	0.27
	2.32	0.38	0.66
	7.49	6.34	2.94
	9.64	4.84	4.24
	12.12	1.87	6.86
	12.46	5.10	7.35
	22.65	9.26	13.31
	23.57	7.42	6.80
	30.01	9.93	10.07
Spruce swamps *Kuusikorvet*	1.35	0.19	0.40
	2.41	0.28	0.57
	5.12	4.98	1.94
	7.91	6.34	2.92
	9.46	4.10	5.35
	9.48	4.48	6.65
	9.93	2.43	6.15
	11.74	9.02	9.71
	23.14	6.82	10.11
	25.67	11.37	9.79

CHAPTER VIII.

Anatomical structure of branch and knot wood.

Because of the special requirements which branch wood and stem wood have to fulfill in supplying the biological demands of a tree, they present in many respects differences in characteristics, as has already previously been mentioned. Consequently, the structure of the wood, the dimensions of the fibers and the chemical, physical and mechanical properties are of a different nature in branch wood than in stem wood. This situation is most clearly reflected in the anatomical structure of wood, and it may be regarded that many of the differences which exist in various properties are a direct result of the distinguishing features for knot wood and the surrounding compression wood in the composition of the wood and the cells. Due to compression wood containing more intercellular cavities than stem wood, it is also more lacking in cellulose. It can likewise be shown that differences in specific gravity and content of moisture are a direct result of the variations in the density of the wood and that the fibrillar structure of branch and knot wood decisively affects the physical and mechanical properties.

In various branches of the wood working industry the anatomical properties play an important role and the occurrence of knots in wood is therefore in many respects of great significance. In the sawmill industry, for example, knots cause an appreciable decrease in strength and value due to changing the structure of the wood. And in the paper industry it has been observed that knot wood gives a fiber yield of inferior value and furthermore often makes the manufacturing process more difficult. A study as to the anatomical structure of branch and knot wood can therefore furnish much of interest from the technical point of view, and the structure of wood as well as the characteristics of the individual cells should be given attention in this connection.

1. The macroscopic structure of branch and knot wood.

The structure of wood, insofar as is apparent to the eye, is the result of numerous biological circumstances. Various species of trees differ macroscopically from each other due to the outer appearance of the wood. Furthermore, the wood in a single stem or tree differs in its various parts to a certain extent. The relationship of sapwood and heartwood to each other varies as is know at different heights. While there is found in the base portions of a stem a well developed and a widely spread formation of heartwood, the top on the other hand consists practically completely of sapwood.

Another characteristic affecting the structure of wood is, as is known, the formation of compression wood. This is the result of the mechanical strain to which the various parts of the stem are subjected because of the effect of the power of gravitation and the pressure caused by wind conditions. As a result thereof, the position and the extent of compression wood vary appreciably.

Even the relation between the extent of springwood and summerwood as well as the rate of growth, ie., the breadth of the annual rings, constitute factors which decisively affect the anatomical structure of wood. It may be maintained as a rule that trees which have grown under identical circumstances present a higher content of summerwood when the increment has occurred slowly and the annual rings are narrow. This apparent tendency, which has been pointed out by Jalava, Klem, Rochester, Savkov, Trendelenburg and others, was likewise very clear in the material for investigation accumulated in connection with the present study. In order to obtain a clear comparison between the breadth of the annual rings and the portion of summerwood in stem and knot wood, there has been made on the basis of the material gathered for the present study a series of microscopic analyses covering these characteristics.

Orthotropic stem wood which has grown under normal conditions without having been subjected to a great extent to outer irritations, such as winds from one side only, snow breaks, et cetera, show as a rule a concentric, radially symmetrical structure of increment. The plagiotropic growth axles, which are subjected to a certain pressure caused by the power of gravitation, present on the other hand, as has previously been ascertained, an eccentric growth of a hyponastic or epinastic nature. This hyponastic eccentricity in the grouping of the annual rings in spruce branches is a characteristic which is reflected macroscopically in various ways. A cross-section of a branch accordingly differs noticeably from that of a stem due to the large portion of compression wood on the lower side of the branch and due to the insignificant breadth of the annual rings in comparison with stem wood.

With the exception of the fact that the pith center in branch wood lies eccentrically on the zenith side of the geometric middle point, the piths in stem and knot wood differ from each other macroscopically. More typical is the difference when it is a question of the pith rays, which are more apparent and noticeable in knot wood than in stem wood. The reason cannot however be regarded to depend so much on the greater occurrence of pith rays in knots as on the fact that the pith rays of knots deviate to a greater extent because of the light color of the parenchymatous cells from the surrounding dark and dense prosenchymatous cell walls of compression wood. In any case it can be recognized that the pith rays in various parts of conifers are to such an extent relatively insignificant as regards volume that they are not a noteworthy factor in judging the technical value of wood.

The annual rings and their breadth and composition often present a good macroscopic picture of the quality of wood, and it is generally regarded that narrow annual rings constitute a guarantee of good fiber material. This rule does not however apply to branch and knot wood. As a result of the insignificant dimensions of knots as compared with those of a stem at a corresponding height, the annual rings of knots are particularly narrow. Because of the eccentric grouping of the annual rings, they are very uneven in breadth and are always wider on the nadir side than on the zenith side.

Compression wood in knots is noticeable in appearance, and the greatly increased content of summerwood appears in cross-section in the form of crescent-shaped arches on the lower side of a knot.

It is only seldom that sapwood can be differentiated with the naked eye from heartwood in spruce. This situation appears to apply to both stem wood and branch and knot wood although the latter often

Fig. 24. Cross section of a branch. — *Kuva 24. Oksan läpileikkaus.*

can appear to have pronounced heartwood because of the accumulation of compression wood.

As far as coloration and texture are finally concerned, knot wood differs from stem wood due to difference in anatomical structure. Because of the abundant occurrence of compression wood, knot wood is darker and more lustrous and the differences in color more noticeable. The great density of knot wood contributes furthermore towards increasing lustre and in giving the wood a darker coloration.

2. The microscopic structure of branch and knot wood.

The differences which exist in the macroscopic structure of stem wood and knot wood can in most cases be traced to varying fiber structure. In order to understand correctly the difference in anatomical structure between stem wood and knot wood, the anatomically structural features of knot wood should therefore be investigated microscopically. In this connection the percentage of summerwood, the percentage of intercellular cavities and the density are primarily of interest. Furthermore, the composition and size of the individual cells and the structure of the cell walls are of utmost significance.

Upon investigating first the grouping of cell tissues in knot wood, interest is attached partly to the unusually high percentage of summerwood, partly to the great portion of compressed fibers and finally to the special joining of the various cells to each other. It is of course axiomatic that the tissues in tension wood must show, because of a higher content of cellulose, a structure deviating from that of compression wood. As should be clearly apparent from the photographs on the opposite page, the rule that narrow annual rings are accompanied by a relatively high content of compression wood is not in this connection applicable. In spite of the annual rings in compression wood being considerably wider than those in tension wood because of pervading hyponasty, they contain a much greater percentage of summerwood.

In order to illustrate furthermore this outstanding condition, there has been undertaken in connection with the present investigation a series of measurements of the breadth of the annual rings and the percentage of summerwood in compression and tension wood of knots. These have been combined in the following set of tables with the investigations which have been made concerning the variation of these characteristics in stem wood. The analyses were made by microscopic measurements with a special mi-

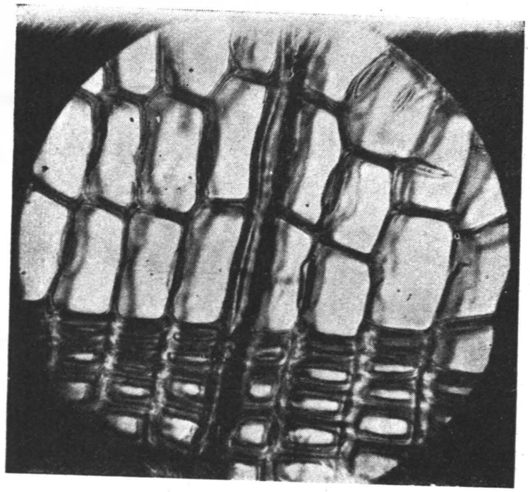


Fig. 25. Cross section of stem wood from OT stand (magnified 250 diameters). — *Kuva 25. Läpileikkaus OT-runkopuusta (250 kertainen suurennus).*

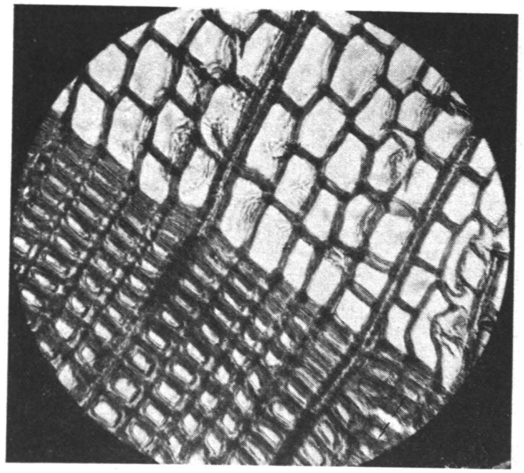


Fig. 26. Cross section of stem wood from spruce swamp stand (magnified 250 diameters). — *Kuva 26. Läpileikkaus korpikuusen runkopuusta (250 kertainen suurennus).*

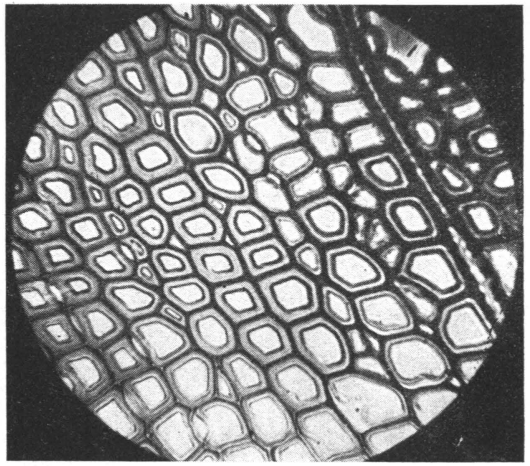


Fig. 27. Cross section of stem compression wood (magnified 250 diameters). — *Kuva 27. Läpileikkaus rungon lylypuusta (250 kertainen suurennus).*

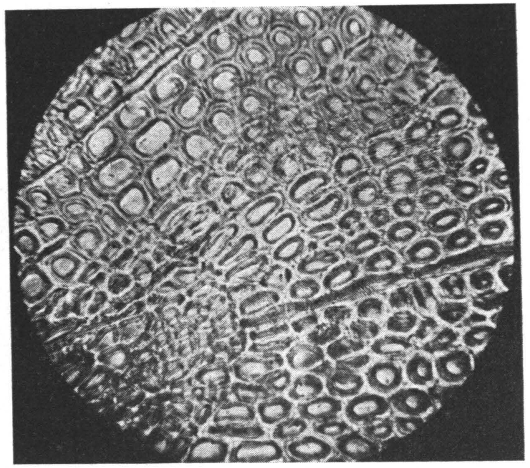


Fig. 28. Cross section of branch wood near the pith (magnified 250 diameters). — *Kuva 28. Läpileikkaus oksapuusta läheltä ydintä (250 kertainen suurennus).*

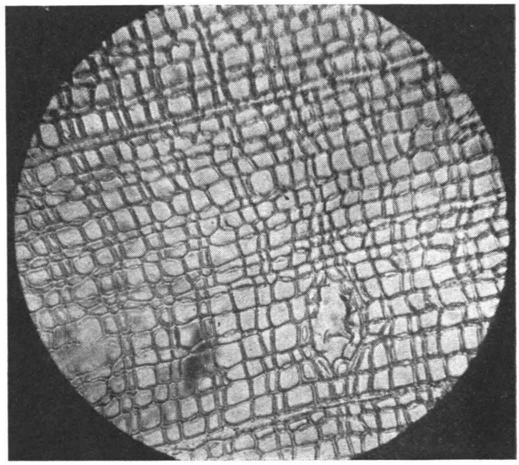


Fig. 29. Cross section of branch tension wood (magnified 250 diameters). — *Kuva 29. Läpileikkaus oksan vetopuusta (250 kertainen suurennus).*

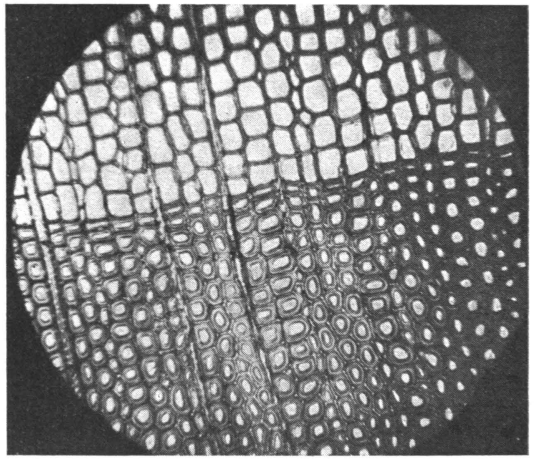


Fig. 30. Cross section of branch compression wood (magnified 250 diameters). — *Kuva 30. Läpileikkaus oksan lylypuusta (250 kertainen suurennus).*

Table XV. — *Taulukko XV.*

The breadth of the annual rings and the percentage of summerwood in stem wood and in compression and tension wood of knots.

Vuosilustojen leveys ja kesäpuuprosentti runkopuussa ja oksan veto- ja lylypuussa.

Forest type *Metsätyyppi*	Stem wood Annual rings *Runkopuu vuosilustoleveys* mm	Stem wood Summer wood % *Kesäpuu % Runkopuu*	Compression wood Annual rings *Lylypuun vuosilustoleveys* mm	Compression wood Summer wood % *Kesäpuu % Lylypuu*	Tension wood Annual rings *Vetopuun vuosilustoleveys mm*	Tension wood Summer wood % *Kesäpuu % Vetopuu*
OT	4.11	6.85	0.16	45.76	0.13	20.32
	4.41	7.41	0.18	40.74	0.15	23.61
	4.75	8.46	0.19	40.00	0.15	20.97
	4.61	8.39	0.15	40.09	0.11	26.11
	3.32	8.34	0.16	47.19	0.13	29.60
	4.16	7.87	0.14	46.11	0.10	16.12
	4.93	7.17	0.17	55.55	0.13	21.33
	4.67	9.00	0.14	42.22	0.09	30.30
	3.40	11.97	0.13	39.37	0.09	30.91
	2.90	10.10	0.15	38.57	0.11	31.71
MT	1.74	16.32	0.12	39.12	0.09	19.47
	1.74	17.54	0.14	42.15	0.11	22.88
	1.58	17.01	0.11	49.87	0.08	18.51
	2.01	14.90	0.13	46.31	0.10	20.90
	1.92	15.82	0.19	62.08	0.14	15.02
	1.34	16.19	0.17	51.51	0.14	17.78
	1.83	16.99	0.16	44.18	0.11	13.34
	1.38	14.26	0.18	49.12	0.13	16.80
VT	1.04	22.37	0.41	71.25	0.21	14.41
	0.79	20.46	0.25	59.82	0.16	16.95
	1.05	19.87	0.25	48.88	0.17	17.13
	0.92	19.01	0.19	39.49	0.14	16.40
	1.08	21.69	0.18	43.38	0.10	14.33
	1.22	19.31	0.14	52.48	0.11	20.92
	0.93	24.98	0.17	48.80	0.12	17.30
	1.15	23.77	0.16	47.13	0.11	15.25
Spruce swamps *Kuusikorvet*	0.55	31.48	0.17	47.16	0.14	37.12
	0.62	30.23	0.20	47.89	0.15	14.17
	0.66	28.09	0.15	50.20	0.09	28.76
	0.73	27.88	0.17	58.33	0.11	17.88
	0.87	29.54	0.18	55.86	0.09	13.09
	0.81	26.74	0.23	49.11	0.14	24.69
	0.83	24.59	0.20	49.64	0.13	24.42
	0.72	26.90	0.24	60.32	0.16	31.72

croscope constructed by Jalava (1933) and equipped with a measuring apparatus and a vernier scale. The results of the investigation are presented numerically and graphically in the following tables and diagrams; stem wood, knot tension wood and knot compression wood being each shown separately.

A graph of the following nature based on available material is obtained upon combining in a diagram the results of the measurements of the breadth of the annual rings and the analyses covering variations in the percentage of summerwood when the stem wood and the various kinds of branch wood are grouped in the one and the same series.

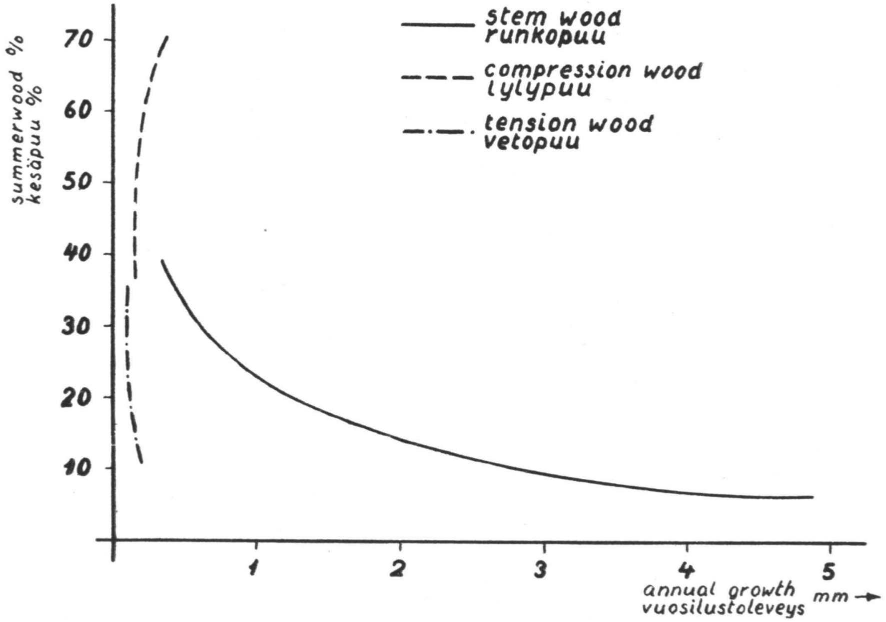


Fig 31. Graph showing the relation between the breadth of the annual rings and the percentage of summerwood. — *Kuva 31. Vuosilustoleveyden ja kesäpuuprosentin välistä suhdetta osoittava diagramma.*

It can be observed in the foregoing graph that the breadth of the annual rings in stem wood decreases with an increase in the portion of summerwood. This tendency is clear commencing with coarse-grained stem wood and includes also compression wood in the nadir part of the knot. But when theb readth of the annual rings decreases furthermore and in the final part of the graph, which embodies principally the tension wood in the zenith part of a knot, it is found that the portion of summerwood decreases rapidly.

A study covering the relationship of the cell tissues to each other and the percentage of space in branch and knot wood as compared with that in stem wood gives rise to particular interest. While the anatomical structure of stem wood is conspicuous for its high degree of regularity and homogeneity, branch and knot wood is very heterogeneous as regards the position of the cells with relation to each other. The reasons therefore are to be traced partly to the circumstances of mechanical loads and partly to physiological conditions depending upon the supply of nutrition. The cells in stem wood are more or less rectangular and, figuratively speaking, are attached to each other like bricks in a brick wall. There are found on the other hand in knot wood numerous, round and thick-walled cells which are not situated absolutely against each other and accordingly give rise to intercellular cavities between the individual cells. This increased percentage of space is particularly characteristic of compression wood in knots.

Hartig (1896) has expended a great deal of effort in explaining the origin and characteristics of compression wood and has in this connection studied particularly the anatomical structure of branch wood. After having considered the reasons for hyponasty, he presents the following:

»Der Druck auf die noch lebenden jungen Holzzellen pflanzt sich durch die elastische zarte Zellhaut umgeschwächt auf den Inhalt fort, und der Protoplasmakörper reagiert auf den Druck in dreifach verschiedener Weise.

»Zunächst wird die Gestalt der Tracheiden insofern beeinflusst, als der hydrostatische Druck auf alle Wandflächen gleichmässig wirkt und eine Abrundung der Zellwände veranlässt.

»In den meisten Fällen suchen sich schon die primären Zellwände abzurunden, indem an den Stellen, wo drei oder vier Zellwände aufeinanderstossen, kleinere oder grössere Intercellularräume sich bilden. Während das normale Holz fast niemals Zwischenzellräume bildet, und solche nur da zu finden sind, wo Parenchymzellen auftreten, zeigt das Rotholz sehr zahlreiche Intercellularräume, die zuweilen so stark ausgebildet sind, das bei Anfertigung mikroskopischer Querschnitte ganze radiale Reihen von Tracheiden sich von den Nachbarreihen los lösen.

»Sehr oft kommt aber die Primärwandung zur normalen Ausbildung ohne Intercellularräume. Die secundären Verdickungsschichten nehmen beim Rotholz auch dann, wenn dasselbe Intercellularräume besitzt, den schon von Sanio (in Pringsheim's: Jahrbüchern für wissenschaftliche Botanik IX Band I Heft., Anatomie der gemeinen Kiefer.) als »differenziertes» Holz bezeichneten eigenartigen Bau an. Es bildet sich nähmlich nachdem die Verdickung der Zellwand schon mehr oder weniger weit vorgeschritten ist, eine oft kreisrunde dünne Lamelle, an deren Innenseiten die Verdickung fortschreitet und gegen das Zellumen durch eine dünne »tertiäre» Wandschicht abgegrenzt wird.» He declares that the noticeably slight shrinkage in compression wood upon a decrease in the content of moisture is due to the occurrence of intercellular cavities which expand when the cell walls dry out and diminish.

Another characteristic property for compression wood is the relatively great thickness of the walls of the tracheids. This is due partly to the great mechanical strains but is also traced to various, physiological conditions of nutrition. When the tree is poorly nourished and grows in barren soil, the cell walls become thin and the cells assume a regular, rectangular appearance, as has been pointed out by Hartig (1901), Klem (1934) and others. On the other hand, if the conditions of nutrition are favorable, the cells become thick-walled and rounded. A lively transport of alimentary substances occurs in branch wood, where the activity of life is particularly extensive, and this in turn may be considered to affect the cell structure which then assumes a thick-walled and rounded outer formation.

Hartig (1896) maintains that mechanical irritations of pressure not only cause a thickening of the cell walls but also affect the rapidity of the process of cell division so that the portion of the annual ring containing compression wood at the same time becomes considerably broader than the portion which is not compressed. The individual cambium will not be as long nor as old on the compression side as on the tension side. Hartig's investigations also show compression wood tracheids to be only seven-tenths to eight-tenths the length of tension wood tracheids.

When studying the tables covering variations in the breadth of annual rings and the percentage of summerwood in stem wood and branch and knot wood, it is found that the springwood zone in normal spruce is always wider than the summerwood zone, while the situation in branch and knot wood varies greatly depending upon how long the process of compression has occurred. If the wood is greatly compressed, only a few springwood tracheids will be found therein, while on the tension wood side of the knot the portion of summerwood is rather normal. This situation can also be traced to various mechanical strains in the different parts of a knot. As compression wood is formed in order to withstand great mechanical pressure, it is very heavily lignified and consists principally of summerwood.

On the other hand tension wood, which is formed to withstand heavy tensile strength, differs from normal wood in that it has developed an extra cell wall (Hartig 1901) outside the actual secondary wall in the summerwood tracheids. This layer, which Hartig terms a tertiary wall, is less lignified and has a greater content of cellulose than the secondary wall and contains closely fitting, spiral, strengthening strips.

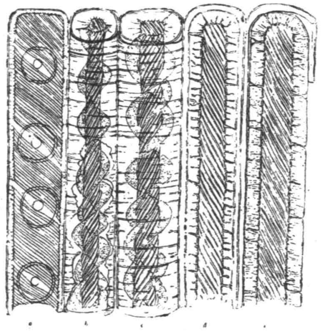


Fig. 32. Compression wood tracheids in spruce (based on Hartig 1901). — *Kuva 32. Kuusen lylypuutrakeideja (Hartig'in mukaan).*

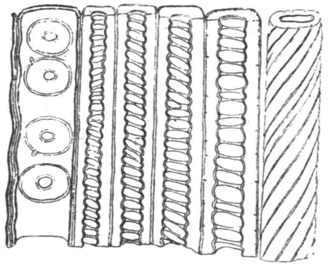


Fig. 33. Tension wood tracheids in spruce (based on Hartig 1901). — *Kuva 33. Kuusen vetopuutrakeideja (Hartig'in mukaan).*

Hartig (1901) states the following concerning the tension wood of branches and its characteristics:

»Bezüglich des Zugholzes der Aeste ist zunächst bemerkenswerth, dass dieses Holz sich durch grossen Substanzreichtum gegenüber anderem Fichtenholze auszeichnet, was als natürliche Reaktion auf Zugreiz gedeutet werden muss. Die ausserordentliche Dickwandigkeit aller Organe des Zugholzes auf der Oberseite der Aeste sind wir voll berechtigt, als Wirkungen des beständigen Zuges aufzufassen, welchen das bedeutende Gewicht des Astes auf die Cambialorgane der Oberseite ausübt.»

Metzger (1908) has also given considerable attention to the reasons for the hyponastic structure of knots of conifers and states in brief as follows concerning the reasons for differences in structure in compression and tension wood:

»Zwischen dem Weiss- und Rotholz der Nadelhölzer existiert andererseits ein Unterschied, der mir für die abweichenden Aufgaben der beiden Holzsorten charakteristisch zu sein scheint. Die einzelnen Zellen des Rotholzes sind meistens kreisrund und wie die Zellen in einer Honigwabe im Dreiecksverband nebeneinander gelagert. Das Weissholz dagegen hat abgeplattete Zellen, welche weit deutlicher in radialen und peripherischen Reihen gelagert zu sein scheinen. Die Gruppierung der Rotholzzellen im Dreiecksverband ist nun gleichbedeutend mit der Anbringung der grössten Zellenzahl auf der Flächeneinheit des Querschnittes mit der besten Ausnützung des Raumes, also auch mit der dichtesten Struktur und der grössten mechanischen Leistungsfähigkeit des Holzes. Die hiervon abweichende Gruppierung der Weissholzzellen scheint mir weniger auf Festigungsfunktionen zu deuten als auf Leitungsfunktionen. Denn diese Lagerung in peripherischen Reihen finden wir vornehmlich in dem Frühholz des Stammes, das ja ausschliesslich aus Leitungstracheiden besteht.»

The Norwegian Elias Mork (1928) has likewise investigated the breadth of annual rings, the percentage of summerwood and the length of tracheids in hyponastically formed trees. He summarizes the results obtained in this connection in the following conclusion:

»I normal ved stiger sommervedprosent og trakeidelengde med avtagende årringbredde. Trakeidelengden er dessuten strengt avhengig av beliggenheten fra margen, således at de i yteveden som regel er omkring det dobbelte av hvad den er inne ved margen.

»I tennarveden synes trakeidelengden å vaere mindre avhang av beliggenhet og årringbredde. Trakeidelengden er her som regel omkring 1,5 mm. De korte trakeidelengder i tennar skyldes sor en stor del brede årringer; men tennar har også under ellers like forhold (samme årringbredde og samme avstand fra margen) kortere trakeider enn normal ved.

»Sommervedsprosenten er alltid större enn i normal ved. Den er her ikke avhengig av årringbredden, men av tennardannelsens intensitet. Jo sterkere tennardannels, jo större sommervedsprosent.

»Strekkveden består alltid av meget smale årringer. Den har litt lengere trakeider enn normal ved og sommervedsprosenten er meget ujevn.»

It is accordingly found that the author's investigations covering the percentage of summerwood and the breadth of annual rings well agree as to tendency with those made by Mork.

In order to illustrate furthermore the differences in anatomical structure between the cell tissues in stem wood and branch and knot wood, there has been made in connection with the present study a series of planimetrical investigations covering the percentage of space and the thickness of the cell walls in various species of wood. These investigations were made by using microscopic sections projected with a projection microscope for suitable enlargement on a sheet of paper on which the measurements were made with a glass area measuring apparatus having a millimeter scale.

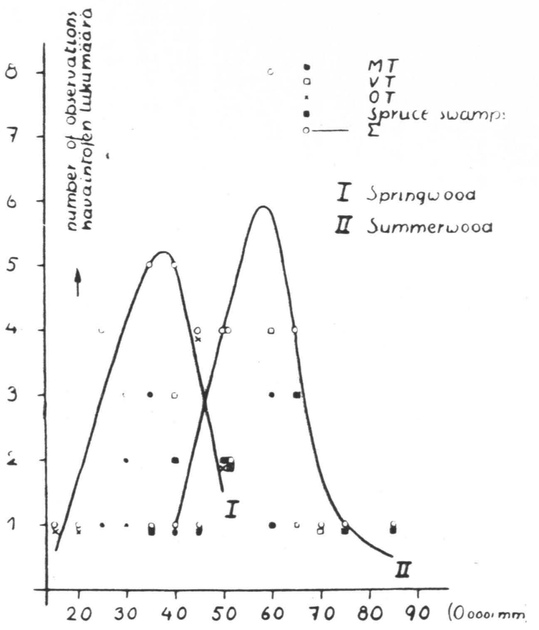


Fig. 34. Planimetrical investigations covering the thickness of cell walls in stem wood. — *Kuva 34. Planimetriset tutkimukset rungon soluseinämien paksuudesta.*

The technical quality of wood is primarily dependent upon the size and strength properties of the fibers comprising it. It has been found particularly in the paper industry that the quality characteristics of the manufactured product are to a great extent effected by the size of the individual fibers. If a comparison is made of the fibers in stem wood with those in knot wood, there will be found very noticeable differences. These arise to some extent from the fact that knot fibers are much smaller in dimension than the tracheids in stem wood, but comprise also differences in the anatomical structure of the cell walls. This apparently affects in turn the physical, chemical and technical properties of wood.

A multitude of measurements have been made covering fiber dimensions and their variations in various kinds of stand and in various part of stems. Since the measurement of the dimensions of the cells in wood is furthermore

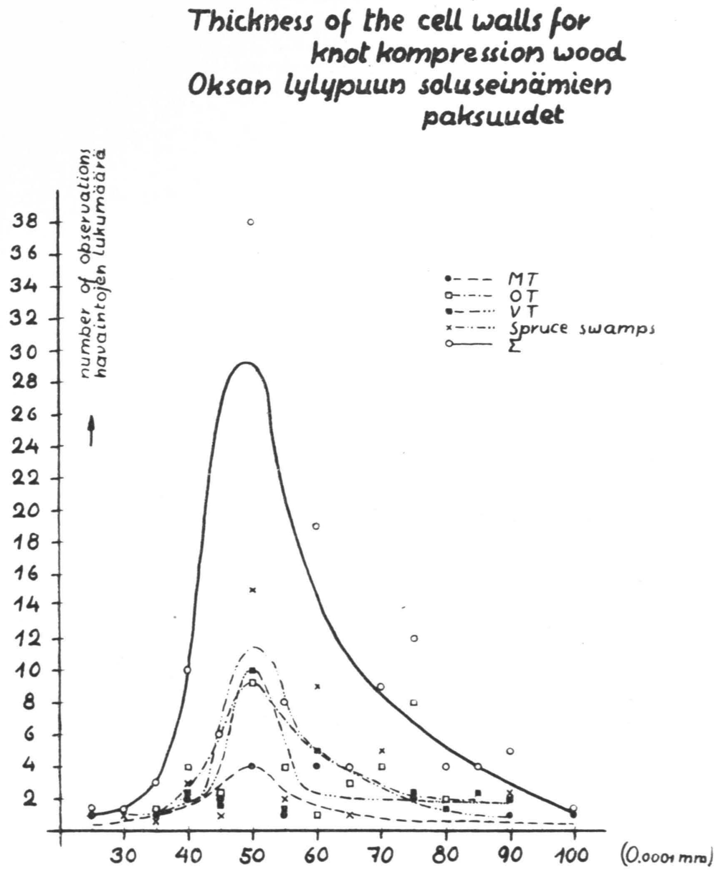


Fig. 35. Planimetrical investigations covering the thickness of cell walls in branchcompression wood. — *Kuva 35. Planimetriset tutkimukset oksan lylypuun soluseinämien paksuudesta.*

a simple and mechanical procedure in which an abundance of material can be easily examined, fiber measurements have already a long time ago reached such a degree of perfection that the material obtained can be regarded as satisfactory and reliable. In this connection it has been found that the length of fibers as also the portion of summerwood and the percentage of intercellular space constitute the consequence of the biological, outer circumstances under which the tree has grown.

Sanio (1872, 1873—1874) was the first to undertake extensive investigations covering the length of fibers in coniferous wood. He

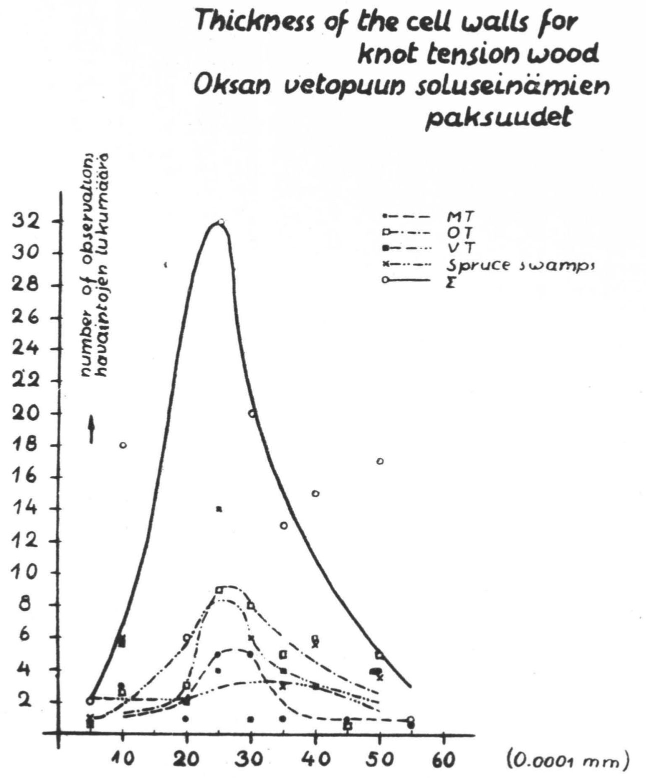


Fig. 36. Planimetrical investigations covering the thickness of cell walls in branch tension wood.
Kuva 36. Planimetriset tutkimukset oksan vetopuun soluseinämien paksuudesta.

investigated material obtained from pine stems and found that the length of fibers increased from the root toward the crown; that upon reaching a certain height the maximum was reached and a decrease occurred thereafter; and that the length of fibers increased upon approaching the bark from the pith. He also ascertained that branch wood contains much shorter fibers than normal stem wood. R. Hartig (1892 and 1898) has likewise made extensive studies concerning the length of fibers and variations in the thickness of cell walls. The thousands of measurements which he undertook concerning the dimensions of fibers in one and the same annual ring showed similarly as those of Sanio that the length of fibers increased when approaching the top from the root and that a maximum was reached at a certain point. He also found that the length of fibers and their tangential diameter increased upon approaching the bark from the pith. The broadest

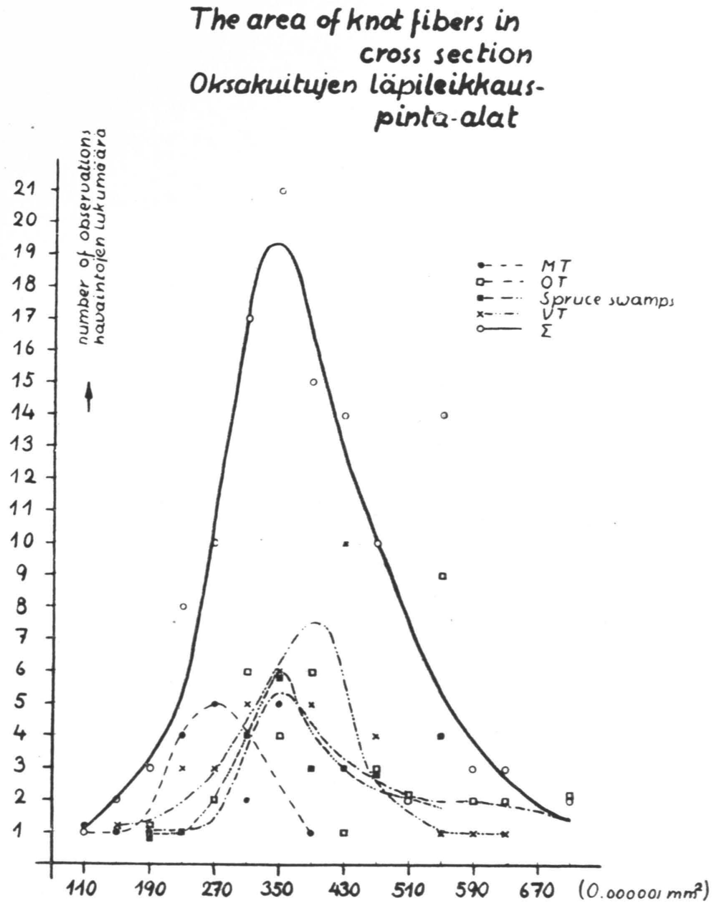
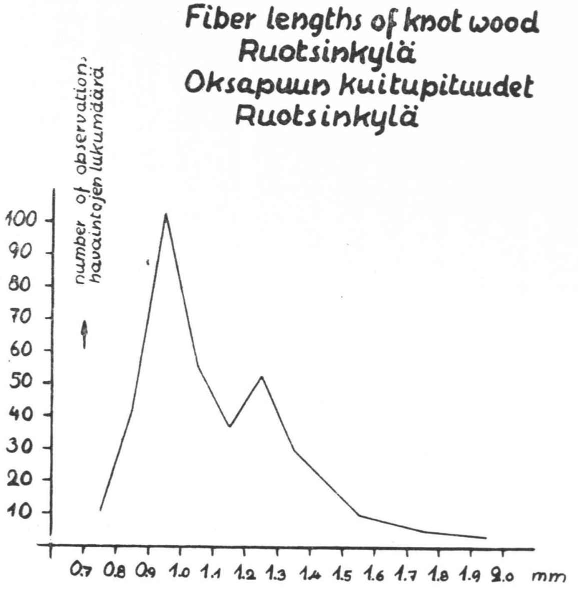


Fig. 37. Planimetrical investigations covering the area of knot fibers in cross section. — *Kuva 37. Planimetriset tutkimukset oksakuitujen läpileikkauspinta-alasta.*

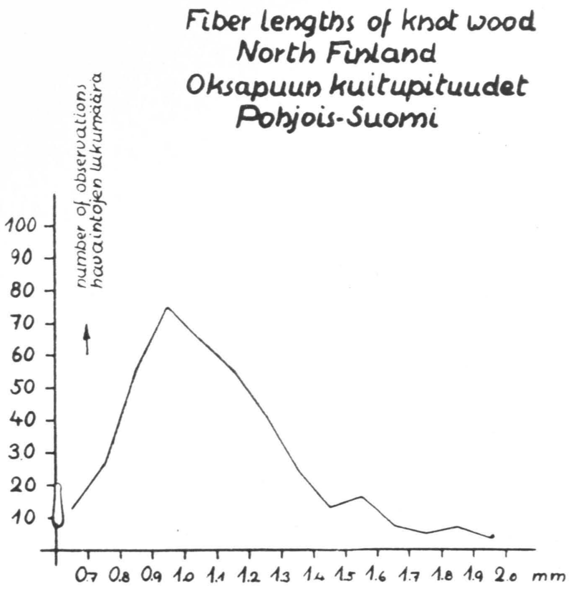
fibers were found in a particular stand in trees of the greatest power of growth while in over-topped trees the fibers were of such size that up to four of them could be contained in the space of a fiber from a predominating tree. Density was greatest in trees having narrow fibers and a high percentage of summerwood. This was due to the fact that in over-topped trees the evaporation of moisture was relatively less and the water canals were not therefore needed to an equal extent. The investigations of Bertog (1895) concerning the dimensions of fibers confirmed those of Sanio and Hartig. He found that springwood had shorter fibers than



F i g. 38. Length of knot fibers. Material from Ruotsinkylä. — *K u v a 38. Oksakuitujen pituudet. Ruotsinkylän aineisto.*

summerwood. Based on his material the length of fibers varied from 0.3 to 0.6 mm. The thickness of fibers was greatest at breast height and decreased thereafter slowly in the direction of the crown. It increased again in the youngest parts of the crown.

Of the later investigations that have been made covering the dimensions of fibers, there may be mentioned of primary interest those of Hägglund (1935) in Sweden, Mork (1928 a and b) and Nergaard (1928) in Norway, Helander (1930) in Finland and Trendelenburg (1936) in Germany. These constitute evidence of the accuracy of the works of Sanio and Hartig but are furthermore of particular interest since the taper of cells, ie., the relationship between length and breadth, has also been considered. It may be maintained on the basis of all of these investigations that they have shown the length of fibers to decrease with an increase in the breadth of the annual rings. They have furthermore shown that sapwood is distinguished for having longer fibers than heartwood. It has also been found that slender-stemmed and slow grown wood contains as a rule longer fibers than rapidly grown wood. It may therefore be maintained that a dense form of stand will furnish raw material having longer fibers than an open forest.



F i g. 39. Length of knot fibers. Material from the mills in North Finland. — *K u v a 39. Oksakuitujen pituudet. Pohjois-Suomen tehtaiden aineisto.*

The series of analyses which have been made by Helander and Hägglund are of particular interest as regards conditions in Finland. Helander has ascertained that the length of tracheids is dependent upon the age of a tree and their location in the stem. The size of the cells is furthermore affected by the breadth of the annual rings and whether the fiber is located in springwood or summerwood. The maximum is reachod at an age varying between 60 and 100 years depending upon the form of stand and site quality. The length of the tracheids decreases with an increase in the breadth of the annual rings. Their length appears likewise to decrease when the portion of summerwood is less. It accordingly seems as if the dimensions of fibers should be more unfavorable in rapidly grown than in slow grown wood and as if the latter should be technically more valuable than the former. Helander's investigations show furthermore that the tracheids in Finnish conifers reach their maximum length at a height of 50 % to 60 % of the length of the stem.

Hägglund's investigations also show that the fibers in slow grown

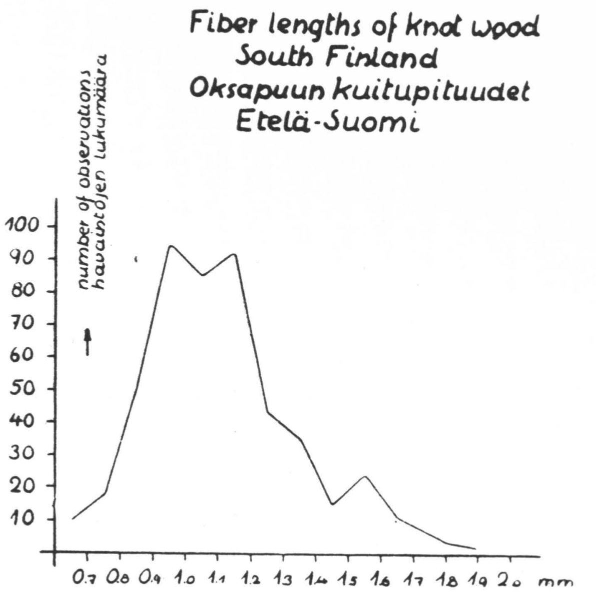


Fig. 40. Length of knot fibers. Material from the mills in South Finland. — *Kuva 40. Oksakuitujen pituudet. Etelä-Suomen tehtaiden aineisto.*

wood are longer than in rapidly grown wood. He draws the conclusion that over-topped trees in forest stand furnish qualitatively a fiber material of higher value than the predominating trees.

The dimensions and structure of fibers in branch and knot wood have however only to a very limited extent been the subject of microscopic investigations. Sanio (1873—1874) has, it is true, made a series of measurements covering the dimensions of branch fibers in German pine, and the contention can be risked that the laws which he found in this connection to be applicable generally also apply to branch fibers of spruce. Sanio has stated the law covering the constant size of knot cells in the following manner:

»1). Die Grösse an der Basis der Aeste und Zweige ist stets geringer als an der Ansatzstelle im Stamme oder Tragebreite.

»2). Die hängt in der Weise von der Grösse der Holzzellen des Stammes ab, dass da, wo diese grössere Zellen führen, auch der Ast oder Zweig mit grösseren Zellen an seiner Basis beginnt.

»3). Von der Basis steigt zunächst (wie im Stamme über den Seitenwurzeln) die Grösse schnell und dann langsamer bis zu einem Maximum

um dann wieder zu fallen. Doch kommen hier wegen des unregelmässigen Wachsens der Aeste Unregelmässigkeiten vor.»

Sanio has also found that the fibers on the upper side of branches, ie., in tension wood, are somewhat longer than the cells on the lower side, ie., in compression wood. Furthermore, he has found that the size of fibers in knots increases in the direction from pith to bark. It consequently appears as if the laws which have been established for the length of fibers in stems and variations therein should also be applicable to branch wood. As regards the size of fibers in stem wood around knots, which is more or less compressed, there is as yet very little information. The Norwegian Mork (1928) has made extensive measurements covering variations in fiber dimensions in compression wood, it is true, and has ascertained that these fibers are considerably shorter and narrower and that the percentage of intercellular space is much less than in normal wood.

The author has made an extensive series of fiber measurements in connection with the present study in order to illustrate the variations which appear in the dimensions of tracheids in knots. The material comprised logs of the various factories in the most important districts of the Finnish wood working industry and wood of test trees in the most important types of forests at the experimental station of the Forestry Research Institute in Ruotsinkylä. The extent and results of the investigations appear in the following graphs.

It is however not only the length and breadth of fibers that affect the technical suitability of wood. This is also dependent upon the structure and strength of the cell walls. That knot wood furnishes a raw material of inferior value for the wood working industry is due to some extent to the fact that this wood is difficult to disintegrate because of its great hardness, dense consistency and high content of incrusting materials. A further reason therefor lies in the fact that the fibers of knot wood are very small as well as brittle and are accordingly not equal to the requirements as to the strength of pulp. In the sawmill industry on the other hand knot wood causes diverse difficulties because of the difference in the structure of the cells. Among other things, the relatively thick-walled cells of knot wood shrink very differently upon drying than the tracheids in stem wood and therefore cause the formation of checks lowering the value of the product.

As has previously been mentioned, Hartig (1896) studied the structure of tracheids in the tension and compression wood of stems and branches. He was able to ascertain in this connection the existence of a

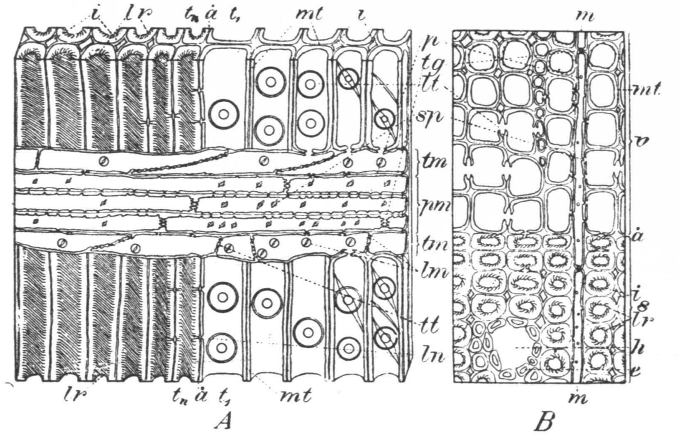


Fig. 41. The tracheids in compression wood, based on Mork. — *Kuva 41. Lylypuun trakeideja Mork'in mukaan.*

clear, spiral structure in the secondary layer of a cell wall. This phenomenon has also been observed by Cieslar (1896). These thickenings appear in a microscope in the form of oblique columns covering the pores.

These columns are very closely located particularly in the summerwood zones in compression wood. Mork (1928) states that the tension strain in compression wood is presumably derived from the spiral-shaped lamellae in the tracheids of summerwood. This cell structure is consequently the reason for the geotropic bends in the parts of plants, which are caused by the formation of compression wood.

The tracheids in tension wood on the opposite side of branches present on the other hand a different structure. Hartig (1896) has ascertained that the tracheids in tension wood differ from those in compression wood and normal stem wood in that summerwood tracheids have an additional cell wall layer outside the actual secondary wall. This is less lignified than the actual secondary wall and consists of closely situated, ring-shaped strips of thickenings. The lamellar structure is accordingly of a different nature than what it is in compression wood fibers. The task of this structural peculiarity is manifestly to counteract a prolongation of the cell through outer mechanical pressure.

A series of microscopic analyses was made in connection with the present study in order that there may be available additional information as to the characteristics of fibers in knot wood. There was also investigated at the same time the micellar structure in solutions of cupric ammonium nitrate

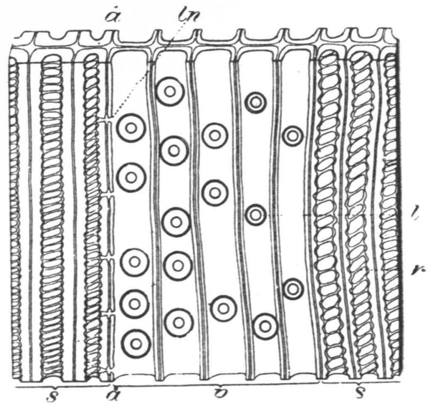


Fig. 42. The tracheids in tension wood, based on Mork. — *Kuva 42. Vetopuun trakeideja Mork'in mukaan.*

based on Lüdtke's method (1929, 1932). These analyses have shown that the size and structure of knot fibers vary appreciably and that a difference in general between summerwood and springwood fibers in knot wood cannot be made in the same manner as in stem wood. The reason lies principally in the great differences in mechanical load and physiological functions which prevail in the various parts of branches and knots. While there are found on the lower side of branches principally compression wood cells with very thick walls, numerous intercellular spaces, a very high content of lignin and a correspondingly very low content of cellulose, the cells in the upper parts of knots, the so-called tension side, have thin walls and an abundance of cellulose. At the base of a knot, ie., in and around the so-called branch base, there is also found a third kind of knot fibers which have the object of constituting the ducts for the products of assimilation for branches. These are located on the upper side of knots and above them, and are thick and contain wide, conveying tubes. On the lower side of the base there is found a supply of thin but compact compression wood cells which have the task of constituting a strong support for the base of the branch and of hindering this from causing upon the movement of a branch irritations in the nutriment conveying parts of the stem.

A maceraion test covering knot fibers in Schultze's solution shows a motley series with thick and thin as well as long and short fibers intermingled. Only in case the samples are taken from a definitely limited part will there be found any homogeneity and similarity in the fibers.

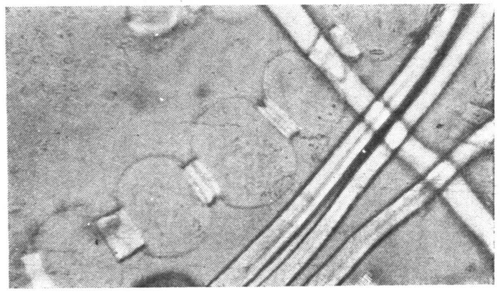


Fig. 43. Knot wood fibers in Lüdtke's solution. (Magnified 250 diameters. — *Kuva 43. Oksakuituja Lüdtken liuoksessa. (250 kertainen suurennus).*

The author has also made studies covering the fiber structure in knot wood viewed in polarized light and has ascertained that there can be obtained in this connection a rather clear picture of the accumulation of cellulose and incrusting materials in fiber walls. The greater the content of cellulose in the cell wall, the more crystalline is also the structure and the greater becomes the double refraction of the entering cone of rays. If this cone of rays is recorded on a photographic plate, the crystalline parts will appear on the positive of the picture in the form of a clear and light

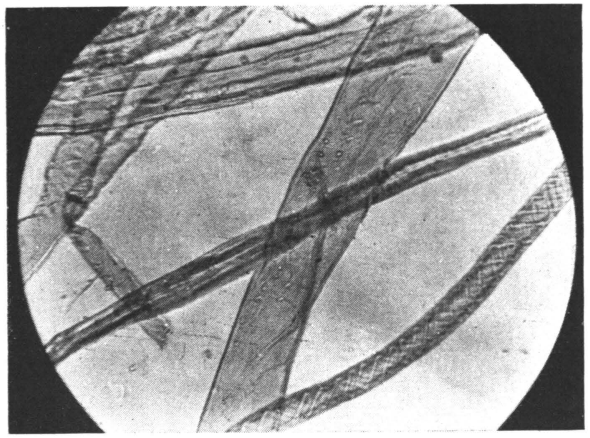


Fig. 44. Knot wood fibers (magnified 250 diameters). *Kuva 44. Oksapuun trakeideja (250 kertainen suurennus).*

Fig. 45. Compression wood fibers in knot. Normal light. (Magnified 300 diameters). — *Kuva 45. Oksan lylykuituja. Tavallinen valo. (300 kertainen suurennus).*

Fig. 46. Compression wood fibers. Polarized light. (Magnified 300 diameters). — *Kuva 46. Oksan lylykuituja. Polarisoitu valo. (300 kertainen suurennus).*

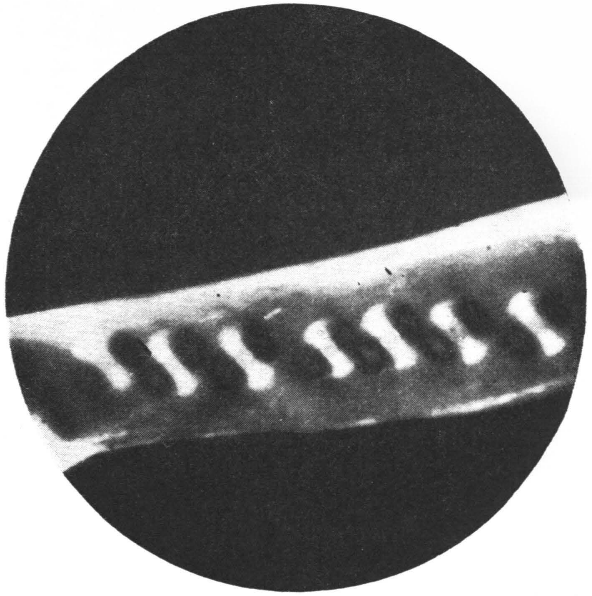


Fig. 47. Compression wood fiber. Polarized light. (Magnified 600 diameters). — *Kuva 47. Oksan lylykuitu. Polarisoitu valo. (600 kertainen suurennus).*

structure while the amorphous constituents on the other hand will assume a darker tone of color with more indistinct contours.

Many points of interest have appeared in connection with this series of investigations. They furnish a picture of the anatomical structure of the cell walls of various tracheids and at the same time of their chemical composition. It is found, for example, that the spiral-shaped strengthening lamellae characteristic for compression wood are formed to a preponderant extent of crystalline substance. Tension wood fibers, due to their greater content of cellulose, also appear clearly as more crystalline than compression wood fibers, which are more lignified.

3. The ultra-microscopic structure of branch and knot fibers.

Lignified cell walls are the basic substance of which wood is formed. It is therefore easily understood that the attention of science has very early been drawn to the structure and composition of cell walls, and the origin, biological functions and chemical and physical properties of

tracheids have long been the subject of persistent and thorough research. Mayer stated as early as 1838 that he had found fibers to be formed of small particles, ie., fibrils. At the same time the chemist Payen (1838) succeeded with the help of various reagents in dividing cell walls into several constituent parts and in dissolving the incrusting materials. In 1852 Agardh discovered a spiral-shaped structure in cell walls and showed that the cell wall is composed of fibrils. Of the greatest significance however are the results which Nägeli (1858) attained as the outcome of extensive, microscopic investigations. Although this work did not attract any noteworthy attention at the time, it has now however, ninety years later, come to constitute the most important basis for analyzing the fine structure of the cell wall.

Nägeli's theory in the main is that organic tissues such as, for example, starch grains and cellulose fibers are not directly formed of molecules but that the molecules have first been linked into molecular groups of a definite form, which are strictly arranged in the cell wall. He gave these very small, ultra-microscopic and anisotropic molecular tissues the name »micelles» (mica = mote of dust). These micelles remind one of small crystals and are optically double refractory. They are held together only by molecular cohesion. The linkage of the molecules into micelles is reflected in the disintegration of the cell wall and in the swelling and shrinkage of wood. Nägeli considered that solvents could not separate the individual molecules from each other but only separate the micelles. This occurs in such a fashion that the solvent penetrates between the micelles and gives rise to sufficient swelling so that the micelles were finally forced apart. Because of the varying degree of swelling of the fibers in different directions, Nägeli presumed that the micelles are elongated, and on the basis of the quantity of liquid which could penetrate the fiber wall, he maintained that they are rectangular and not round in cross-section.

By means of extensive analyses it has been ascertained that the individual, lignified cells are formed similarly as the cells in pure cellulose. It has therefore been concluded with the greatest probability that it is pure cellulose which determines the skeletal structure and the cell form of wood. Since Frey (1926) and others have shown that cellulose is crystalline in nature while lignin is amorphous, it can easily be thought that ligneous materials constitute a means of connection which link the cells to each other. On the other hand there is no reliable evidence that lignin should also serve as the means of connection for micelles.

Nägeli's contention is that the cell substance is composed, even as far as the very smallest particles, of two separate chemical components of which one is crystalline, ie., the micelles, while the other, which serves as a connecting link for the micelles, is of an amorphous character.

A spiral-shaped thickening of the cell wall was later (1882) ascertained also by Strassburger through microscopic analyses. Wiesner (1886) believed that he had succeeded in separating the cell walls into their minutest parts after having treated the cell wall with various acids at various temperatures. The stuff-like substance which he thereby obtained was termed »dermatosomes».

It was however only upon the development of improved optical methods that it became successful to prove seventy years later with complete evidence the accuracy of Nägeli's hypotheses. Particularly the microscopic investigations made by Ambron and Frey with polarized light have been in this connection of epochal significance. The microscopic investigations of polarization have shown that the organic cell walls consist of anisotropic, oblong-shaped crystals lying more or less in the longitudinal direction of the fibers.

Freudenberg (1935) has also investigated cell membranes in polarized light.

It has been successful also by X-ray examination to prove the accuracy of Nägeli's micellar theory. The first of such series of investigations was made by the Japanese Nishikawa and Ono (1913). Similar investigations of a more extensive nature have later been undertaken both in Europe and North America. Of the foremost originators of such investigations may be mentioned G. L. Clark, T. Kerr, I. W. Bailey, W. K. Farr and G. J. Ritter in the United States of America, and W. Polanyi, R. O. Herzog, C. Steinbrinck, S. H. Clarke, K. H. Meyer and H. Mark in Europe.

The principle of research with X-rays is based on atoms and molecules in a crystal being able to be placed together in a stereometric schema Because of the multitude of varying characteristics, this system can assume the greatest variations. The structural characteristics of the system cannot however be discerned in a microscopic investigation since the wave length of light is altogether too great to make possible an observation of the ultramicroscopic particles. The insignificant wave length of X-rays however makes these particularly suitable as research material in studies covering the ultra-microscopic, structural system formed of atoms and molecules. If X-rays are projected through a crystalline body, such as for example a cellulose fiber, this diffracts the light according to definite laws depending upon the molecular structure. If the spectrum so arising is recorded on a plate sensitive to light, there is obtained a typical diagram which can be used as the basis for drawing certain conclusions concerning the form and structure of crystals.

Herzog and Jancke (1928) have proved that there can be established on the basis of the regularity and concentricity of the diagram whether the micelles are regularly or irregularly parallel or divergent as regards their position to each other. It has furthermore been able to be established that lignin and the hemicelluloses are not chemically attached to the cellulose crystals but on the contrary are found as intercellular filling material of an amorphous character. X-ray vision has also made possible an approximate calculation as to the size of micelles. G. L. Clark has estimated the diameter of cellulose micelles to be 50 to 60 Ångström units and their length as 500 to 1,000 Ångström units. These investigations prove the complete accuracy of Nägeli's assumption as to the oblong-shaped structure of micelles.

S. Pienkowski (1930) and Barbara Schmidt (1931) have ascertained that there exists a relationship between the micellar structure of fibers and their strength properties. The more parallel the micelles are to each other, the greater is the tensile strength of the fiber. If a comparison

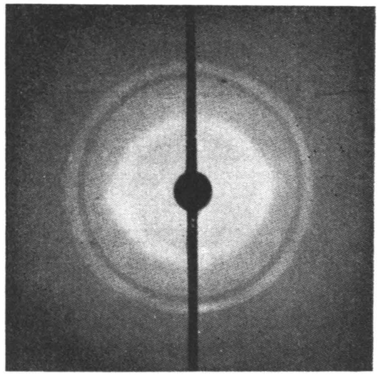


Fig. 48. X-ray diagram of a fiber in spruce stem (Photograph by F. Luft, I.-G. Farbenindustrie). *Kuva 48. Kuusen runkokuidun röntgendiagramma.*

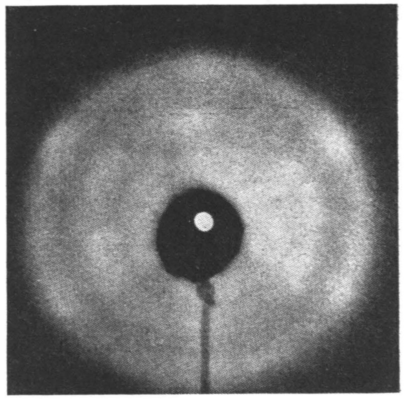


Fig. 49. X-ray diagram of compression wood (Photograph by G. L Clark) *Kuva 49. Kuusen lylykuidun röntgendiagramma.*

is made between the X-ray diagrams for stem wood and compression wood of spruce, it will be found, as shown by the following figures of F. Luft and G. L. Clark, that the diagram for stem wood is more regular and more concentric. Therefore, stem wood must likewise show a more regular and parallel grouping of the fibers. G. L. Clark, G. J. Ritter and W. A. Sisson have shown that the crystalline materials in compression wood are orientated in a direction of about 60° calculated from the fiber axle. This shows also the slight tensile strength of compression wood in relation to density.

CHAPTER IX.

Physical properties of branch and knot wood.

The physical properties of wood have constituted for a long time one of the most significant bases for determining the suitability of timber for various purposes. It has in particular been regarded that strength and weight stand in a direct relationship to each other and that heavy woods such as oak and beech are the most suitable building timbers in wooden structures carrying heavy loads.

As a result of this prevailing view, the weight of wood was also one of the first characteristics which attracted the interest of scientists. During ancient times there were already made such series of investigations, of which the popular scientific works of Aristotle, Marcus Porcius Cato, Columella and Palladius are of interest (Lassila 1926). Aristotle divided wood into various quality groups and based this system on the weight of the wood. This systematization of Aristotle was still during the middle ages the basis for the scientific valuation of wood and there is found in Praedium rusticum, the most significant work in wood technology of this period (Lassila 1926), various species of trees grouped on the basis of weight.

The first treatise handling more thoroughly the physical properties of wood is the classic work »Mémoire sur les propriétés mécanique du bois» (1845) by Chevandier and Wertheim. This extensive study contains among other things a resumé of the majority of the results previously attained.

It had later been ascertained however that the old school of thought represented by Chevandier and Wertheim, Buffon and Duhamel du Monceau, according to which the technical value of wood stands in relation to density, is not always applicable in practice. The anatomical structure of wood, particularly the width of the annual rings and the dimensions of the fibers, also play in this connection an important role. Furthermore, strength properties are influenced by the moisture content of the wood, the length of time in storage, and other circumstances.

A study of the results of previous investigations based on analyses by weight is made difficult to a great extent since determinations as to how density shall be measured were not previously standardized. This is of course affected to a very high degree by the moisture content of wood. Now it is usually determined when absolutely dry (with a moisture content of 0 %) or air dry (with a moisture content of 15 %).

It has for a long time been regarded in the paper industry that heavy wood is the best raw material since it gives quantitatively the highest fiber yield. This conception is still prevalent in many places and as an example Kollmann (1936) states:

»Für Papierholz ist hohe Dichte wirtschaftlich besonders erwünscht, da der Einkauf des Rohholzes nach Raummass, der Verkauf der Fertigware nach Gewicht erfolgt. Die Bestimmung des Holz-Raumgewichts ist deshalb von allen holzverarbeitenden Industrien in den Papierfabriken am eifrigsten erforscht worden.»

This conception must however be considered as unsuitable and antiquated and does not at all meet the demands of the present day paper industry on its raw material. As has previously been presented, heavy timber often contains a very high percentage of qualitatively low value material such as knot and compression wood, and cannot be availed of as rationally as homogeneous and evenly grown timber. Furthermore the strength properties of the individual fibers in very densely grown wood are often reduced. Such timber having very thin fibers and narrow annual rings has been extensively found by Klem and others in northern Norwegian forests. He calls this timber »hungerved» (under-nourished wood) (Klem 1934).

Of the remaining physical properties, the principal interest is attached to the moisture content of wood since it has an influence on numerous other properties, particularly on the change in the form of the wood, ie., shrinkage, swelling and the formation of checks, and on strength.

1. Density of branch and knot wood.

The majority of the investigations made previously as to the density of wood and its variations in various parts of the tree have shown this to stand in direct relationship to the width of the annual rings and the percentage of summerwood. Under such conditions it is self-evident that knots must have the greatest density since they contain the narrowest annual rings and have the highest percentage of summerwood.

In connection with the present work, there has been made a series of analyses as to the weight of wood and its variations in different parts of a tree. There was gathered for this purpose material from stands in the most important types of Finnish spruce forests. The material originated partly in the experimental districts of the Forestry Research Institute in Ruotsinkylä, near Helsinki, and partly in the storage yards of the wood working industries in various parts of Finland.

Since it is a question of determining the weight of wood, it must be observed that wood does not constitute a compact mass but comprises a quantity of fibers and contains numerous cavities. Therefore, it is not possible to speak of the specific gravity of wood since this implies the weight of the wood substance, which has been calculated as 0.56 (Lassila 1926). This figure cannot be considered as final but must be influenced by the chemical composition of the wood. Lignin and cellulose substances show varying specific gravities and this situation affects in turn, because of absolute necessity, condition concerning the weight of the cell walls.

When determining the weight of a piece of wood and comparing this with its volume, there is obtained a figure of comparison for the weight and toughness of the particular species of wood. This comparative figure is given many different terms in literature. There are found among others the terms »specific gravity», »dry and wet density», and »weight of the dry substance». All of these actually imply the same idea, the percentage of dry substance in a known volume. Brax (1936) points out that it is not possible to speak of the specific gravity of a porous material in any other case than when the weight is calculated on the basis of a complete saturation of the material or refers to a weighing in an absolute vacuum. Such a saturation of the material is possible in practice only upon submerging wood for a period of time. During this process however some of the incrustations of the stem dissolve in the liquid. The weighing of small, crushed and pressed parts of trees while in a vacuum can be undertaken in a laboratory but the procedure has no practical significance. Actual specific gravity can also of course be ascertained by calculating the specific gravity of all the component parts. It is known for example that the specific gravity of pure cellulose is 0.56 according to the investigations of R. Hartig while the density of the cellulose in wood is on the other hand about 0.55. By extracting and analyzing all the elements contained in the dry substance of a tree, it is possible to calculate specific gravity, but neither does this procedure have any practical significance. The expression »specific gravity» is not correct when it is a question of wood substance.

The expressions density while dry and density while wet, or »Darrgewicht», appear in German literature. The former expression is understood to be the weight calculated per unit of volume of absolutely dry wood while the latter on the other hand implies the weight calculated on the basis of a cubical unit of wood in which the moisture content is so great that the extent of the swelling of the wood has reached its maximum.

Kinnman (1923) recommends a calculation of density based on volume while wet and weight when absolutely dry. He bases this on the fact that wood is measured and sold when in a hydrous state. Niethammer (1931) and Kollmann (1932 and 1933) on the other hand consider that the point of departure should be density when absolutely dry since density only in this state is absolutely definite and the results are fully comparable.

In connection with the present study, the author has investigated density while absolutely dry because of numerous, practical reasons. Firstly, it has been endeavored to attain the most exact and relatively comparable results possible. Secondly, density while absolutely dry is the only method which is applicable when it is a question of determining the relative proportion of the various chemical constituents in the wood. And thirdly, the samples must be stored for practical reasons for a period of time before measurements can be made.

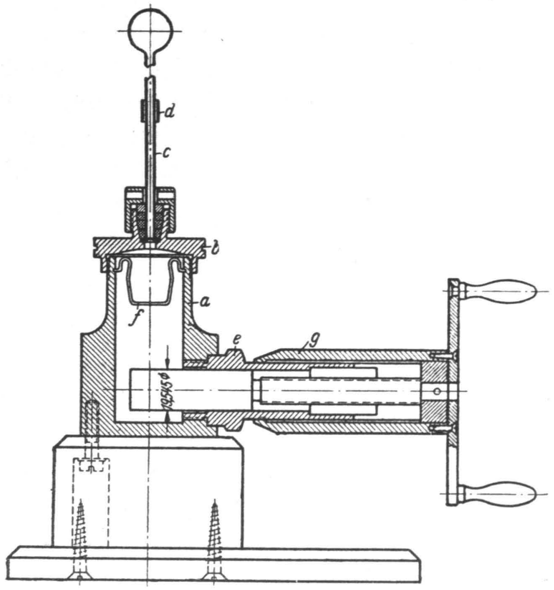


Fig. 50. Merkury xylometer (according to Breuil).
Kuva 50. Elohopeaksylometri (Breuil'in mukaan).

In order to attain results as accurate as possible, the calculation of the volume of the accumulated material was done first by measuring the samples and then by computing the cubical content xylometrically by displacement in liquid. For the first procedure, cubical samples were prepared and the sides of the cubes varied in length depending upon the possibilities of sawing samples as uniform as possible. The xylometric determinations of volume on the other hand were made in a quicksilver xylometer of the Breuil model (Amsler & Co., Schaffhausen).

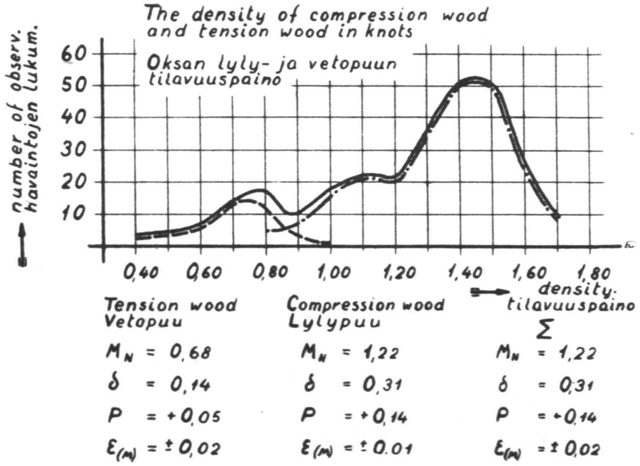


Fig. 51. — *Kuva 51.*

For the latter procedure there were used cylindrical samples in order to eliminate the occurrence in the edges of possible sources of error. In determining the volume and in weighing, the samples were dried until absolute dryness was attained. Volume at this point was also at the minimum. The results of the measurements appear from the following tables and graphic presentations.

When studying the foregoing tables it will be found that density of branch wood varies within particularly wide limits, from 0.5 to 1.4. The reason for this great spread in the results is to be found in the irregular and composite structure. Tension wood has throughout shown itself to be lighter than compression wood, the averages being 0.68 and 0.89 respectively. The closer to the knot the sample was located, the heavier it was as a rule. Particularly the samples prepared from knots were very heavy. As a rule the density of compression wood in knots is in excess of 1. This can be considered to depend upon the great pressure the surrounding stem wood exerts on the wedged-in knot. If the values obtained for the density of knot wood are compared with corresponding values for normal stem wood and compressed stem wood, it will be observed that knot wood is often up to three times heavier than normal stem wood and up to twice as heavy as compressed stem wood.

Of the earlier investigations of this nature which are of interest there may be mentioned the studies of Hartig (1901), Burns (1920) and Trendelenburg (1932) as to the physical properties of compression wood. The results which have in this connection been attained show that compression wood in stems is on the average 50 % heavier than normal wood. This increased weight is divided in such a manner that springwood is about 100 % heavier while summerwood has approximately the same density in both normal and compression wood. The investigations of Hartig as to the density of compression wood give values lying between 0.51 and 0.872; he gives as an average 0.693. For the purpose of comparison it may be mentioned that density in normal spruce wood varies according to Ekman (1922) between 0.31 and 0.53, with an average figure of 0.42. In accordance herewith the maximum weight of normal wood is insignificantly greater than the minimum of compression wood.

When taking into consideration all the difficulties and complications which compression wood gives rise to particularly in the production of cellulose, it might be thought possible, in view of the foregoing, to sort by weight the chips at cellulose mills by using a casting screen or a similar apparatus. In practice this is as yet unfeasible however because of the great variations in the content of moisture in chips (Wegelius 1938).

2. The content of moisture in branch and knot wood and its effect on changes in volume.

The content of moisture in wood is of interest on the one hand since it gives a picture of the ability of the wood to absorb and give off water, which is of practical significance in cellulose cooking, and on the other hand since it gives rise to a series of changes in the volume of wood, which are of technical significance.

Since branch wood is much more compact as regards structure and contains fewer cavities than stem wood, conditions as regards its moisture are also different from those of stem wood.

The content of moisture in wood is calculated in percentage of the dry weight of the wood. In a growing tree it varies appreciably in the various parts of the tree depending upon anatomical, structural circumstances and upon the physiological functions of life of the tree. Siimes (1938) states in this connection that the content of water in a growing tree increases with the distance from the base; in sapwood it is approximately one fourth greater in the top than at the base and in heartwood on the other hand only several percent greater. Lassila (1930) and Jalava (1933) show that the content of moisture is also dependent upon the type of forest and upon the position of the tree in the stand. The content of moisture is furthermore affected by the time of the year, the relative humidity of the air and various climatological factors.

In a growing state sapwood of coniferous trees contains on an average about 50 % water (Mayr) while heartwood is considerably drier, having a moisture content of about 15 %. Living knots contain a relatively large amount of water, according to Th. Hartig between 40 % and 50 % and according to Siimes between 25 % and 46 %.

There are consequently always to be found water solutions in growing trees, often even in quantities two or three times greater than the dry weight of the wood. These water solutions are principally alimentary solutions which carry nutritious substances from the roots to the young parts of the stem where extensive structural activity takes place. In the longitudinal direction of the tree trunk the liquid is conveyed along the tracheids and in the cross direction along the pith rays. Water is found not only in the cell spaces but also in the cell walls; having been drawn into the cell walls since they do not constitute a compact mass but are formed of fibrils. This fibrous texture can absorb relatively large quantities of water. It is not fully known how this absorption takes place; whether it occurs in the form of a chemical solution or in accordance with definite capillary laws (Jalava 1932). By means of various experiments it has however been successfully ascertained that the cell walls cannot absorb unlimited quantities of water but that there is a definite limit for this absorption. This fiber saturation point for the cell walls is between 25 % and 30 %, ie., the fiber walls are fully saturated with water when the wood contains 25 % to 30 % moisture. The degree of saturation varies somewhat with different species of trees. The existence of this definite limit has been explained in various ways (Koehler and Thelen 1926). One such explanation provides that the attraction of the fibrils to each other is decreased upon the entry of water. The ability of the water to enter is however lessened even faster than the attraction of the fibrils to each other. This results in a state of equilibrium in which the ability to enter and the attraction of the fibrils are equally great and when new water can no longer be absorbed. According to another explanation, certain constituent parts of the cell wall become dissolved and the water saturates to a definite concentration. According to a third explanation however, the fibrils are not parallel to each other but form a series of network around each other, and this system cannot be extended beyond a certain limit because of physical reasons. It is supposed that the fibrils are not changed in any way during the process of absorbing water and that the water is drawn into the cavities between them.

Because of the differences in fibrillar structure in stem wood and branch wood, these must also react in different ways upon changes in moisture content. It has consequently been found that the phenomena of shrinkage and swelling occur differently in branch wood and stem wood. Siimes states that branch wood in pine shrinks in the direction of the fibers on an average of 2.31 %, in the tangential direction by 34.30 % and in the radial direction by 2.26 %. The corresponding values for stem wood, according to Lassila (1930), are 0.08 %, 4.5 % and 2 %. The investigations of the author made in connection with this study from samples of spruce branch wood show values for compression wood in the longitudinal direction ranging from 1.548 % to 3.72 %. On the other hand such values vary in the tangential direction from 2.12 % to 3.9 % and for radial shrinkage between 1.71 % to 3.0 %.

It is consequently found that compression wood is noted for its particularly heterogeneous characteristics in this respect. The reason therefore can doubtless to a great extent be traced to the complicated fibrillar structure in compression wood cells, but can possibly also be thought to depend on the differences in chemical composition. Jalava's contention that the greatest technical drawback of compression wood lies in the fact that it cracks, warps and shrinks much more irregularly than normally developed wood is consequently well-founded.

The physical properties of compression wood have been investigated by not only the authors previously mentioned but also by Hartig, Müller, Schwendener, Zimmermann and Sonntag in Germany and Pillow and Luxford in the United States.

Hartig (1896) has presented the following bases for determining the phenomenon of shrinkage in wood. He presumes that two thirds of the volume of a cell wall while fresh consists of organic substance and one third water. Half of the dry volume should therefore show the percentage that fresh wood shrinks upon drying. The computation is made so that by dividing by 0.56 (the specific gravity of cellulose), the established dry substance is changed into dry volume and the result is divided by 2. Investigations as to the conditions of shrinkage in compression wood show however that this is not always the case. Hartig maintains that this depends on the fact that the air-filled spaces in the tracheids enlarge whereas the wood substance always shrinks according to definite laws which are the same for both normal wood and compression wood. Sonntag (1904) shows however that Hartig's formula for the calculation of shrinkage is incorrect. There is on the one hand no reason for assuming that one third of the volume of a cell wall while fresh consists always of water. On the other hand it must be regarded that the changes in the volume of the membranes are dependent upon their physical and chemical consistency. As has been established by Müller, Schwendener and Zimmermann, the fibrillar structure is of the greatest significance for shrinkage. In bast cells as well as in the tracheids, shrinkage and polarization ellipses have identical positions, it is true, but are reciprocal as regards extent. The most insignificant changes in volume occur in the direction of the greatest optical axle, the middle axle represents the average degree of shrinkage and the shortest the greatest change in volume. The axles which lie in a direction parallel to the position of the pores show the least prolongation since they correspond to the greatest optical axle, while the radial axle on the other hand always shows the greatest prolongation (Sonntag 1904).

The obvious and pervading phenomenon that compression wood shrinks in its longitudinal direction much more comparatively than other wood finds its exhaustive explanation in the foregoing point of view. According to Hartig this shrinkage for compression wood in the lower side of a branch is 1.287 % as against 0.09 % for tension wood in the upper side of branches. As has been explained in the preceding chapter, the cell walls in compression wood show spiral-like thickenings which form an angle of about 40 ° to the longitudinal direction of the cell. The axis of the least change in volume accordingly does not correspond to the long axis of the cell. Greater shrinkage will therefore occur in the longitudinal direction of the cell. In tension wood on the other hand obliqueness in the position of the pores varies between 10° and 37° with an average of 20.5°, while the series of pores in stem wood is usually absolutely parallel to the longitudinal direction of the cells. This situation is illustrated very clearly by the variations in shrinkage. While shrinkage in the longitudinal direction of stem wood is insignificant, in compression wood with its fibrils placed obliquely it is relatively high.

Steinbrink has maintained that the structure of the fibrils is not however the only factor determining the amount of change in volume. Even in identical structures of fibrils shrinkage can be dissimilar depending upon the chemical conditions of the wood. Sonntag (1901) shows consequently that the presence of incrustations in wood offsets the phenomenon of shrinkage and that changes in volume become much greater when the incrustations have been removed. According to this statement changes in the volume of compression wood are accordingly considerably less when compared to what they would be if the wood were freed of incrustations through chemical treatment. Branch wood accordingly constitutes a proof that strongly lignified membranes show much less shrinkage than those which are less lignified.

Hartig (1901) emphasizes that the varying bending phenomenon of branches in weather of varying humidity is a result of the different circumstances of shrinkage arising in tension and compression wood.

Pillow and Luxford (1937) in the United States have conducted a series of investigations concerning compression wood and its various properties. Although the material for the investigations has comprised principally Douglas fir (Pseudotsuga Douglasii), Ponderosa pine (Pinus ponderosa) and Redwood (Sequoia sempervirens), it can be considered that the results correspond on the whole to the situation as regards spruce wood. They show that while the longitudinal shrinkage of normal wood from the green to the absolute-dry condition ranges between 0.01 and 0.02 percent; compression wood on the other hand shrinks from 0.3 % to even 5 % for very pronounced compression wood. The mean value is somewhat in excess of 2 %, ie., as much as 13 times greater than shrinkage in normal wood. As regards radial and tangential shrinkage, Pillow and Luxford state that very dense wood as a rule shows greater radial and tangential shrinkages than wood of less density. An exception to this rule is however the tranverse shrinkage in compression wood which, in spite of its great density, shows lower shrinkage figures in radial and tangential directions than normal wood. Hartig (1896) and Trendelenburg (1932) also found the transverse shrinkage in compression wood to be lower than in normal wood.

As has become apparent from the foregoing, compression wood is very different from stem wood as regards the change in form with variations in moisture content. This situation is a detriment particularly in the sawmill industry since wood bends and warps upon drying. As a result thereof various tensions which take the form of bending of the wood and fiber breaks parallel to the direction of the knot arise around the knots in the compression wood surrounding the knot wood. Siimes (1938) states in this connection that the high percentage of longitudinal shrinkage in compression wood can cause much grief. Since wood in the portion of the sawn product which is free of knots shrinks by 4 % and in the knot by 2 %, the surfaces in the sawn board become uneven and the knot will stand out above the surface. The percentage of radial shrinkage in the knot is on the other hand much greater than the corresponding, longitudinal shrinkage in stem wood. If the knot is not surrounded by a layer of compression wood to even out the tensions, it would loosen from the stem wood. The percentage of tangential shrinkage in knots fits of course very well with the shrinkage in the compressed wood above and under the knot but causes however tensions between the wood on the sides. As a result thereof, the knot is often separated from the stem wood.

3. Other physical properties.

Of the other physical properties of wood, there may be mentioned as of interest the conductive power of wood for heat, sound and electricity.

Since wood is an anisotropic body, it reacts differently to heat along its different axles. With an increase in temperature, wood expands very insignificantly in its longitudinal direction, but in its perpendicular direction it shows somewhat greater changes in volume with changes in temperature. These values are not however to such an extent insignificant that they do not call for close study.

Kollmann (1936) states that the composition of cellulose and lignin in wood as well as its porous consistency give it very remarkable and valuable heating properties. It appears as if its ability as a heat insulator stands in direct proportion to the content of cavities. On the basis thereof, it is possible to draw the conclusion that branch wood, being dense and compact, has poorer characteristics as a heat insulator than the porous stem.

As regards electrical properties, the electrical conductiveness of wood according to Stamm's investigations (1927) is directly proportional to the moisture content and increases with an increase in moisture. Suits (1931) has made investigations in the United States concerning the heat conduction characteristics of American species of trees and has found that the power of electrical conduction is different in the various anatomical directions; it is doubly greater in the longitudinal direction of the cells than perpendicular thereto. Because of the varying directions of the fibrils in branch and knot wood, there should however be reason to presume that this situation is in this connection less obvious.

The acoustical properties of wood, similarly as the other conductive characteristics, have been the subject of scientific research to only an insignificant extent. Knoblauch (1858) has given attention to this question and has come to the conclusion that the ability of wood as a conductor of heat is proportional to its sound conductive power and that the latter is greater in the direction of the fibers than perpendicular thereto. Landolt-Börnstein has investigated the velocity of sound in the direction of the fibers in various species of trees. He has found that it is 5,256 meters per second for normal spruce wood and 4,180 meters per second for compression wood while the corresponding figure for iron is 5,000 meters per second. The velocity of sound perpendicular to the fibers in normal wood is about one half of what it is in the direction of the fibers while in compression wood, because of the size of the fibrils, it is about the same in either direction.

Because of its acoustical characteristics, spruce wood has shown itself to be an excellent and irreplaceable material for the construction of musical instruments. But in order that these characteristics may be utilized properly, there should be used wood having homogeneously structural properties, and compression wood and particularly knots should be avoided.

CHAPTER X.

Chemical properties of branch and knot wood.

The chemical composition and properties of wood have attracted increased attention during recent times, and an immense development has occurred in chemical research in wood. This is doubtless a result of the particular significance that the chemical methods of wood production have attained in the economic life of our times. The widely operative improvements made in these industries, with the production of artificial silk, explosives and wood sugar mentioned as examples, depend primarily upon the results of research in wood chemical science. Wood chemistry is accordingly a science of great practical value. Many questions in this branch of science are nevertheless still awaiting their final solution and both practical and purely theoretical wood chemistry still has a multitude of problems to solve before the composition of wood substances and their rational and expedient use are ascertained.

The chemical wood working industry can be of two different types in the main, depending upon whether it is intended to use the anatomical structure of the raw material, such as for example in the cellulose industry where the cells are retained as fibers in the finished product, or whether the state of the form of wood and its structural properties are completely changed, such as is the case in the artificial silk industry. Regardless of which method of production is used, it is self-evident that wood chemistry is of decisive significance for the quantitative and qualitative yield as well as for the consumption of chemicals and the calculations of profitableness covering the entire production.

Of primary interest in the chemical properties of wood are the content of cellulose, lignin, resins and ash as well as the concentration of hydrogen ions in wood and the resistance of wood to water, alkalies and acids.

Investigations which have been undertaken by many persons previously as well as those in connection with the present work clearly show that branch and knot wood and stem wood present divergent characteristics in many respects insofar as the structure of wood is concerned. As a direct result of this situation, the physical and chemical properties are also appreciably different in branch and stem wood.

In the production of chemical pulp the content of pure cellulose in wood is naturally of decisive significance as regards the quantity and value of the yield. Numerous investigators such as Klason, Hägglund, von Euler and Schultze have shown that the content of cellulose is inversely proportional to the content of lignin. Because of the complicated procedure required in making a direct, quantitative analysis of cellulose, it is therefore easier to ascertain directly by a quantitative analysis of lignin the suitability of the wood in the production of pulp.

The content of lignin in wood is of great importance in the manufacture of pulp. It is a question of dissolving by the use of acids the binding tissues between the cells, which have been formed by lignin, in order to release the cellulose fibers from each other.

The rosin in wood like the other incrustations which resin contains, has properties which make difficult in many respects the production of pulp. On the other hand a high percentage of resin can be of advantage in other divisions of the wood industry such as in dry distillation, the manufacture of turpentine and others. The fact that the percentage of resin has in addition an effect on the chemical-physical properties is generally known. The percentage of fats, which appears to stand in proportion to the percentage of resin, is of great significance in the production of »pine soap» and diverse oil products.

The degree of acidity of wood, pH, is worthy of special interest in the chemical woodworking industry. The concentration of hydrogen ions varies to a great extent in wood and it is a question of applying production methods in accordance therewith.

The resistance of wood to chemicals in the form of acids and alkalies is important in cellulose cooking as regards both the quantitative and qualitative yield and the choice of the method of production. This question has up to the present been examined to a comparatively slight degree, although similar analyses give results that explain in a particularly graphic manner the suitability of the wood as a raw material for the pulp industry. In order to judge the effectiveness of chemicals, it is necessary at the same time also to determine solubility in hot water, which for certain species of trees in particular can be appreciably high. Through heating by the use of alkalies, so-called gum is dissolved from the wood. This portion dissolved by alkalies is however not homogeneous as regards its composition and contains both carbohydrates and easily dissolved lignin. Knot wood dissolves in general to a lesser extent than stem wood, and broad-leaf wood as a rule more easily than coniferous wood. By cooking with acids a portion of the carbohydrates is dissolved, and this part, which is easily dissolved and easily hydrolyzed, is classed in the group of hemicelluloses. The chemical resistance of wood, similarly as the percentage of cellulose and lignin, appears to stand in close relationship to the anatomical characteristics of wood, ie., the volume of dry substance and the percentage of summerwood.

The percentage of pentosans and its importance has up to the present been to a great extent unsolved, but it is believed to affect the cellulose cooking process and to delay defibration.

The percentage of ash in pulp wood is primarily of significance in the production of artificial silk pulp in the wood working industry. In this pulp the demands of quality, as is well-known, are very great and the percentage of ash should be held to the possible minimum.

Investigations which have up to the present been made as to the chemical properties of spruce have practically entirely concerned stem wood. In this connection it has become apparent that chemical properties, particularly the percentage of cellulose and lignin, are relatively constant. The weight of the dry substance of wood accordingly constitutes an index of the content of cellulose. Since knot wood shows in many respects as regards its chemical composition properties which deviate from those of stem wood, the presence of knots therefore plays an important role in judging the chemical properties of wood. One of the aims of the present work is to contribute to an understanding of the chemical properties of knot wood and their effect on the quality of the wood.

1. Percentage of cellulose in branch and knot wood.

It is a generally acknowledged fact in the manufacture of pulp that chips containing knots and compression wood defibrate upon cooking considerably less thoroughly than normal stem wood. The reason for this condition can surely be traced to a great extent to differences in the structure of knot wood and stem wood. The former is much more compact and dense. As a result it is more difficult for the cooking liquor to be absorbed. On the other hand, stem wood is able to absorb the liquor much more readily because of its large cell cavities. The difference in structure is not however the sole reason for the variation in the degree of ability of absorption. It is accordingly not possible to cook knotted chips and stem chips separately and then by applying the proper method of cooking in accordance with the density of the wood to obtain quantitatively similar yields. Ulfsparre among others has shown by a series of cooking tests that the yield from knotted chips is less than that from stem chips in spite of the former having been cooked to complete defibration. This shows that there are also differences in chemical composition between normal wood and knot wood and that the latter clearly contains a lower percentage of cellulose.

In order to give proof of this situation and at the same time to contribute toward an explanation of the degrading characteristics in the yield of knot wood, the author has made a series of analyses covering knot and stem wood.

Many different processes can be employed in determining the content of cellulose in raw materials. The most general of these is the Cross-Bevan procedure, by which the incrusting materials in cellulose are isolated by treatment with chlorine and alkalies. Schmidt has later used chlorine dioxide instead of chlorine. Kurschner recommends a method in which the incrusting materials are dissolved by oxidation using nitric acid with an alcoholic content. Klason on the other hand makes use of a solution of sodium bisulphite under high pressure. According to König raw fiber, ie., technical cellulose, can be obtained through an alternating treatment by cooking with diluted sulphuric acid and potash lye. Kiesel and Semiganowskij change the cellulose into glucose. And finally, Bühler isolates the incrusting materials by means of phenol.

The Cross-Bevan process has been subjected to many changes with the passing of years. In connection with the present investigations, the analyses were made in the following manner:

After the material for the analysis was dried and freed of resin, it was treated in a finely pulverized form with natron lye for one-half hour and thereupon washed. It was then subjected in its damp state to the effect of active chlorine gas for one hour at a time. Between each new chlorination, the washing was renewed by treatment with potassium permanganate. In order to remove the quantity of nitric acid which had possibly appeared during the process of analysis, the substance was thereupon washed two or three times additionally with distilled water. A twopercent solution of sodium sulphite was poured over the mass that was thus obtained. The mass was then heated slowly to the boiling point. Sodium hydroxide amounting to 0.2 % of the volume was now added and the liquor held at the boiling point for a period of five minutes. A new wash with hot water was now made and the mass then bleached with a solution of 0.1 % potassium permanganate. Any secreted permanganic oxide which could possibly come into existence in this connection was drawn off with sulphur dioxide. After a final wash with warm water the mass was dried and then weighed. The resultant corresponded to the content of cellulose in the wood.

The author decided upon the Cross-Bevan process, firstly, because it is the most generally used and the results of this investigation are therefore directly comparable to those of many previous ones, and, secondly, because this method must be considered as particularly exact, especially since the pentosan content in cellulose has also been taken into consideration. In performing the analyses, chlorination has often been made up to as many as six times.

The series of analyses made as to the cellulose content of stem wood in connection with this investigation shows that such content in various kinds of Finnish spruce varies very little. Similar results have previously been obtained in Sweden by Hägglund and Kinnman. They maintain that the content of cellulose in normal spruce wood is practically proportional to the dry weight of the wood, and state that weight accordingly constitutes a good characteristic in determining the content of cellulose. Klason has proved that the quantity of lignin in percentage of the absolutely dry weight is constant in wood of normal quality. Kinnman on the other hand shows that the quantity of cellulose can vary appreciably in the various parts of an individual stem. He has found among other things that the content of cellulose decreases somewhat upon approaching the center of the stem and that it is greater in sapwood. According to

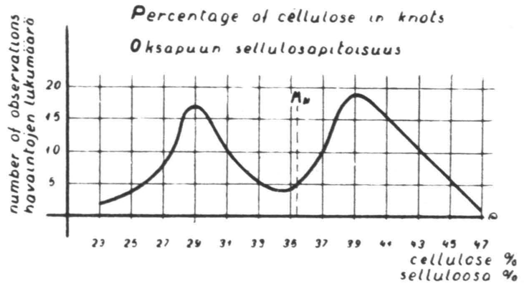


Fig. 52. Percentage of cellulose in knots. — *Kuva 52. Oksapuun selluloosapitoisuus.*

Kinnman the content of cellulose reaches its maximum at a point somewhat above breast height (D 1.3). He maintains that the quantity of cellulose in branch and knot wood is less than in stem wood, especially on the compression side of the branch and knot.

Based on the author's investigations, the content of cellulose varies within particularly wide limits (28 %—48 %). The lowest content of cellulose is to be found in knot samples, while stem samples show a rather insignificant spread.

As Hägglund has already ascertained, compression wood shows an appreciable decrease in cellulose content. When it is considered that up to 30 % of the volume of a knot can consist of compression wood, it can be seen that this peculiarity acts to a high degree in reducing the yield of cellulose. Furthermore, since the low content of cellulose is accompanied by a heavily increased quantity of lignin, the manufacturing process becomes to a high degree more difficult.

The upper side of knot wood has on the other hand generally speaking a normal content of cellulose and defibrates more easily comparatively than the lower side in the manufacture of pulp.

2. Content of lignin in branch and knot wood.

With the exception of cotton fibers, the raw materials offered the fiber industries by nature are more or less ligneous. The ligneous material which in this connection gives the cells increased strength has been referred to by the term lignin. There are many theories as to its composition. But up to the present its nature cannot be regarded as having been completely determined and analyzed.

The technical problem of the pulp industry is to free the raw material of its content of lignin. Under such circumstances it is self-evident that both production difficulties and also the quantity of the yield are directly affected by the content of lignin. When it is desired to ascertain the quality of a raw material, it is therefore important to determine the quantity of lignin, which constitutes a direct index of the value and suitability of the wood for pulp manufacture.

The determination of the lignin content of wood is a method which in all respects in cheaper, simpler and faster than the methods for ascertaining the content of cellulose. Since the relationship between these characteristics has been found to be very definite, as has previously been mentioned, the content of lignin can by itself be regarded as giving on the whole a satisfactory picture of the chemical composition of the wood.

The ligneous material can be qualitatively determined by color reaction. Phloroglucin-hydrochloric acid for example gives the lignin material a red-color, while aniline sulphate causes a yellow color reaction. Ligneous materials have furthermore the ability to absorb chlorine, a characteristic which is missing in pure cellulose. The content of lignin can be quantitatively determined by both direct and indirect methods. In the direct methods it is attempted to bring the cellulose and hemicelluloses of the wood in a solution in order to obtain pure lignin as the dissoluble remainder. In the direct methods on the other hand, it is endeavored to make use of the characteristic reactions of lignin in order to obtain comparable values that are usable.

As early as 1838 Payen was successful in obtaining pure cellulose from wood by treating with alcohol, ether and alkalies. The materials which in this connection went into solution were termed by him as incrustations. Schultze has later extricated wood cellulose through the use of nitric acid and potassium chlorate. He presumed that the elements which in this connection went into solution were composed of one and the same element which he called lignin. We now know that Schultze's lignin also contained a portion of the carbohydrates of the wood, primarily in the form of hemicelluloses. Lignin is on the other hand understood to be the parts of the wood substance which cannot become xylose.

In determining the lignin content of wood, it should be observed that this element is very little understood as regards its composition and properties in spite of the fact that chemical science has long struggled with the lignin problem. It is not known with complete certainty whether lignin appears as a mechanical mixture or a chemical union with cellulose in the cell walls, nor whether it is amorphous or crystalline, although the latter seems to be the case. In various methods of analysis, lignin easily undergoes changes. Numerous investigations have shown by means of spectral analysis for example that lignin in various species of wood is not identical.

The function of lignin is primarily to strengthen and support the flexible and elastic cellulose membranes in the cell wall. It is present principally in the middle lamella which separates the tracheids and in the secondary layer of the tracheid (Katz 1928, Trogus 1928, Lüdtke 1929). Lignin is present according to Klason (1932) also in the wood without being directly joined to the cell wall, and it then appears in the form of a dark stripe between the annual rings. Similar lignin is found particularly in the lower portions of the knot and in the other compression wood formations. This lignin, which Klason characterizes as reserve lignin, is soluble in alcohol, as contrasted with the remaining lignin, so-called total lignin. Klason states that reserve lignin and total lignin are otherwise completely identical.

In determining lignin quantitatively by direct methods, there are generally used acids which cause a crystallization of the carbohydrates of wood into sugar and accordingly isolate the lignin. Klasson and König made use of a 72 % solution of sulphuric acid. It can however be pointed out in opposition to this method that the lignin will not be entirely unchanged as a result of the strength of the acid but loses its acetyl residue and becomes rosin. Schwalbe and Lange have modified the method and make use of 62.5 % sulphuric acid, the so-called Guignet concentration.

Willstädter and Zechmeister have on the other hand isolated lignin with the assistance of concentrated hydrochloric acid having a specific gravity of 1.21. There is reason as regards this method also to test how completely hydrolysis of the cellulose has taken place. This is best done by a microscopic study as to whether the cellulose reagent elements such as iodine, sulphuric acid or chlorine zinc iodine effect a bluish coloration of the mass (Schwalbe-Sieber 1931).

Hottenroth (1918) and Schwalbe (1925) have recommended a combination acid treatment of the analytic substance in order to isolate the lignin elements in wood. There is used in this connection a concentration of about 60 % sulphuric acid and the treatment thereafter is made with a diluted solution of hydrochloric acid.

Wenzl (1925) has found a combination method using hydrochloric acid and phosphoric acid as applicable in the direct determination of the quantity of lignin.

J. König and E. Rump have ascertained the content of lignin by heating in 1 % hydrochloric acid under high pressure for six to seven hours. This method however requires an expensive and complicated apparatus.

Hägglund maintains that there exists no fully accurate method for determining the content of lignin by indirect analysis.

Since Klason's method of isolating lignin by the use of concentrated sulphuric acid is indisputably the most general method of analysis, and since the results which are accordingly attained in this manner are directly comparable to the majority of the statements appearing in literature, the

author decided to make use of this method in the present investigations. As it however has the drawback that sulphuric acid forms with lignin a sulphonic acid which is difficult to dissolve, as pointed out by König and others, the analyzing work has been made according to Klason's modified system for obtaining a product as free of sulphur as possible. The process of analysis was as follows:

One gram of pulverized wood substanse extracted with ether is placed in an Erlenmayer flask containing 50 cm³ of 64 % sulphuric acid. The flask is then shaken well. The solution, diluted with water, is allowed to stand for 48 hours and is then filtered and dried at 100 degrees Centigrade. The lignin is extracted hot with 50 cm³ of alcohol and there is then added a 0.1 normal solution of potassium hydroxide. When the substance so obtained has been washed, it is finally dried at 105 degrees Centigrade and weighed. The ash content in the lignin is thereafter determined by burning and is deducted from the result.

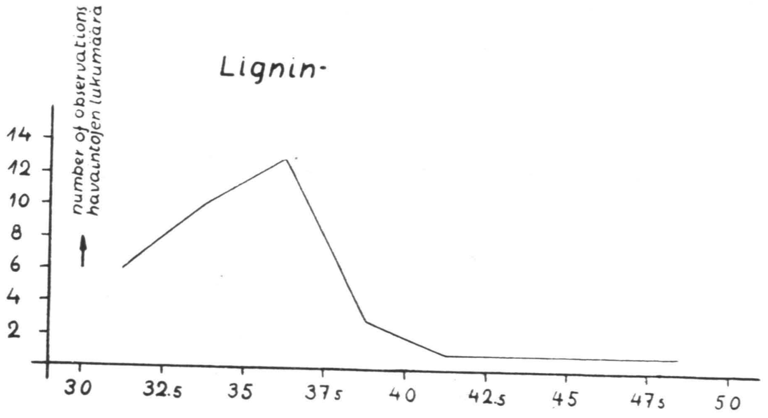


Fig. 53. Percentage of lignin in knots. — *Kuva 53. Oksapuun ligniinipitoisuus.*

3. Content of pentosans in branch and knot wood.

The most important constituent parts of wood, in addition to cellulose and lignin, consist of hemicelluloses and the resin and fats of the tree. Hemicellulose consists of a large number of polysaccharides insoluble in water, which are hydrolyzed easier than cellulose in diluted mineral acids. Hemicellulose differs only slightly from other polymeric carbohydrates such as for example starch and inulin, and gives off upon hydrolysis the same kind of sugar as other polysacchrides.

Very little is known about the hemicelluloses in various species of trees as well as about their resistance to weak mineral acids. Schwalbe and Klason maintain that some pentosans react to hot mineral acids in approximately the same manner as cellulose. Sulphite pulp can in other words contain considerable quantities of pentosans. Determination of the content of hemicelluloses is accordingly closely associated with determining the content of cellulose. So long as there exists no perfect quantitative method of analysis for cellulose, it is not possible to state exactly the quantity of hemicelluloses.

Of the constituent parts of hemicellulose, many investigators have given special attention to the content of pentosans in various species of trees. The results which have so far been obtained vary however appreciably.

The content of pentosans is usually determined by Tollen's method through isolating furfural by means of 12 % to 13 % hydrochloric acid. This method has during the course of years undergone a great many changes and improvements. After furfural has been separated from the substance of analysis by treatment with hydrochloric acid, the quantity of furfural is determined as phloroglucide by means of a phloroglucine solution or through being precipitated with barbituric acid. Other investigators such as Powell and Whitaker (1924) have proposed the determination of furfural through titration with bromide-bromate.

In the present investigations the following method recommended by Klingstedt has been used:

About 2 grams of airdry substance are weighed carefully and placed in a Cleisen flask equipped with a cooler. There are then added 100 cc HCL (13 %, specific gravity 1.065 at 15° C +) and 17 grams Nace. Distillation occurs in a Babo funnel isolated with asbestos wool at a temperature of about 250 ° C. The products of distillation are assembled in a graduated measuring glass. For each 30 cc of distillate there is added into the flask an additional 30 cc of the foregoing HCL solution out of a suitable measuring funnel. The distillation is continued in this manner until 180 cc of distillate have been obtained. The period of distillation for each 30 cc of distillate should be 15 minutes. The distillate so obtained is mixed with 30 cc of a barbituric acid solution (2 % in 13 % HCL) and allowed to stand 24 hours. The precipitation is then filtered through a glass

filter (Jena No. 4), washed with a specified volume of water (50 cc), dried for 4 hours at 95° to 98° C. and weighed. The content of pentosans is calculated in accordance with the following formula:

$$\frac{(\text{precipitation in milligrams} + 1.22 \times \text{number of cc distillate}) \times 0.4559}{100}$$

$$= \text{milligrams furfural.}$$

$$\text{Quantity of pentosans} = \text{quantity of furfural} \times 1.71.$$

The content of pentosans in various parts of the stem and in knot wood based on the foregoing investigations varies in the manner outlined in the attached graphic presentations.

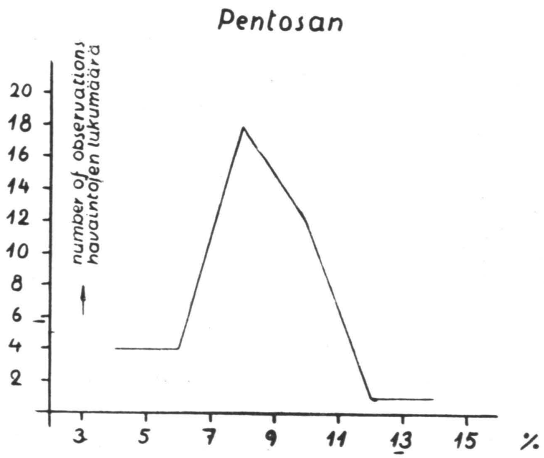


Fig. 54. Percentage of pentosans in knot.
Kuva 54. Oksapuun pentosaanipitoisuus.

4. Content of resin and fats in branch and knot wood.

While the volume of cellulose, lignin and hemicelluloses, as will be observed from the foregoing, remains rather constant and appears to be clearly influenced by definite laws, the content of resin on the other hand is a particularly varying factor when determining the chemical composition of wood. It has for example been shown that the base of a tree always contains a greater abundance of resin than the parts of the stem higher up, and similarly that the base of a branch always shows a greater quantity of resin than its other parts. Heartwood is also much more impregnated with resin than sapwood.

Hägglund maintains that resin is not understood to be a unitary substance but a quantity of fixed or semi-fixed elements made up of carbon, hydrogen and oxygen. These are formed in definite textures in wood and are characterized by their not being soluble in water but forming glutinous solutions ether, alcohol and benzol. The biochemical process in the formation of resin is as yet unknown. It has accordingly not been ascertained whether resin is produced within the cells or whether it originates through some kind of process in the outer layer of the cell walls.

A difference is drawn between resin which originates in a physiological manner and that originating in a pathological manner. The former is formed in normal, living textures while the latter is secreted as a protecting agency for impregnation since the living organism can be damaged by outer action. Resin which is found in a dead knot accordingly consists principally of resin which the surrounding stem wood has secreted for preventing the formation of infection from the dead matter arising within the stem.

Physiological resin appears in wood partly within the intercellular containers, ie., resin canals, and partly on the other hand inside the cells and in the cell walls.

According to Tschirch resin consists principally of resin or resinol acids which have not been esterified, resin alcohol and resene. Resin acids are the most important of these and constitute the major portion of the resin. The physiological and pathological resin acids differ to a certain extent and they produce dissimilar torsion when analyzed in polarized light.

Pathological resin which is found in newly sawn coniferous wood is more soluble (according to Hägglund) than physiological resin. While physiological resin contains relatively little turpentine, about 7 % in spruce wood according to Klason and Köhler, pathological resin contains from 32 % up to 60 % turpentine oil, as has been shown by Mayer.

The organic solvents such as ether and alcohol used in the extraction of resin dissolve not only the resin elements but also the fats which are present in wood. The quantitative relationship of these elements in the extract depends on their reciprocal relationship in the wood as well as on the solvents used, and finally on the length of time that the wood has been stored. The absolute quantity of extract on the other hand is dependent upon the foregoing factors and furthermore on the method and length of time of the extraction and on the temperature at the time it takes place.

A great many investigations have been made as regards the content of extract elements in wood. The content of resin and fats in spruce has been examined by Schroeder (1874), Müller (1877), Griffin and Little (1894) and others. Schroeder ascertained that heartwood in spruce contained more resin than sapwood and that the quantity of resin varied during different times of the year with a maximum of 2.86 % in June. Griffin and Little obtained a resin content in spruce of an average of 1.67 % with ether extraction and 1.61 % with alcohol.

The most comprehensive investigations of the content of resin in wood have been made by Mayer. He has investigated the variations in resin content in various parts of the stem and how it is affected by the soil and climate. Mayer conducted his analyses using alcohol as the agency of extraction and ascertained that spruce wood contained an average of 1.69 % resin. Based on Mayer's investigations spruce contains its greatest quantity of resin in the root system. Thereupon follow the base portions of the stem, the branches and the stem inside the crown. The part of the stem free of knots which is closest to the crown contains the least resin. Mayer ascertained likewise that heartwood has a greater abundance of resin than sapwood and that the south side of a stem contains more resin than the north side. The content of resin appeared to be greater the older the tree, the warmer the climate and the more open the stand. The quantity of resin according to Mayer is accordingly dependent upon the amount of light and heat.

Later investigations such as those of Wahlberg (1921) and Klem (1934) as to the content of resin and its variations do not show the quantity of resin and fats to vary in the stem according to any definite laws, neither from pith to bark nor from root to top. On the other hand compression wood appears in general more lacking in resin than tension wood, as has previously been maintained by Hägglund (1933) and others.

Sieber (1925) has expended a great amount of work in investigating to what extent the storing of wood affects the content of resin. In this connection he found that the condition of the wood while stored was furthermore of great significance. He shows that the quantity of extract is greatest in newly felled and fresh wood and decreases little by little when storing. The quantity of extract in round timber after three months' storage had reached such a state that it thereafter remained fairly constant and no great changes occurred. If the wood was cut up into chips, the reduction in the amount of resin occurred faster until about half the resin had disappeared than in the case of newly felled wood. Sieber's investigations have furthermore shown that the content of fats decreased faster than the content of resin; an observation that has also been made in sulphate mills producing sulphate soap.

A large number of organic elements are found recommended in chemical literature as suitable solvents in the extraction of resin and fats. The solvents can be either of a kind which can be mixed in water or those which cannot be mixed with water. Alcohol and ether are classified among the former while the most important of the latter group is benzol.

The suitability of these extracting elements is discussed by Schwalbe in the following manner:

Ether is presumably the most generally used solvent. Similarly as alcohol, it possesses the advantage of being able to be mixed with water so that a complete impregnation of the raw material containing water is obtained. Its greatest drawbacks are its volatility and the great danger of fire and explosion. Ether has furthermore the tendency to form condensation products and in this manner lead to inaccurate results. These do not have however any particular significance according to Schwalbe.

Although alcohol is not a specially good solvent for fats and wax, it has the advantage of being able to penetrate the substance of analysis completely. Unfortunately it also dissolves at the same time carbohydrates such as sugar, with the result that altogether too high values are obtained.

Benzol dissolves resin, fats and wax very effectively but has the disadvantage of not being able to penetrate membranes containing water. There is therefore often made use of a mixture of benzol and alcohol, which has also become very popular. Comparable investigations of the various elements of extraction have shown that the benzol-alcohol mixture has given the greatest yield of extracted substance. The reason for this situation can be found according to Hägglund in the fact that alcohol attacks not only resin and fats but also the lignin in wood.

Extraction for the series of investigations concerning the content of resin and fats in wood which the author has conducted in connection with the present work has been made with the aid of ether. This method appears to be the most exact. Errors cannot arise otherwise than as a result of condensation (Schwalbe 1931).

The extractions were made in a Soxleth apparatus in an electrically heated bath of water at a temperature of 35° to 40° for eight hours. The results of the investigation appear in the graphic presentation entered below. In similarity with the investigations of Wahlberg and G. Klem, these series of analyses also show that the content of resin in stem wood fluctuates within very wide limits. No definite relation can be discerned between anatomical properties such as the breadth of the annual rings and the percentage of summerwood. The series of analyses as to the variations of resin content in knot wood offer however great interest. Since similar analyses have not been previously undertaken to such an extent, the results cannot be directly compared with such previous analyses. It has been found in the first place that the content of resin is dependent upon the part of the branch from which the sample has been taken. The farther from the stem this takes place, the lower is the content of resin. The maximum is reached in the base of the branch and in the knot. The reason for this situation is to be found in the fact that the tree endeavors in this manner to impregnate the base of the branch and the knot in order to prevent infection in case of fracture. This accumulation of resin depends on the other hand partly on physical circumstances such as the power of gravitation. In other words it is found that the knot has a very high content of resin and as a result thereof can appreciably increase the content of incrusting materials in a stem and accordingly affect its fitness as a raw material for the cellulose industry.

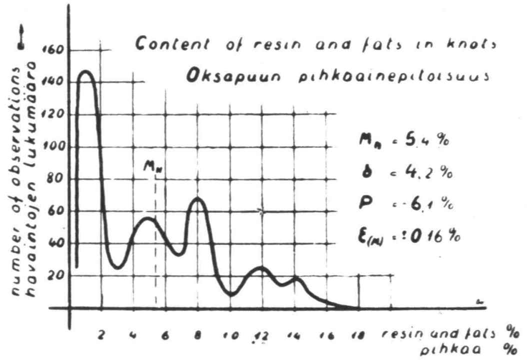


Fig. 55. Content of resin and fats in knot wood. — *Kuva 55. Oksapuun pihka- ja rasva-ainepitoisuus.*

The upper part of a branch, which consists of tension wood, is as regards its chemical composition much different from the lower side, which is built up of compressed wood. The content of resin in the upper part is accordingly much higher than in the lower, and this must be considered to depend upon the limited presence of intercellular cavities and resin canals in compression wood.

It is found that Mayr's hypothesis as to the increasing influence of the supply of light and heat on the content of resin also applies to branch wood. Branches taken from OT stand have accordingly as a rule a much greater supply of resin than those which have grown in a denser stand and in more sterile soil.

5. Content of ash in branch and knot wood.

An analysis as regards the ash in wood substance furnishes as a result the quantity of mineral elements in wood such as K_2O, P_2O_5, CaO, MgO, Fe_2O_3, SO_3, SiO_2 and NaO_2. Ash content is in general very insignificant. It varies in the stem wood of spruce from 0.2 % in heartwood to 0.26 % in sapwood. According to Kollmann (1937) it is influenced by the place of growth, age and the possibilities of the tree's development and can even within a stem be very different as regards both quantity and composition. The branches, crown and bark have a greater abundance of ash than the stem. Schröder (1878) has investigated the content of mineral elements in spruce. He has found that the needles have the greatest quantity, tontaining about 3 % ash. Even slender branches having a diameter of less chan 1 cm. are high in ash and show a content of about 2.5 %. Thicker branches having a diameter in excess of 1 cm. contain from 0.3 % to 0.35 % ash while finally the ash content in the stem is from 0.2 % to 0.3 %. While the most important constituent part of knot ash consists of 32 % MgO_2 and 29 % K_2O, the most important constituent part in stem wood is K_2O. According to Schröder stem wood contains 45 % K_2O and 25 % MgO.

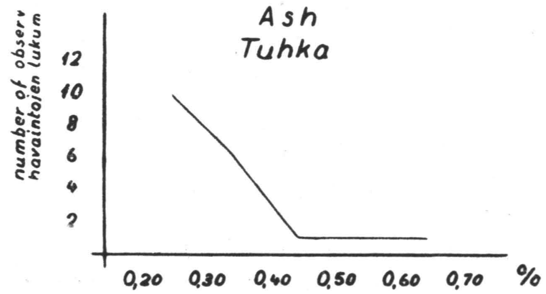


Fig. 56. Content of ash in knot wood.
Kuva 56. Oksapuun tuhka-ainepitoisuus.

The analyses concerning ash which were made in connection with the present work show that the content of ash in the branch is considerably higher than in stem wood. The more compression wood that is contained in branch wood, the higher is its content of ash.

The analyses were made by igniting in a platimum melting pot. Through repeated weighing it was ascertained that complete burning had occurred. Any remaining, unburnt carbon particles were oxidized by using 3 % hydrogen superoxide (based on Schwalbe-Sieber 1931).

The results of the investigation appear in the following graphic presentation.

The presence of branches in wood accordingly affects clearly the content of ash. In this connection we find an important reason why knotty wood is not suitable as raw material for the artificial silk cellulose industry. As is known, this industry strives to attain as low an ash content in its products as possible.

6. The resistance of branch and knot wood to chemicals.

It is often of great importance in many different kinds of enterprise where the use of timber is made to be able to specify the power of resistance of various qualities of wood to chemicals. In the cellulose industry the degree of defibration is directly dependent upon the resistance of wood to the solvents which are used. It is likewise of importance in the production of wood sugar to know to what extent various kinds of wood are suitable for the extraction of saccharides. In the sulphite pulp industry there arises primarily the question of the resistance of wood to weak acids. On the other hand the resistance of wood to diluted lye solvents in the sulphate industry is of significance for the cooking process and its application.

In order to judge the effect produced by different chemicals, there is reason to make at the same time analyses as to the solubility of wood in water. In certain kinds of wood this can be remarkably high. There are mentioned and described in available literature a number of different methods with various acids, concentrations and cooking pressures.

a. Solubility of branch and knot wood in water.

The solubility of wood in water has as yet been the object of interest only to a very limited extent although its importance particularly in cooking the wood substance is fundamental. Vegetative raw materials such as wood for example always contain components which dissolve in water, although often only in small quantities. The degree of this solubility is of course dependent upon the anatomical structure of the wood and its ability to absorb solvents. Fine grained timber has a greater power of resistance than that having a coarse grain because of its reduced ability to absorb water. The solubility of wood in water is furthermore affected by its physical condition. Timber which has long been stored and dried out contains much less substance soluble in water than fresh and newly felled wood.

The component parts of wood soluble in water consist of the saps of the tree such as albumin and carbohydrates of various kinds. Furthermore, certain tannins and pigments can become dissolved. In the United States the solubility of wood in water has been the object of some interest, and Wise (1926), Ritter and Fleck (1923) and others have made investigations in this matter. The investigations of Wise show that Picea species, as compared to other coniferous trees, have a rather high power of resistance to water. While 1.12 % of Picea canadensis wood dissolved in cold water and 2.14 % in warm water, the corresponding figures for Pinus palustris were 6.20 % and 7.5, for Pseudotsuga taxifolia 3.54% and 6.50 %, and for Larix occidentalis 10.61 % and 12.59 %. Ritter and Fleck have found that the resistance of coniferous trees to water is greater in heartwood than in sapwood. They have furthermore ascertained that no definite relationship can be found between solubility in water and percentage of summerwood.

In connection with the present work there was undertaken a series of analyses covering the solubility of wood in hot water made in accordance with the standards of the Forest Products Laboratory at Madison. The analysis was made in the following manner:

Two grams of pulverized wood having a known percentage of dryness and extracted in ether were placed in a 200 cc Erlenmeyer flask equipped with a reflux condenser, and 100 cc of distilled water were added. After the wood was allowed to swell for an instant in the water, the flask was sunk into a bath of water so that the surface of the liquid in the flask was somewhat below the surface of the bath, which was held constant. The bath was brought to the boiling point and the flask held in this boiling water for 3 hours. At the end of one and one-half hours the contents were shaken somewhat, at which time the flask was taken out of the bath. After heating for 3 hours, the substance of analysis

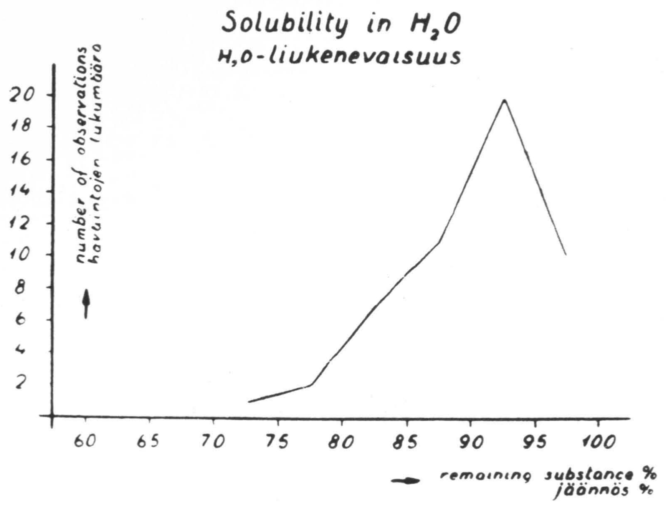


Fig. 57. Solubility of knot wood in water.
Kuva 57. Oksapuun liukenevaisuus veteen.

was filtered, washed with hot water (300 cc) and then dried at 105° C until a constant weight was obtained. The remainder was calculated in percent of absolutely dry wood.

b. Solubility of branch and knot wood in diluted acids.

Through cooking with acids a part of the carbohydrates is dissolved out of the wood, and a portion of this part, which is easily dissolved or more accurately stated easily hydrolized, is placed in the group of hemicelluloses. Little is as yet known about its quantitative extent and the attempts that have been made cannot be regarded because of the scantiness of the material to have given entirely accurate results concerning various species of wood. Attempts with strong acids have been made for a long time to turn into sugar for the needs of the sugar industry the starches in wood. Kirchhoff's investigations of 1811 and Praconnot's of 1819 are worth mentioning in this connection. Melsens in 1855 was the first to accomplish a conversion of wood into sugar by the use of sulphuric acid under high pressure. This method has later undergone a great many changes. (Hägglund, 1928).

It is self-evident that the power of resistance of wood to withstand the effect of various acids stands in direct relation to the concentration of the acids, or in other words, to their pH values. Mörath has shown that wood is surprisingly able to withstand the resistance of acidulous fluids and that a breakdown of the fiber substance does not take place until pH is less than 2. Alliot showed that 80 % acetic acid did not affect cross-breaking strength in spite of the wood having been soaked for four months. Wood is likewise very firm against most organic acids such as tannic acid, lactic acid, oxalic acid, phthalic acid, salicylic acid and citric acid, and is well suitable as a constituent for retaining these acids. Kollmann has shown that 5 % nitric acid little affects coniferous wood while cold, but when the acid is warm parts of the wood substance dissolve. On the other hand 5 % hydrochloric acid does not generally attack conifers but damages most broad-leaf woods. Sulphuric acid behaves in much the same manner as hydrochloric acid, while sulphurous acid and sulphur dioxide even as diluted solvents attack, as it is known, the lignin elements in wood. It is nevertheless worth while mentioning that conifers are subject to much less corrosion because of these latter acids, ie., they have greater strength to resist these acids, than ordinary iron. For this reason they are also better suited as material for receptacles and conduits in the sulphite cellulose industry.

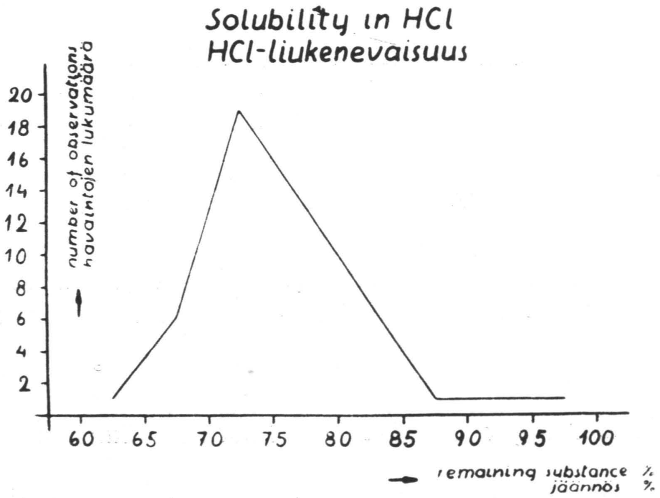


Fig. 58. Solubility of knot wood in diluted acids. —
Kuva 58. Oksapuun liukenevaisuus laimeihin happoihin.

There exist no data as yet in literature as to how the various parts of wood, such as summerwood and the anatomical structure of wood, act to corrosion in weak acids. In order to contribute toward making these matters known, the author made upon the suggestion of Professor Klingstedt a series of analyses covering various qualities in both the stem wood and branch and knot wood of spruce. The object of this investigation was to ascertain to what extent properties of wood affect its power of resistance against weak acids. Corrosion was tested in 1 % hydrochloric acid. The process of analysis was in brief as follows:

Five gram of pulverized wood extracted in ether and 100 cc of 1 % HCl (concentration checked by titration) were heated for 6 hours in a boiling water bath. The cooking was done in a 200 cc Erlenmeyer flask equipped with a reflux condenser. The remaining substance was washed free of acid by using 500 cc of lukewarm water and dried at 105° C until a constant weight was obtained. The result was calculated in percentage of absolutely dry wood substance.

The results of the foregoing series of analyses are apparent in the attached graphic presentation.

c. Solubility of branch and knot wood in diluted alkalies.

A constituent element called wood gum is dissolved from wood by heating with the use of diluted alkalies. The part which is soluble by using alkalies is not however unitary as regards its composition but consists partly of carbohydrates and partly of small quantities of easily soluble lignin. Any resin elements that are possibly present are turned into soap in this chemical process. If the wood is cooked in an alkaline solution under high pressure, the membranes between the wood fibers are dissolved rapidly. This method has been utilized by the natron cellulose industry.

It is self-evident that wood in large pieces has a greater power of resisting the effect of alkalies than fine wood substance. Kollmann maintains that wood reacts in both cases to strong intumescence even when soaking in cold, diluted alkalies. This results in only the most outerly layers of wood being penetrated by the lye solution. This swelling is greater if natron lye rather than potassic lye is used. The degree of swelling appears to be primarily affected by the concentration of hydrogen ions, ie., OH ions. Alkalies increase the degree of swelling while acids appear to decrease it.

Alliot (1926) and Mörath (1921) have investigated how the strength properties of wood are affected by soaking in alkalies. According to Mörath cross-breaking strength in kilograms per cc after soaking for four weeks in an NaOH solution was 578 when the solution was 2 %, 455 for a 5 % solution and 316 for a 10 % solution.

Mörath maintains that perceptible corrosion of wood does not occur with slight alkalinity, ie., with pH values between 7 and 11. Under these circumstances containers of wood are more suitable than those of iron. As a general rule the more lignified the wood, the less it will dissolve. Broad-leaf wood dissolves in general more easily than that of coniferous trees. It is worthwhile mentioning further that wood is protected by alkalies from fungus infections.

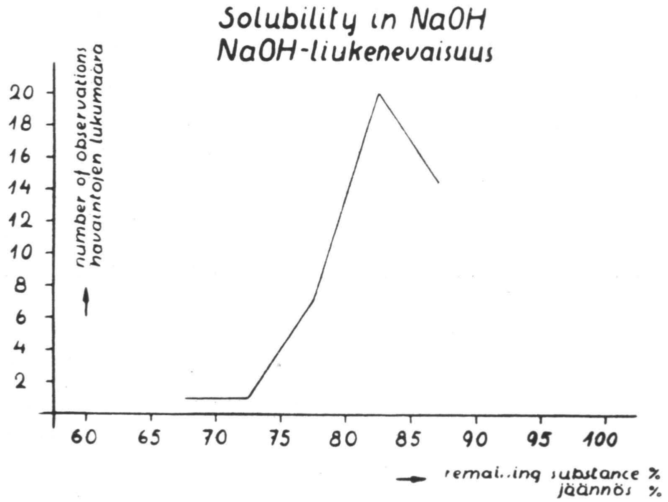


Fig. 59. Solubility of knot wood in diluted alkalies.
Kuva 59. Oksapuun liukenevaisuus laimeihin emäksiin.

The solubility of wood in alkalies has been tested only to a very limited extent as yet. Ritter and Fleck (1923) have made investigations as to the solubility of various species of trees in percent of NaOH and have found that this is not affected by the structure of the wood, and that sapwood and heartwood as well as summerwood and springwood show on the whole similar resistance. In connection with the present studies there has also been made a series of analyses concerning the resistance of wood to diluted alkalies. In these cases a 1 % solution of NaOH has been used as a solvent. The procedure for the analyses was in the main as follows:

Two grams of air dry pulverized wood from which the resin has been removed were placed in a 250 cc Erlenmeyer flask and 100 cc of 1 % NaOH were added. (NaOH content was checked by titration). The flask was made air tight by using the crystal of a watch and placed in a water bath to a depth so that the surface of the liquid in the flask was somewhat below the surface of water in the bath, the level of which was held constant. The bath was brought to the boiling point and the flask held there for one hour. The contents were stirred slightly every 15 minutes with a glass rod, filtered with a glass filter, and washed first with 400 cc of hot water, then with 200 cc of 10 % acetic acid and finally with 500 cc of hot, distilled water. The substance was thereupon dried at 105° C and the result calculated in percentage of absolutely dry wood.

The results of this series of investigations appear in the attached graphic presentation.

CHAPTER XI.

Mechanical properties of branch and knot wood.

The very earliest technical investigations concerning wood, such as the works of Duhamel du Monceau, Muschenbroeck, Nördlinger and others, have indicated that there exists a particularly close relationship between the strength of wood and its anatomical structure. The heavier and more compact the wood is as regards consistency, the more favorable are its strength properties. In this connection the breadth of the annual rings and the percentage of summerwood in conifers appear particularly to be of decisive significance.

The mechanical properties of coniferous trees are especially of significance when the wood is used in such a manner that its anatomical structure remains unchanged, ie., principally as timber in construction work and in the sawmill industry. Numerous investigations have shown that the presence of knots in wood used in these fields of activity is of extreme significance. Every person having a knowledge of the value of construction timbers knows that where wood is subjected to extra stress in such work, the wood containing knots has a lesser value. It is therefore self-evident that the presence of knots affects to a high degree the valuation placed on construction timber and sawn goods.

Knots affect strength properties primarily since the grain of a knot runs in a different direction from that in stem wood. Its axis for splitting is located more or less at a right angle to the longitudinal axis of the stem, resulting in breaks easily arising in places where the parallel fibers are otherwise intercepted.

Garratt (1931) states in part as follows: »The influence of a knot in a beam is determined by its location and the area of its projection on the cross section of the piece, the method of measurement being such as to give the best approximation of the influence. Knots in posts and large beams are likely to show on one face only or to run diagonally through

the piece, and reduce the strength in practically direct proportion to their size as measured. In dimension sizes, such as joist, the knot is likely to run directly through the piece, and the strength is measured by the square of the effective depth, assuming the knot in its worst position, near the edge of the piece; the reduction in strength due to the knot is approximately twice the ratio of the size of the knot to the width of the face. In similar material used flat, as plank, the influence of a knot is directly proportional to its size, as on the top and bottom edges of beams.»

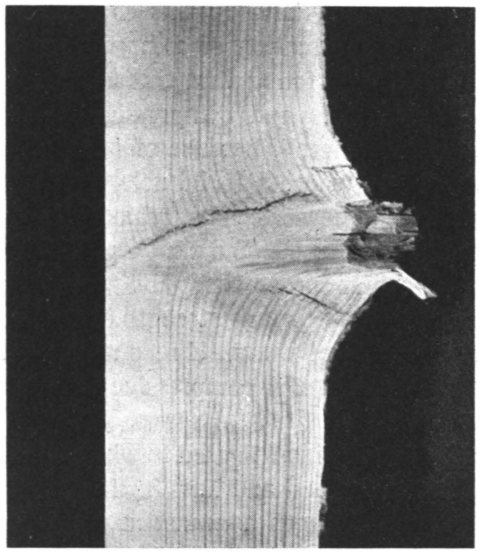


Fig. 60. Fiber breaks around knot wood.
Kuva 60. Kuitukatkeamia oksatyven ympärillä.

Because of the fact that upon drying a knot shrinks in a different manner than the surrounding stem wood (Siimes 1938), it also causes a lowering in the strength of the wood. Stem wood shrinks only to an insignificant extent in its longitudinal direction, but in a block of wood the longitudinal direction of the stem corresponds to the radial direction of the knot, and this occasions certain drawbacks. The radial shrinkage of a knot varies by about 2 %. This figure is altogether too great when compared with the percentage of longitudinal shrinkage in the surrounding stem wood, but on the other hand too little when compared with the tangential shrinkage of the surrounding stem wood. If the knot were not surrounded by a transitional layer of compression wood, which evens the tension, it would when drying and shrinking easily loosen from the surrounding wood. A cut across the longitudinal direction of the stem and through a knot shows therefore fiber breaks parallel to the knot and somewhat above it.

Since it is a question of examining closely the characteristic properties of knot wood which cause it to be different from stem wood, attention is first of all called to the differences in anatomical structure. Hartig (1891 and 1896) and Mer (1887) have made investigations as to the anatomy of branch wood and have in this connection given particular attention to the extensive formation of compression wood on the lower side of branches. It has been found that this compression wood is noteworthy for its great hardness and compressive strength. Their works clearly present that branch wood, because of its special structure which has been brought together in order to be able to withstand great cross-breaking loads, must also show special mechanical properties which are different from those in stem wood. Sonntag (1904) has gone to great pains in investigating these properties. His work comprises tests for tensile, compressive and cross-breaking strength as well as studies covering the elasticity and stretching of wood. Ursprung (1901) has furthermore investigated the tensile and compressive strength of tension and compression wood.

Garratt (1931) has also investigated to what extent knots of various kinds affect the strength of wood and has in this connection ascertained that encased knots affect strength as much as empty knot holes.

1. Toughness of brauch and knot wood.

Because of the great mechanical strains particularly originating from the effect of the power of gravity to which branch wood is subjected, it is anatomically different from stem wood which has grown vertically and has not been continually subjected to bending pressure in an identical manner. Branch wood must therefore also have different strength properties than stem wood. As has previously been explained, a branch consists of wood of especially great toughness and elasticity in order that its bending and compressive strength during chronic strains is able to meet the demands placed upon it by nature. In similarity to all compression and tension wood, living branches also contain very great toughness. This constitutes a result of the micellar structure of branch fibers, a subject which has previously been treated more thoroughly.

The ductility (toughness) of branch wood has been investigated by Sonntag. He has found that both tension and compression wood stand stretching of 1.5% to 2% depending upon the degree of moisture content. However, because of its doubly greater modulus of elasticity, tension wood requires a load twice as great in order that this stretching is able to take place.

2. Elasticity of branch and knot wood.

The demands of elasticity in branches are very high because of their plagiotropic position. The anatomical structure of branch wood is also such as to increase elasticity. It has already been mentioned in Kalevala (1836), the Finnish national epic, that compression wood in branches makes it particularly suited as material for bows and crossbows because of its increasing the elasticity of the wood. Compression wood is similarly considered as being especially suitable as wood for skis since it increases their springiness.

Hartig has undertaken a series of analyses in order to determine the modulus of elasticity in compression and tension wood, and for his material he has principally made use of hyponastic samples of spruce. He has found a cross-breaking elasticity between 56,800 kg. per cm. and 58,900 kg. per cm. for compression wood while the corresponding values for tension wood varied between 10,700 and 10,800 kg. per cm. He draws therefrom the following conclusion: »Aus vorstehenden Versuchen ergiebt sich also, dass das Rothholz im frischen Zustande mit nahezu der halben Kraft, die man beim Zugholz anwenden muss, bis zu einem gewissen Grade sich biegen lässt, was wohl zweifellos der Zusammensetzung der dicken Zellwände aus Schraubenbändern zuzuschreiben ist. Das unter Zug entstandene Holz der Astoberseite biegt sich weitaus schwerer.» The moduli for tension were 63,900 and 11,600 kg. per cm., and for compression 68,650 and 121,800 kg. per cm. in compression wood and tension wood respectively. The modulus for tension wood is accordingly about twice as great as that for compression wood.

3. Strength properties of branch wood.

Because of denser anatomical structure, higher percentage of summerwood and greater weight, knot wood has in many respects greater strength values than stem wood. This is particularly true as regards cross-breaking and compressive strength. Hardness is of course also greater in knots than in the stem, as has been shown by Janka, Lassila, Jalava, Wallden and others.

Numerous difficulties are however encountered in practice in ascertaining exactly the strength properties of branches. This depends in part on the difficulty of obtaining sufficiently large specimens of clear branch wood. The equipment used in wood technical laboratories has been primarily constructed for ascertaining the suitability of stem wood for structural timber and similar requirements. The smallest apparatus which the author was successful in making use of for this purpose was an Amsler machine of the Forest Technical Institute of the University of Helsinki. The dimensions of the specimens used in this machine were 2 × 2 cm. in cross-section while their lengths varied of course depending upon the quality of the specimens for the strength tests. It was found to be extremely difficult to obtain suitable material for research particularly as regards knots. It was therefore necessary to limit the research material to a comparatively small quantity.

As will clearly appear from the following series of analyses, the strength properties of branches are dependent to a great extent on the amount of compression wood and its location in the specimen. Since branch wood is composed primarily of compression wood, the compression side in cross-breaking tests should be placed on the side of the pressure in order that the greatest effect can be attained. If it is on the other hand found on the tension side, the figure concerning strength can decrease by up to 50 %.

The strength of wood is of particular significance in manufacturing in which the structure remains unchanged, as in the sawmill industry. In these divisions of production all strength properties play of course a role when judging the quality of the raw material. On the other hand, compressive strength and hardness directly affect both the manufacturing process and procedure as well as the yield of pulp in the ground wood pulp industry. The importance of these factors is clearly evident in the works of Kirchner and Per Klem. The results of the investigations made by the author concerning the consumption of power and time in grinding various kinds of spruce wood likewise show that the friction against the grinder is principally affected by the presence of knots in wood.

The shearing strength of wood as well as its cleavage strength and tensile strength perpendicular to the grain also have a noticeable effect on the yield of the grinding process, principally on the percentage of splinters in the pulp. These conditions are treated more thoroughly in the second part of this study.

The compressive strength of wood plays of course an important role in mining. Experience of this kind has shown that pit props of coniferous trees give way in general at the knot clusters. Max Linke (1921) maintains that in judging the quality of pit props it should be observed that while the presence of knots increases their weight and tenability on the one hand, it decreases however on the other hand their ability to point out when the danger point is being reached.

The strength properties of wood constitute in many cases good indices of fiber quality.

It is therefore possible to consider that a simple strength analysis, such as for example a hardness test made according to the procedure of Brinell-Janka, could constitute in a characteristic manner a practical basis for judging the quality of pulp wood. In order to illustrate this condition more thoroughly, the author has likewise made a series of strength tests with branch wood.

Because of the small dimensions, it was however impossible to make investigations based on material of knots. The research was therefore carried out with specimens taken from the bases of branches. Two spruce trees felled on the experimental grounds of the Forestry Research Institute at Ruotsinkylä in Tuusula were limbed for this purpose. One spruce tree had grown on a Myrtillus type of ground, was 80 years old and had a diameter of 33 cm. at breast height. The other had grown in a stand of the Oxalis type. It was 50 years old and had a diameter at breast height of 44 cm. Both trees had grown in open stand where the coverage of the crowns was 0.5. The branches were therefore long and coarse. Approximately 100 such branches numbered according to position and age beginning with the base of the stem were obtained from each of the trees.

a. Tensile strength.

Analyses for ascertaining tensile strength have not been made since this characteristic is not considered as being of noteworthy importance in the manufacture of ground wood and chemical pulp. Because of knot wood being of denser structure and since the upper side of a knot consists always of tension wood, it can nevertheless be maintained that knot wood doubtless has much greater tensile strength than corresponding stem wood. Compression wood on the other hand is not particularly capable of withstanding stretching, as has been shown by Trendelenburg (1932) and others. The tensile strength and the modulus for tensile elasticity of compression wood amount to only 50 % to 60 % of what it is in wood of ordinary structure. This situation is explained by the fact that the fibrils in compression wood form a large angle to the direction of the increment.

As shown by Graf (1929) and others, the presence of knots affects tensile strength very materially. While the tensile strength of pine free of knots was for example 780 kg. per square centimeter, it was 384 kg. per sq.cm. for pine wood having an average amount of knots and only 119 kg. per sq.cm. for that having an excessive abundance of knots. The reduction in tensile strength for that having an average amount of knots was accordingly 51 % and for that having an excessive abundance of knots was as much as 85 %.

Sonntag has made investigations as to the tensile strength of the various parts of branch wood. He has found that the tension side of the branch, which is composed of tension wood, shows double the tensile strength of the lower side which consists of compression wood. Ursprung (1901) has likewise found that the wood in the upper side of a branch is much stronger as regards tension than wood in the lower side. Springwood in tension wood has double the power of resistance of springwood in the lower side of a branch and the difference in strength is still greater when it is a question of the respective divisions of summerwood. The investigations of Ursprung also concern spruce branches.

b. Compressive strength.

The compressive strength of wood in test pieces has significance only in cases where the length of the sample is a maximum of five times its diameter or when it is placed so that it cannot be bent (Lassila 1926). It plays a part in mining and piling work. Even in the ground wood pulp industry, the compressive strength of a knot can have theoretically certain significance since the knot in the grinding apparatus will often press at an angle against the grinding stone. In practice however the grinding pressure per square centimeter will never increase to such an extent that the maximum load will be reached. Because of the great stresses to which wood has been subjected during growth, compressive

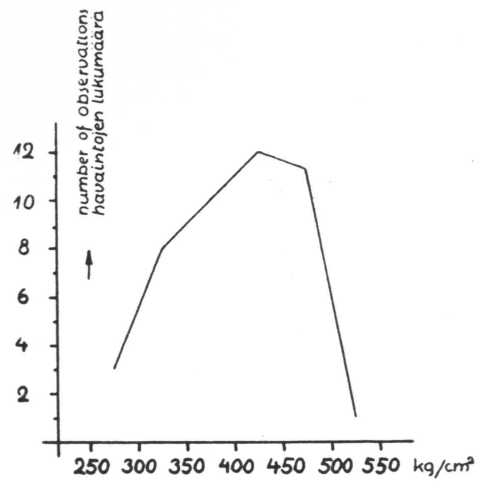


Fig. 61. Compressive strength of knot wood.
Kuva 61. Oksapuun puristuslujuus.

strength is different in the upper and lower parts of a knot. In the lower side containing compression wood, it is much greater, as has been shown by Metzger, Sonntag and others, than in the upper side which is formed for maximum tensile strength. The author has also attempted to show this by a series of strength analyses made at the Forest Technical Institute of the University of Helsinki. The results appear in the following graph They show clearly that compressive strength is directly proportional to the content of compression wood in the sample.

Sonntag has also found, similarly as the author, that the lower side (compression side) of a branch has greater power of resistance to mechanical pressure because of the abundance of dense compression wood than the upper side of the knot, the tension side. He explains that this difference depends upon the difference in anatomical structure and the sizes of the cells. Ursprung has likewise come to similar conclusions and he explains teleologically on the basis of a series of tests covering the compressive strength of tension and compression wood the necessity of nature in having tension wood on the upper side of the branch and compression wood on the lower side.

Branches do not affect the compressive strength of a section of a tree to nearly the extent that they affect tensile strength. Graf (1929) states for example that when the compressive strength of wood free of knots is 403 kg. per square centimeter, it is 361 kg. per sq.cm. for sections having an average occurrence of knots and 314 kg. per sq.cm. for sections which have an abundance of knots. The decrease in strength is accordingly 10 % and 22 % respectively.

c. Cross-breaking strength.

As has previously been presented, a branch, being a part of the biological unit which comprises the individual tree, is subjected during its period of functioning primarily to strains of a mechanical nature which take the form of a chronic bending load caused by the plagiotropic position of the branch and by the effect of the power of gravitation. As was already shown by Duhamel du Monceau (1738) in his tests of bending samples of wood, the neutral plane in bending is not the center of the sample but approaches more or less the most out-stretched surface. This phenomenon is particularly clearly exemplified by the increment process of the branch. Upon cutting through a branch it can accordingly be always verified, as has been previously explained, that the pith lies on the upper side. As has been maintained by Lassila (1926), cross-breaking strength can be considered as a combination of compressive strength and tensile strength. When a sample is bent upwards at the middle, the upper side becomes stretched and the lower side compressed. An analogous phenomenon in nature is the plagiotropic branch. Since compressive strength, as is known, is less than tensile strength and the lower side is subjected to heavy pressure while the upper side is subjected to tension, a branch should break on the lower side first and then on the upper side, but the situation in nature is exactly the reverse, as is well known.

Kollmann (1936) makes the following statement concerning the effect of knots on cross-breaking strength. »Allgemein ist zu sagen, dass die Unregelmässigkeiten des Wachstums bei auf Biegung beanspruchten Baugliedern nur dann die Festigkeit erheblich beeinträchtigen, wenn sie gleichzeitig in der Nähe des grössten Biegemoments und der Randschichten auftreten. Hier liegt ein Gegensatz zu gezogenen Teilen, in denen Äste und Wuchsfehler überall gleich gefährlich sind.»

Because of the heterogeneous structure of branch wood and the greatly varying properties of its various parts, it is difficult to calculate exactly its compressive strength and tensile strength. But since the plagiotropic branch is constructed because of physical necessity to have as great a cross-breaking strength as possible with a minimum amount of structural material, a series of analyses as to the variations in cross-breaking strength becomes of great interest. Cross-breaking strength accordingly varies within very wide limits depending firstly on how the compression wood is placed when making the test, ie., if the compression wood is on the tension or the compression side. And secondly, the proportion and extent of compression wood plays naturally an important role. The conditions mentioned in the foregoing are illustrated in the following tables explaining the bending strength analyses of branch wood which the author made of branch material taken from Ruotsinkylä.

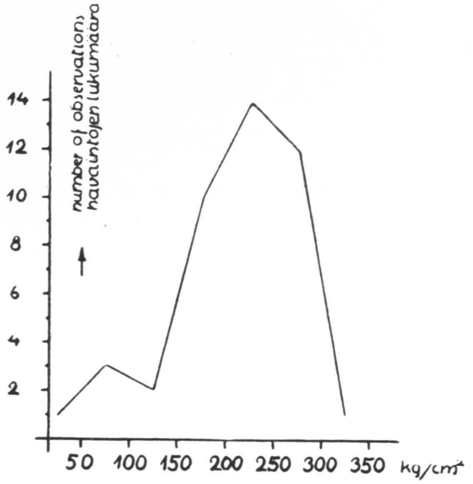


Fig. 62. Cross-breaking strength of knot wood. Compression wood on the compression side. — *Kuva 62. Oksapuun taivutuslujuus, lylypuu puristuspuolella.*

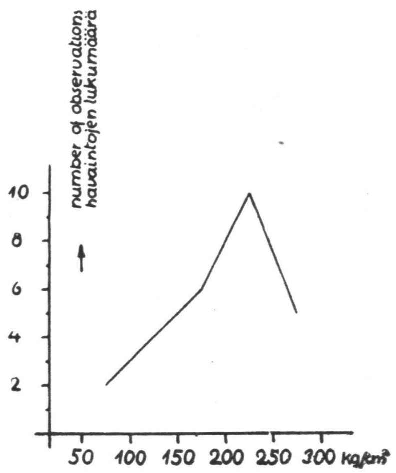
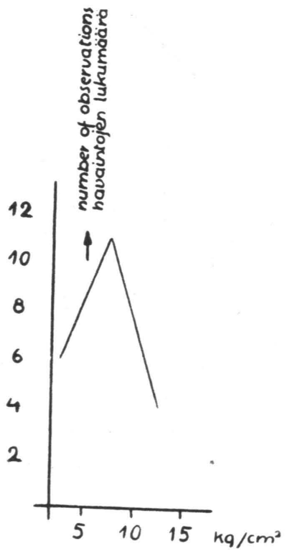


Fig. 63. Cross-breaking strength of knot wood. Compresson woodi on the tension side. — *Kuva 63. Oksapuun taivutuslujuus, lylypuu vetopuolella.*

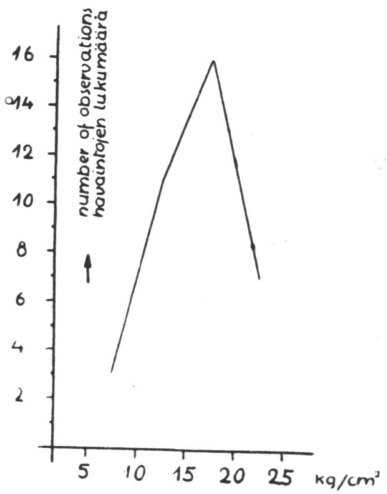
The foregoing table clearly shows that a branch bears its greatest load when it is in the same position, in relation to the direction of the load, as in nature, ie., with tension wood subjected to bending and compression wood subjected to pressure. The results agree with the investigations which Sonntag has made. He summarizes the results of his bending tests in the following conclusion: »Die Biegungsfestigkeit, speziell die Elasticitätsgrenze für Biegung des nicht homogenen Trägers, welchen die Ästen darstellen, wird durch diese Anordnung erhöht, aber nur in seiner natürlichen Lage in der Richtung der Schwere (bei Stämmen in der Richtung des Winddruckes)».

d. Tension perpendicular to the grain and cleavability

In the following section of the investigation as to the strength properties of wood, cleavability is understood as the stress required for splitting a sample along the grain so that the stress acts only on one end of the specimen like the impress of a wedge. On the other hand tension perpendicular to the grain implies that the sample of wood is divided in the direction of the grain by the stress affecting both ends of the sample. The tests were made with the Helsinki University's Amsler machine. The cross-section areas of the samples were 2 × 2 cm. The results obtained appear in the following table.



F i g. 64. Cleavability of knot wood. — *K u v a 64. Oksapuun halkeavaisuus repäisykokeessa.*

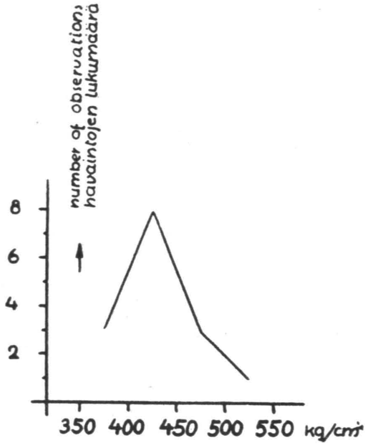


F i g. 65. Tension perpendicular to the grain, knot wood. — *K u v a 65. Oksapuun halkeavaisuus vetokokeessa.*

It is found that these strength properties are not affected to a great extent by the content of compression wood but correspond somewhat to the values presented by Ekman (1922).

e. Hardness.

As has previously been often mentioned, a particular characteristic of knot wood, especially on the side of compression wood, is its very great hardness. This can often be a detriment in production. In the sawmill industry it increases to a certain extent power requirements and produces wear on saws and planing machines. In the ground wood pulp industry it is on the other hand injurious and a hindrance since it increases friction against the grinding stone and accordingly adds to the time consumed and power requirements and causes a repeated sharpening of the stone.



F i g. 66. Hardness of knot wood.
K u v a 66. Oksapuun kovuus.

Hardness is usually determined, as stated by Janka (1909), in accordance with his adaptation of the Brinell method. This consists of sinking a hemispherical end having a diameter of 11.284 mm. and a projected area of one square centimeter, half its diameter in the surface of the wood. The required force is directly the figure for hardness in kilograms per centimeter.

As is well known, spruce is considered as belonging to soft species of trees and its stem wood according to Wijkander and Janka has a hardness of 280—300 kg. per cm. The hardness of spruce knots has as yet been investigated only to a limited extent. Brax (1936) has made in Finland measurements of hardness in order to ascertain the hardness of spruce pulp wood and its effect on the ground wood pulp process. He has found that knot wood and compression wood showed much higher figures for hardness than normal stem wood, and presents as examples figures between 320 and 350 kg. per cm. The author has also made a series of determinations of hardness with the Helsinki University's Amsler apparatus. The results, which are calculated for absolutely dry wood, appear in the following table.

It is accordingly found that hardness differs considerably in the various parts of branches and knots. The figure for hardness of compression wood is usually more than 400 kg. per cm. while tension wood shows a hardness figure varying between 300 and 350 kg. per cm. Mörath's investigations (1932) showing hardness to be proportional to density and to increase as the width of the annual rings decreases are accordingly applicable also as regards branch wood. It is also explainable that dense wood must show greater values for hardness than timber that is less compact as to its consistency.

f. Other strength properties.

Of the other strength properties, there are of primary interest shearing strength, torsion strength, shock-resisting strength and the endurance strength of wood. Because of the lack of suitable apparatus, these tests have had to be left outside the framework of this study. Upon the basis of available literature and previous investigations, the following points should also be applicable to knot wood. According to the investigations of the U.S. Forest Products Laboratory, the torsion strength of wood is dependent upon the content of moisture and the anatomical structure, and decreases with an increase in moisture content. Huber has found that torsion strength rises with an increase in density. As a result thereof the breadth of the annual rings is less suited for expressing this strength characteristic than the percentage of summerwood. Kollmann (1936) maintains that an increase in the content of medullary rays decreases torsion strength due to their lower power of resistance. The conclusion can therefore be drawn that because of the weight of knot wood it is relatively capable of withstanding torsion but that a great occurrence of medullary rays possibly lowers somewhat these strength values.

Schlüter and Winberg (1929) have found that density as a rule increases shearing strength. It can therefore be presumed that knot wood is relatively strong in this respect.

Because of the great elasticity of tension wood in knots, it can be presumed that this part of a knot shows great tenacity upon tests of dynamic strength such as test for impact and repeated shocks. It is furthermore known that the figures for dynamic quality as also for dynamic strength rise with increased density, as shown by Baumann (1922), Newlin and Wilson.

4. Survey of the mechanical properties of branch and knot wood.

Since branch wood is not homogeneous as regards its anatomical structure but is comprised of tension and compression wood because of certain physical demands, it is impossible generally to consider branches as a unitary whole when investigating their mechanical properties, and tension wood and compression wood must each be considered separately. These differ in many respects from each other, as will clearly appear from the foregoing.

If tension wood is examined alone, it will be found to be composed of wood of qualitatively very high value with great toughness and elastic-

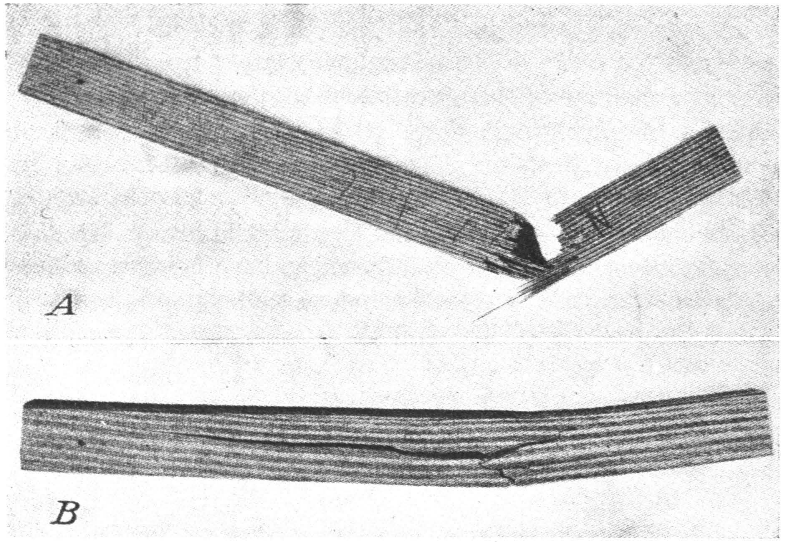


Fig. 67. Typical static bending failures of normal spruce stem wood.
Kuva 67. Kuusen runkopuun taivutusmurtumakohta.

Fig. 68. Typical static bending failures of spruce compression wood.
Kuva 68. Kuusen lylypuun taivutusmurtumakohta.

ity. Its tensile strength and cross-breaking strength exceed corresponding values for first-class stem wood and it is also somewhat harder than stem wood. On the other hand compression wood on the lower side of a branch is distinguished for its very great hardness. There would consequently be reason to expect, on the basis of Janka's theory, high strength values also for the other properties. This is however not the case. Because of the small sizes of the fibers and the non-parallel micellar structure, compression wood has relatively insignificant toughness and elasticity, and the great density and hardness is accompanied only by great compressive strength, while the remaining strength properties are appreciably less than those in stem wood.

If branch wood on the other hand is considered as a unit, it is difficult to draw any general conclusion regarding its strength because of its heterogeneous structure. The strength values obtained are influenced primarily by the extent and quantity of compression wood and by the position of the compression wood with relation to the direction of the affecting load. As a result of variation in elasticity, the broken surfaces accordingly become different in the nadir and zenith parts of a knot. In a cross-breaking test, the former part, which has dynamically more power of resistance, presents a split, particularly uneven and splintered surface while the fibers in the latter have been sharply broken off.

It can be maintained on the basis of the foregoing that knot wood as a rule has somewhat higher strength properties than stem wood. This applies particularly clearly to compressive strength, cross-breaking strength and hardness.

Where knot wood is found in large samples, it always has the effect of lowering strength properties with the exception of hardness, cleavability and shearing strength. The reason therefor is to be found in the divergent grain and the weakening of the physical structure of the wood caused thereby.

CHAPTER XII.

Chemical-physical properties of branch and knot wood.

Knots in sawn timber as well as in wood pulp stand out to the human eye primarily because of their divergent color characteristics, and knots of coniferous trees appear as a rule darker in color than the surrounding stem wood. The reasons for this condition are to be found principally in the differences in the anatomical structure of knot and stem wood. In this connection knots are conspicuous for their proportionately much greater percentage of summerwood fibers. While the annual rings in normal stem wood of spruce appear as dark concentric circles of summerwood with a lighter base of springwood, the increment in the structure of the annual rings in knot wood is characterized by the light, eccentric ellipses of springwood with a darker background of summerwood. This is a result of springwood in knots forming only a limited part of the wood content while the principal part of the mass consists of summerwood fibers. The reasons therefore are to be found in the phytonomical phenomena which were considered more thoroughly in connection with the origin and development of branch and knots. These appear in the hyponasty of branches and the development of tension and compression wood. Particularly the high content of compression wood appearing as dark, horseshoe-shaped arches on the lower side of the knot is one of the distinctive features for knot wood. Furthermore, knot wood is as regards its structure much denser and contains an appreciably smaller percentage of cavities; a condition which also gives it a darker tone color.

The chemical properties of knots also affect their color, and it appears as if a high content of lignin makes for a dark color in general. Pure lignin is in itself dark brown. Knot wood presents a considerably higher content of lignin than the surrounding stem wood, as has been previously ascertained. This appears in one way in the form of a brown coloration of the timber. Variations in the amount of resins and pentosans naturally effect also the color of knot wood.

The taste and odor of knot wood constitute primarily the reactions of its chemical properties, while the anatomical characteristics are in this connection of secondary significance. The higher content of resin in knot wood is of primary significance in this connection and gives rise to the more aromatic properties of knot wood. This is particularly characteristic of the small branches covered with needles, which, as is known, show the highest content of resin and fats. Among the remaining chemical-physical properties of special interest may be mentioned the differences between branch and stem wood which can be traced to the variations in concentrations of hydrogen ions. Branches are conspicuous for their considerably lower pH values, and, as a self-evident consequence thereof, branch wood is also as regards taste appreciably more acetous than stem wood. The degree of acidity appears to vary proportionately depending upon the size of the branch, its age and height above the ground.

As has appeared from the foregoing, chemical-physical properties constitute the result of numerous contributive factors. In this connection the chemical properties are primarily of decisive significance, but the structure of the wood, ie., its anatomy, can also affect color conditions. The taste and odor of Finnish spruce are of little importance since such spruce is used principally to satisfy the needs of the paper industry. The primary role played by these characteristics is in the manufacture of packing for the storing of food products. On the other hand, differences in color characteristics are of considerably greater significance. These affect decisively the grading and the valuation of products of the sawmill industry, and dark knots are generally regarded as greater defects than lighter ones. Even in the production of ground wood and chemical pulp a dark tone of color in the fibers is a factor to be considered. Because of their darker color knots accordingly affect color characteristics in the manufacture of ground wood pulp and bleached sulphite and sulphate pulp, and lower the appearance and value of the products. Due to the technical construction of pulp drying machines, these color differences appear primarily in the form of dark streaks and spots in the pulp line. The color of the wood plays on the the other hand no part in the production of unbleached sulphate cellulose and brown, cooked ground wood pulp.

Of the remaining chemical-physical properties, the tenability of wood against wear and tear and its value for fuel are of prime interest. As is known (Lassila 1930), the tenability of wood is affected by climatological, mechanical and chemical conditions and by fungus infections and insect damage.

Knot wood is in practice more susceptible to changes in climate than normal stem wood. This is due to its being more compact as regards structure than stem wood and therefore, as has previously been thoroughly ascertained, it shrinks and swells more than the more porous stem wood.

Since knot wood is formed in order to withstand greater physical loads than stem wood it also withstands mechanical wear and tear better. The reason therefore is to be found primarily in its denser structure and greater hardness. As has previously been presented, knot wood can be up to twice as hard as stem wood at the same height, and this makes it also more capable of withstanding wear and tear. It is accordingly found in a wooden floor, which has been used for a long time, that the knots have been worn away to a much less extent than the surrounding surface and are higher than the general surface of the plank or board.

Since knots contain a higher percentage of resins and incrustations than stem wood, they also have a greater power of withstanding the effect of various chemicals. This appears clearly in the cooking of cellulose, where it can often be ascertained that knotted chips are much more difficult to disintegrate. The reasons therefore have been thoroughly considered in Chapter X.

Finally, as regards fungus infections and insect damage, it has been found that soft timber generally moulders faster than hard timber and that insects demolish coarse-grained wood faster than fine-grained. It can be maintained in other words that knot wood is also in this respect more tenable and more permanent, but it should at the same time be observed that because of its greater tendency toward the formation of shakes knot wood opens greater possibilities for infections than stem wood.

Kollman (1936) has shown that coniferous trees as a rule have a greater value as fuel than broad-leaf trees, calculated in heat units per unit of weight. He also maintains that the value as fuel increases with an increase in the content of resin and lignin (species of trees having a high content of cellulose such as willow and poplar show a very low value as fuel since the value for cellulose is 4,150 kcal kg). There is therefore every reason to suppose that the presence of knots tends to increase the value of spruce wood as fuel, and it can be maintained that knot wood of spruce should show at least as high a fuel value as pine stem wood, based on what is known concerning the chemical composition of spruce knot wood.

CHAPTER XIII.

Investigations covering the relationship to one another of the various properties of branch and knot wood.

Like every other part of a living organism, branch wood must also follow certain, definite laws of nature. Its various properties accordingly influence the expression of each other in accordance with given rules. The coherence of the different functions has been the subject of interest since ancient times. Investigations covering research in wood technic were made already by Archimedes, Aristotle and Pythagoras as to the relationship between the structure of wood and its strength. Even in ancient Rome men of science were interested in such problems. The names of Cato and Columella may be mentioned in this respect.

The first person to give attention to the properties of branch wood as compared with those in stem wood was the Netherlander Musschenbroeck (1762). He investigated among other things how the strength properties of trees vary in their various parts, and what kind of wood is found in the stem portion free of branches and in the portion supporting the branches situated within the crown. He likewise investigated the relationship between strength properties in branch and stem wood.

Buffon (1825—1829) investigated the effect of the rapidity of increment on the strength properties of wood as well as the effect of the soil, the content of moisture and other factors. (Lassila, 1926)

The density of wood constitutes an accurate characteristic, as has previously been mentioned, in determining the quantitative yield which is obtained upon grinding into ground wood pulp or upon cooking cellulose. Due to the great and practical difficulties arising if wood is directly given a valuation based on weight, there appears to be reason for finding another procedure both suitable and in practice usable which well illustrates the condition as regards weight. When it is realized that density is the direct result of the anatomical structure, it is found that the macroscopic, structural characteristics are particularly suited to serve as a basis for the

classifying of timber by weight. The anatomical properties are identical with numerous, typically macroscopic features, of which especially the breadth of the annual rings, the content of summerwood, the taper of the tree or log and the presence of knots have been taken into consideration to a great extent as a basis for evaluating the suitability of wood for various purposes. Klem (1934) has set up a number of diagrams in which he has shown the bounded regularity of taper to density, the breadth of the annual rings to density and the presence of knots to density. He has found particular regularity as regards the relationship between taper and density. Burgman (1930) on the other hand finds a close relationship between the average breadth of the annual rings and the weight of the dry substance.

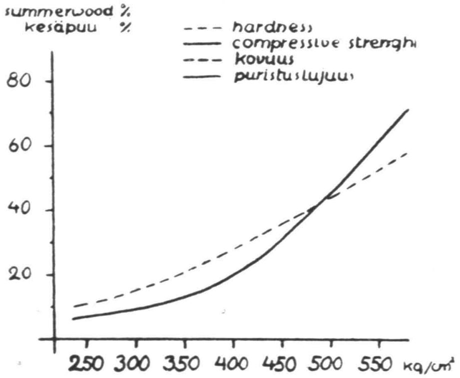


Fig. 69. The relation between the content of summerwood and the hardness an compressive strength of knot wood. — *Kuva 69. Kesäpuuosuuden suhde puun kovuuteen ja puristuslujuuteen.*

As will be observed in the author's diagram (see Fig. 31 pag. 101). there is a very close relationship between the percentage of summerwood and the average breadth of the annual rings. There is likewise a clear connection between the percentage of summerwood and the taper of a tree. The following diagram shows this series for all the material available for the present investigation. In considering that the percentage of summerwood constitutes a particularly apparent characteristic and that the content of summerwood is the anatomical property most clearly affecting the suitability of wood for various purposes, as has been shown previously in the chapter covering the mechanical properties of wood, it is consequently a good basis for evaluation.

There is also a close, direct relationship between strength and anatomical properties. The attached, graphic presentations illustrate that the content of summerwood stands clearly in direct proportion to the hardness of wood and to its compressive strength.

A close connection can be found in the chemical properties and the anatomy of wood. This depends primarily upon the various properties which are contained in summerwood and springwood and which have been pointed out by Montigny and Maass. There can accordingly be ascertained a relationship between the content of summerwood and lignin as well as between the former and the content of cellulose. The content of resins and incrustations in wood does not on the other hand appear to be influenced in the same degree by the amount of summerwood.

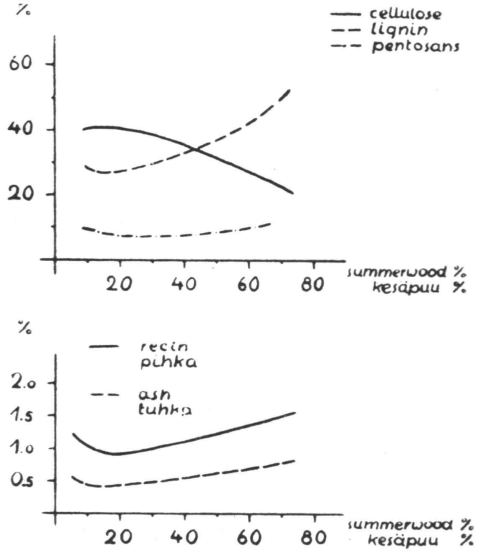


Fig. 70. The relation between the content of summerwood and the chemical properties. — *Kuva 70. Kesäpuuosuuden suhde puun kemiallisiin ominaisuuksiin.*

When it is realized that branch wood is composed to an essential degree of compression wood which has a great resemblance to summerwood as regards its chemical properties, it will be understood that the chemical properties of branch wood are affected to a great extent by its anatomical structure. The greater the proportion of thick-walled summerwood or compression wood cells containing incrustations, the greater is also the content of lignin and the less the percentage of cellulose.

Branch wood and knot wood vary appreciably as to structure, as has already been presented in the chapter covering their anatomical characteristics. Both the angle of declination of the branch and the age of the tree as well as the rapidity of increment operate in this connection in various ways. Upon examining the following graphic presentation covering variations in the chemical properties of the entire material for investigation, it will be found that these also present particularly wide divergence. The reason therefore can be easily traced to the unusually heterogeneous character of branch wood.

The chemical-physical properties of wood are a direct result of the physiological functions of various part of a tree and the demands of such functions on the anatomical structure. A high content of summerwood is accompanied by a dark color tone, while the phenomena of taste and smell are a result of the alimentary, physiological condition of the wood at the time of felling. If investigation is made on the other hand as to the manner in which the physical properties of wood affect the remaining properties, it will be found that there is a relationship only as regards anatomy. The physical and chemical properties as also the physical and mechanical properties are not on the other hand able to show a relationship to each other. To a certain extent however they influence the weight of the wood and its strength properties as well as also its properties as fuel.

CHAPTER XIV.

Comparisons of stem wood with branch and knot wood as regards their various properties.

There are in all respects appreciable differences, as has appeared from the foregoing, in the properties of normal, orthotropic stem wood on the one hand and in the plagiotropic branch wood within and outside of the stem cylinder and the wood of abnormal structure which exists around the knot in the stem on the other hand. These differences are due not only to anatomical structure, which is caused by the various physiological and mechanical functions of the axles of increment, but includes also the physical condition and the chemical consistency of the wood as well as its mechanical and chemical-physical properties.

Since studies concerning the quantity of knot wood in stems and the location thereof have shown that the compressed, structurally irregular wood caused by the occurrence of branches constitutes a relatively high percentage by volume of the entire stem which is used in production in sawmills and pulp mills, it may be justifiably maintained that the presence of knots constitutes one of the foremost factors in determining the technical quality of the raw material. When considering practical requirements, this situation shows primarily that the quality of wood need not necessarily be so varying as it as a rule appears to be but that by rational and appropriate measures of forest management it can to a high degree be improved upon and made more uniform. That such is the case is not something new, but when considering the practical and economic bearing of the question, this fact cannot be given sufficient emphasis. The main object of the present work has been to contribute by means of series of analyses and the presentation of tangible, illustrative material toward an understanding of the practical significance of the quality of wood and the effect of the presence of knot wood on the raw material value.

As has previously been presented, there exist a great number of publications covering the possibilities of bringing about by rational methods of

forestry wood which is as free of knots and as suitable technically and qualitatively as possible. In order that success in this respect may be attained, the principal requirement is that seedling stage stands and young forests be brought up as dense and even as possible. In spite of this causing a delay in mass increment to a certain extent, such forest management will nevertheless produce the most valuable yield, as can be proved. It can of course be maintained that the extensive wood working industry of the present day demands quantity primarily in order to satisfy its need of raw materials. Experience has however shown that the more advanced stages of manufacture having at its disposal present-day apparatus and technical means call for prime raw materials in order that the product shall have the required qualifications.

Upon undertaking a survey of the manner by which the occurrence of branches and knots affects the various properties of wood, it will be found that practically all characteristic features are influenced by their extent and volume. The extensive research of many investigators such as Klem (1934), Olberg and Kühn (1930), Mayer-Wegelin (1929, 1930, 1932 and 1934), Brunn (1932), Bentson (1930 and 1932) and others shows also that the occurrence of branches and knots is particularly well suited as a norm in determining the technical value of wood and is in this respect in many cases more accurate and more applicable in practice than a classification based on any other characteristic feature such as the breadth of the annual rings or density.

Of all the technical properties of wood, the presence of knots affects anatomical structure most clearly and tangibly. As regards knots in this connection the divergent grain, the differences in the position of the cell walls with relation to each other, the density of the wood, the average breadth of the annual rings, the content of summerwood and finally the size, shape and structure of the tracheids are of the greatest significance. Although these special features have previously been analyzed in detail, there is nevertheless cause for recapitulating in brief the effect that knots have on the anatomical structure of a stem and by presenting several practical examples to illustrate the importance of these changes in form upon the technical quality of the wood.

In the sawmill industry the presence of knots impairs the appearance of the product and its mechanical properties, and gives furthermore rise to the formation of cracks upon drying. In the production of ground wood and chemical pulp, knot wood furnishes inferior fiber material. The tracheids are particularly short and brittle and furthermore often cause a

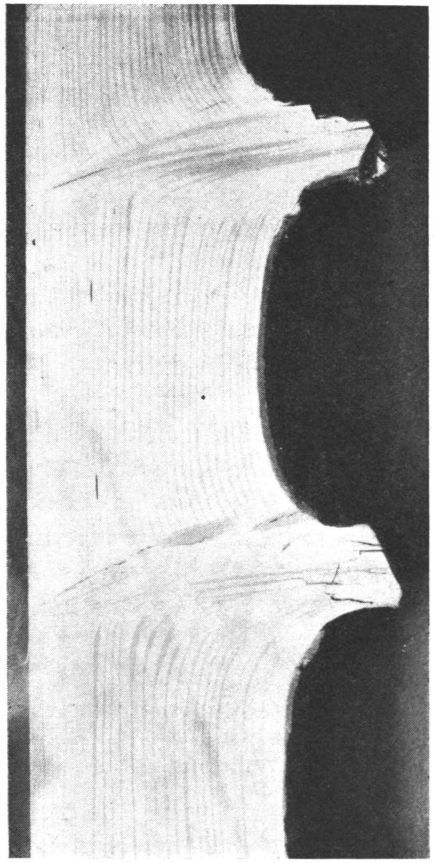


Fig. 71. Knots in rapid grown pulp wood (Scale 1 : 5). — *Kuva 71. Oksapuuta nopeakasvuisessa kuusipaperipuussa. (M.k. 1 : 5).*

coloration of the pulp. The divergent grain of knots can also increase greatly the friction against the grinding stone in ground wood pulp production and cause an added consumption of power and time. In the cooking of cellulose knot wood becomes impregnated with the cooking liquor much more slowly because of its great density than normal stem wood.

Due to differences in anatomical structure, the physical properties are also different in knot wood and normal stem wood. This is due partly to the difference in density and the position of the cell walls with relation to each other and partly to the structure of the individual tracheids. For this

reason the weight of knot wood can be as much as double that of the surrounding stem wood. As a consequence of the anatomical features, the content of moisture in knots and the changes in volume caused thereby are of a different nature than in stem wood and can give rise to numerous technical complications.

When regarded from the point of view of the raw material requirements of the cellulose industry, the chemistry of wood plays an important role. Since knot wood is to a great extent unlike stem wood as regards its chemical consistency, due partly to differences in anatomical structure and partly to alimentary-physiological circumstances and mechanical stresses, it can be presumed that the presence of knots very obviously affects the chemical uniformity of the raw material and its qualitative value. Upon determining the variations in content of lignin and cellulose, it is consequently found that the presence of knots and the content of compression wood are of appreciably greater significance than the breadth of the annual rings and the percentage of summerwood.

It has always been a known fact that the presence of knots affects the mechanical properties of wood and lowers the strength to resist mechanical stresses. This is due partly to the continuity of the rectilinear fiber walls being interrupted, with weaker transitional sections thus arising, and partly to the inferior strength properties of the knot fibers in certain respects. Uponde termining them echanical properties of branches and knots as well as upon scrutinizing their remaining properties, there is furthermore always reason for taking into account that knot wood is not at all uniform as to structure and that compression wood and tension wood have differences in structure, tasks and properties.

The remaining properties of wood, such as the physical chemical features, are also influenced clearly and incontrovertibly by the presence of knots and their extent. Studies as to the quantity of knots in stems have therefore numerous qualifications for giving a somewhat clear picture of the composition of wood with regard to the technical demands of production. In order that this contention may be verified by satisfactory evidence, there are also required, however, series of technical analyses of production and tests of manufacturing on a sufficiently comprehensive scale. The author has therefore made of the research material test grindings for ground wood pulp and series of cooking tests with corresponding material based on the sulphite and sulphate cellulose methods in order to prove the correctness of the assumptions presented in the present study concerning the technical nature of production. These studies as well as the observations and conclusions made in connection therewith, which constitute a direct result of the present series of investigations, are to be published in the form of a supplementary section to this work concerning the various properties of branch and knot wood.

Satisfactory norms for classifying the quality of pulpwood in accordance with the presence of knots in wood can be drawn up only on the basis of the results obtained from the technical tests of production. In order that such a valuation can have practical significance, the problems which arise in connection with the manufacturing process must also be fully considered.

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