

**METSÄNTUTKIMUSLAITOKSEN
TIEDONANTOJA**

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MEASUREMENT AND EVALUATION OF WOOD FUEL

Proceedings of the

I E A/BE TASK VI ACTIVITY 5 WORKSHOP

in Jyväskylä, Finland
October 25—27, 1989

JUHA NURMI & KEIJO POLET (ed.)

KANNUS 1990

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PREFACE

The new Implementing Agreement of the International Energy Agency (IEA) started on January 1st 1989. The agreement has three Annex Tasks which are in progress for three years. These are Improvement of Energy-Dedicated Biomass Production Systems (Task V), Biomass supply from Conventional Forestry (Task VI) and Improvement of Methods for Conversion of Biomass Feedstocks (Task VII). Task VI has seven activities, Activity 5 (Measurement and Evaluation of Wood Fuel) being one of them. The objective of this activity is to develop methods for sampling, measuring and determination of different properties of wood fuels on a practical scale.

The first Activity 5 workshop was held in Jyväskylä, Finland on October 25, 1989, followed by a two day field and laboratory excursion. Seven papers were presented from five countries. They represent a rather wide spectrum of interests and methods in the participating countries which gives a rather non-homogenous view of the activity. This, however, should be viewed as a benefit to the project, the participating institutions and individuals as it is bound to widen common knowledge on this field.

On the behalf of the IEA Activity 5 I wish to thank Jaakko Lehtovaara for the hospitality at Vapo Co., Veli Seppänen for the visit to VTT's Fuel and Combustion Laboratory as well as Imatran Voima Oy and Metsä-Botnia Oy. Thanks to Maire Ala-Pönttiö, Reetta Kolppanen and Sirpa Puranen for the valuable help in preparation of the meeting, Elva Nurmi for the language editing, and to Keijo Polet for being the co-editor of these proceedings.

Juha Nurmi
Activity 5 leader

CONTENTS

ANDREW BAKER:

Practices for sampling and testing wood fuel in the United States.....p. 4

ERKKI VERKASALO & JUHA NURMI:

Scaling of forest chips and chipwoodp. 7

LARS BJÖRKLUND, HANS FRYK & MATS NYLINDER:

Drying of wood samples in drying ovensp. 18

MIKE CARR:

An assessment of the fluidised bed combustion of chipped forestry wastep. 28

MARTTI FLYKTMAN:

An indirect method for the determination of fuel energy in district heating plants using wood and peatp. 35

RAILI VOIPIO:

Chemical composition of small-sized tree componentsp. 39

DAVE BOOCOCK:

The effects of chemical and physical characteristics of feedstock on wood liquefaction by steam/water pyrolysis.p. 56

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PRACTICES FOR SAMPLING AND TESTING WOOD FUEL IN THE UNITED STATES

INTRODUCTION

The practices for sampling and testing by large industrial users of wood fuel in the United States varies by geographic region, the source of the fuel, and type of industry using the fuel. The practices vary between regions because of the moisture content variations of the tree species of the regions, for example, the moisture content of western species can vary from 40% to 65% where as in the south eastern states the moisture content of all of the southern pines is nearly the same. The forest products industries purchase wood fuel in addition to using wood fuel from residues generated internally and the purchased fuel is sampled differently than the internal fuel. It was found that the forest products industry is less concerned about sampling and testing wood fuel than utilities that generate electricity from wood fuel.

The following are examples of sampling and testing practices of several industries. These examples indicate the range of sampling and testing practices being used.

INTEGRATED SAWMILL AND PULP AND PAPER MILL

Great Lakes Site

Internally generated, on-site sawmill wood and bark residue used for fuel is randomly checked for moisture content and the amount of fuel is estimated from the logs processed and lumber production. The on-site pulpmill wood-room residue used for fuel is not sampled but the amount is estimated from the amount of pulp wood processed.

Internally generated wood fuel from an off-site wood processing plant is weighed and random samples are taken for moisture content.

The amount of wood fuel used is estimated from the steam production and an assumed efficiency factor. A weighing device is available on the fuel delivery conveyer to the boiler but it is not used.

Western Site

Internally generated, on-site wood residue fuel from the sawmill and pulpmill debarker is not sampled. The quantity is estimated from the volume of logs processed.

Purchased fuel is weighed on the trucks. The delivery truck driver takes a 500 gram random sample from the truck load and he submits it with the delivery weight ticket. The moisture content is determined on the sample and payment is made on the weight of moisture-free wood. The fuel is then placed in storage. As the fuel is delivered to the boiler it is continuously

weighed on the delivery conveyer but no additional moisture content analysis is made. For boiler efficiency calculations an average moisture content is used.

PULP AND PAPERMILL

Pacific North West Site

Pulpmill No 1. — Wood fuel is purchased from several suppliers and delivered by truck and barge. The fuel delivered by truck is weighed. The truck driver takes on 500 gram sample through a small door located on one side of the truck. The sample is placed in a container labeled for that supplier. The moisture content is determined daily on the combined sample from each supplier. Payment is made on a moisture-free basis. Fuel that is delivered by barge is sampled by an employee from four locations on the barge for moisture content determination. The weight is determined by displacement of the barge.

Pulpmill No 2. — Fuel is delivered by trucks from several suppliers. An employee takes one random sample per day from each supplier for moisture content determination.

Southeast Site

Southern pine sawdust and bark is purchased for fuel. The delivery trucks are weighed but no samples are taken for moisture content analysis. The moisture content is assumed to be constant at a mutually agreed upon value.

LAKE STATES ELECTRIC UTILITY (15 MW)

Fuel is delivered by truck and dumped into a unloading hopper, screeded, and oversized pieces are hammermilled to size. A belt scale is used on this belt to measure the weight of each truck load of fuel. A direct-reading moisture analyzer is used in conjunction with this scale to determine the moisture content to determine the weight of moisture-free wood.

NORTH EAST ELECTRIC UTILITY (25 MW)

This utility purchases whole tree cips on a moisture free basis. The fuel is delivered in 48 foot (15 meters) trailers and as the fuel is unloaded a fixed cage in the unloading hopper automatically collects a sample from about 2/3 the distance from the back of the trailer load. After the truck is unloaded, a 500 gram sample is taken from the cage and used for moisture content determination. This is fairly new operation and they are still calibrating a volumetric feeder to the boiler by measuring the bulk density in a box of one cubic foot capacity. A moisture content monitor is mounted on the conveyor from the fuel storage to the boiler. This moisture content indicator is used to adjust combustion airflow. A moisture sample is also taken from the fuel conveyor belt once per day to monitor moisture content variation of the stored fuel and to measure the higher heating value. These values are used to estimate the efficiency of the system. If additional fuel is produced from brush piles and tree tops that are available after conventional logging operations it will be analyzed for ash content also.

PELLETIZED WOOD FUEL

Several wood pelletizing plants are operating in the U.S. making pelletized wood fuel from wood and bark residue from sawmill. The pelletizing process consists of hammermilling, scree-

ning, drying, and pelletizing with either a roller type pellet mill or with pellet puncher type press. The pellets are about 1 centimeter in diameter and 1 to 2 centimeter long. They are burned in specially designed domestic or school/hospital sized stoves and furnaces. The fuel is sold in 23 kg bags or delivered in bulk. The pellets are automatically fed to the stove or furnace by screw conveyers from a fuel hopper. The fuel feed rate and combustion air are controlled by a thermostat. The combustors tend to slag if the fuel does not contain fines from broken pellets. Quality control tests for the pelletizing fuel include ash, moisture, and strength. The strength test consists of measuring the amount of fines produced by tumbling the pellets in a standard test.

CONCLUSIONS

Sampling and testing of wood fuel in the United States is usually done only to determine the moisture content so that payment can be made on a moisture-free basis.

For most users, additional tests to determine fuel quality are not necessary at this time because most of the wood fuel comes as a byproduct from primary wood processing plants. The sawdust, shavings, and bark from sawmills that is the usual source of wood fuel is usually of uniform quality and subject only to seasonal variations in moisture content. This fuel is usually not subject to contamination except from accidental inclusion of soil if it is piled on bare ground. The utility that is burning whole tree chips does not have problems with ash content because the chips are burned in a circulating fluidized bed combustor. With other types of combustors the ash content in some sources of whole tree chips might be a problem during combustion.

Other primary manufacturing residues from particle board plants, plywood mills, and pulpmills do contain non-wood ingredients but so far these materials have not been a contamination problem. In some areas in the U.S. however, the combustion of particleboard manufacturing residues is not permitted in ordinary combustors. There is little experience however, to indicate how to combust wood containing non-wood combustibles or to know if there are problems due to combustion.

In the future as wood fuel is obtained from other sources and it is handled through wood fuel brokers there will be a need to monitor the quality more closely. Good examples of presently unutilized sources of wood fuel are from used wood pallets and post-consumer newsprint that has no outlet in recycling. In the near future, as we are trying to keep used pallets and used newsprint from the landfills, there will be more material that can be used or recycled. Combustion for energy recovery will be necessary to use the surplus. It will then be necessary to monitor the fuel for moisture content, ash, and suspected contaminants such as heavy metals.

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SCALING OF FOREST CHIPS AND CHIPWOOD IN FINLAND SOURCES AND UTILIZATION OF FOREST CHIPS

Reduction in the need of fuel wood and the resulting difficulties in the silviculture of young stands has caused an increasing growing stock of small-dimensioned, low-quality trees in Finnish forests since the 1960's. Since also the extensive Scots pine plantations and drained peatland forests from the 1950's and 1960's have, to some degree, already reached the age for the first thinning, the development of logging and utilization practises for small-sized trees has been one of the main tasks in Finnish forestry. It has resulted in the interpretation of "new" timber assortments, forest chips and tree sections on a practical scale. New is placed in quotation marks, because forest chips were actually introduced already in the 1950's to promote the demand of small-sized hardwoods.

In Finland forest chips are mainly made from whole-trees with tops and branches, to some extent also from logging residues and pulpwood of hardwoods, in particular aspen (*Populus tremula*) and grey alder (*Alnus incana*). In the early 1980's the allowable drain of commercial roundwood was 60.4 million m³/a (in 1987 67.1 million m³/a) (Yearbook of ... 1989). If it were totally harvested, a biomass reserve of 42.6 million m³/a of small-sized stems, tops, branches and stump and rootwood would be left in the forests. The technically and economically available reserve for forest chips is naturally lesser, 15.3 million m³/a (Table 1).

* paper presented by

Table 1. The available harvestable forest biomass in Finland which does not fulfill the present requirements for the dimensions and quality of industrial roundwood.

Assortment	Southern Finland	Northern Finland million m ³ /a	Total
Logging residues			
With foliage	3.50	0.83	4.33
Foliage	1.12	0.20	1.32
Without foliage	2.38	0.63	3.01
Stump and root wood	2.00	0.42	2.42
Small-sized whole-trees with tops and branches			
Sapling stands	2.53	0.73	3.26
First thinnings	0.79	0.23	1.02
Under-productive hardwood stands	5.10	0.44	5.54
Total	12.80	2.45	15.25

Reference: Hakkila 1984

Stands in which forest chip procurement is relevant, are describes as follows:

- Regeneration fellings in under-productive hardwood stands
- Liberation cutting of hardwood trees shading young Norway spruce stands
- Delayed cleanings of sapling stands
- First thinnings in thickets
- Logging residues from final felling areas

The best use of biomass reserves worth consideration is for energy production. However, some of the reserves can simultaneously be considered a raw material for the pulp, particle board and fibreboard industries. According to Valtanen (1981), 0.4 million m³ of the timber from the first thinnings and 2.2 million m³ of the timber from the under-productive hardwood forests mentioned in Table 1 should be reserved for industrial purposes. Especially in the long term, this is the Finnish policy: only the otherwise unmerchantable forest biomass should be converted to heat and electricity.

In the top year of 1982 the total consumption of forest chips was 646 000 m³, excluding small consumers (Hakkila 1984). About 60% was used by the 102 0.5—10.0 MW heating plants (Fig. 1a). Afterwards low-priced oil, coal and indigenous peat have superseded chips in several heating plants. Nowadays chips are used by only 60—70 heating plants, mostly thanks to their long-term contracts with the chip deliverers (Verkasalo 1988). Chips have maintained their status on farms with the annual use of 200 000—300 000 m³. About 20% of forest chips were used in the forest industry as raw material and another 20% as fuel in 1982 (Hakkila 1984). Since its introduction, the main industrial use has been in kraft pulping, where 6—10% of whole-tree chips are mixed in with the traditional pulpwood chips (Verkasalo 1989). Other pulp processes (sulphite, refiner mechanical) have not been able to use whole-tree chips at all. In 1988, a total of 170 000 m³ of whole-tree chips were used by 5 kraft pulp mills (Kuitto 1988). (Fig. 1b). The amount is expected to rise only slightly during the next years - partly due to the development of tree-section logging methods. After being given an enthusiastic recep-

tion in the beginning of the 1970's, forest chips are now used only occasionally by the particle board and fibreboard industries.

Even at its best, not more than 1/20 of the reserves for forest chip production has been utilized in Finland. Neither do the geographic distributions of the reserves and the utilization points correspond to each other, since more chips are utilized in the Northern part of the country than are situated there.

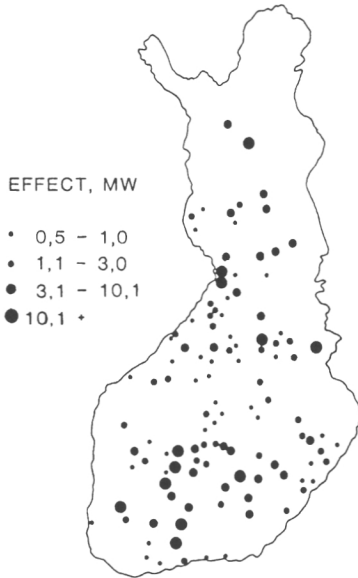


Fig. 1a.
The heating plants (excl. those for forest industries) that used forestchips in Finland at the end of 1982 (Hakkila 1984).

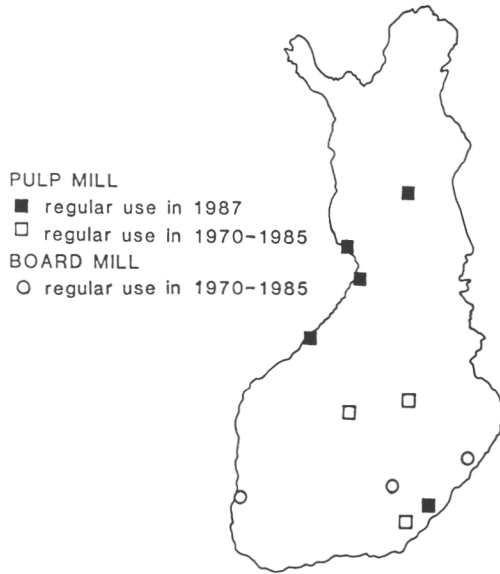


Fig. 1b.
The forest industries that used forest chips as a raw material in Finland at the end of 1987 and in 1970-1985 (Hakkila 1984).

AIMS AND PROBLEMS IN THE SCALING OF FOREST CHIPS

The scaling of forest chips comprises the acquisition of quantitative and qualitative information on chip properties. The properties of chips for energy purposes differ from those of chips for pulping. At the heating plants they are mostly interested in the dry weight, biomass composition and moisture content, which have the greatest effect on the heat value of the chips. In pulping dry weight and basic density are the most important chip properties. Moisture content is of very slight importance, but chip particle size, in particular chip thickness, and content of bark and inorganic impurities are critical instead.

This article concentrates on the quantitative properties of forest chips. They are needed for

- fixing purchase prices for chips and chipwood
- determining contract fees for cutting work, forest and long distance transport and chipping
- controlling chip amounts transported and
- comparing costs of various fuels.

The fundamental differences in wood chips compared with the scaling of roundwood are caused by the inhomogeneity of the material; fuel chips especially are often made up of various tree species with various proportions and of, in addition to wood (60—85%), also bark, foliage, twigs, buds and even cones (Hakkila et al. 1975). As a result, great difficulties exist in the determination of solid volume. Solid volume is still the chip property that has been strived for in

commercial scaling, even if it is actually of no importance from the point of view of the heating plant or the pulp mill. The reasons arise from the traditions of the Finnish timber trade: people are used to scaling and setting the price of timber on the basis of solid volume. In this situation the use of other scaling units for chips has been considered to cause confusion.

The solid volume of forest chips is in practice determined by the loose volume of chip load (scaling unit loose m^3) and a special conversion factor, solid content (m^3 solid/ m^3 loose) at nearly all the heating plants and all the pulp mills (Fig. 2). Alternative methods for solid volume determination are based on the measurements of uncomminuted chipwood. Scaling by standing trees is conducted by circular sample plot survey and counting the DBH:s of trees to be felled (Fig. 3). Scaling of piled chipwood at a road-side landing is in principle similar to that of delimbed pulpwood (Fig. 4).

Dry weight is the best meter for the commercial value of forest chips. That is why dry weight based on weight scaling and moisture content sampling should be used instead of solid volume. It would result not only in fairer pricing but also in encouraging the improvement of chip

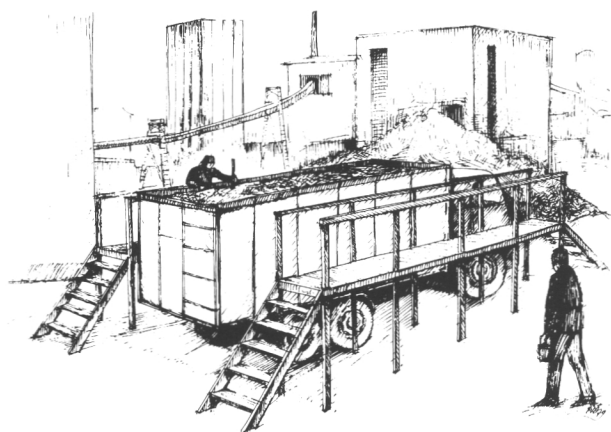


Fig. 2. Scaling of chips by loose volume at a pulp mill (Kanninen et al. 1979).

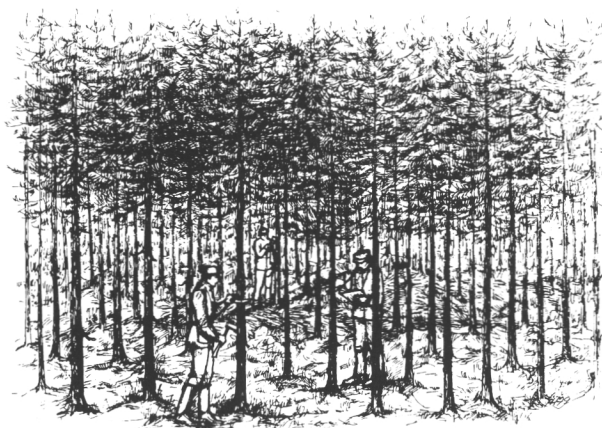


Fig. 3. Scaling of standing chip wood (Kanninen et al. 1979).

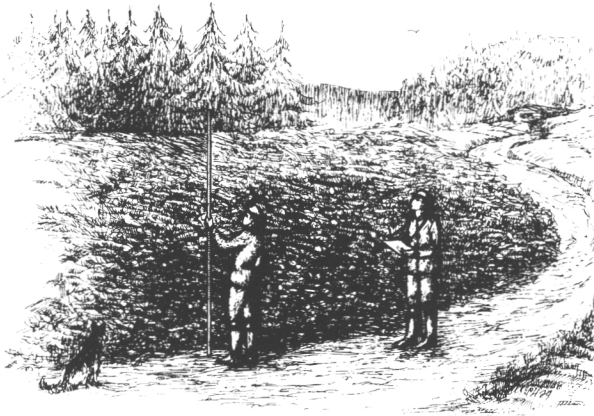


Fig. 4. Scaling of piled chipwood (Kanninen et al. 1979).

quality. Dry weight determination has been used at a few bigger heating plants some years already. On the whole, it has not become very usual mostly because of the following facts:

- the need and high expenses of weight scaling equipment: weight scaling service costs 30—50 FIM /load and a stationary weight scaling equipment costs 300 000—500 000 FIM including the foundation
- slowness and laboriousness of the measurement of moisture content and questionable accuracy of the results,
- difficulties in the conversion of dry weights to other scaling units (solid volume, effective heat value)

THE BASIS AND PRACTICE OF SCALING METHODS

The scaling of forest chips by loose volume

The measurement of the loose volume of a chip load is an uncomplicated, rapid and inexpensive measure, which is probably the most important reason for the popularity of the scaling of forest chips by loose volume. As the nominal dimensions of the vehicle load are known, only the measurement of the mean deficiency, or excess, in chip load height is needed. Regarding general truck and tractor loads of 25—60 loose m³, an error of 5 cm in the estimate of the height causes an error of only 2—3% in the measurement of loose volume.

Some heating plants determine the chip volumes as equal to the nominal load volumes. This results in a systematic over-estimate in the chip volume, even if the vehicle would be fully loaded in the forest. This is due to the settling of the chips by 2—14% during transport. The maximum solid contents for each chip type is reached in nearly every haulage, since most of the settling occurs during the first kilometers. That is why the measurement of loose volume should be done at the delivery point of the chips. The greatest risk for the validity of the results is the use of solid content factor, which is needed in the conversion of loose volume to solid volume. The average solid content 0.40 has been generally used. However, the true variation between chip lots has been 0.34—0.56, which means an error of -29—+18% in the estimation of solid volume.

The problem of solid content factor has been researched rather extensively in the Nordic countries in the 1970's and 1980's. As a rule, the softer the wood is the higher is the factor. Kanni-

nen et al. (1979) found the solid volume percentages of 42.1, 38.9 and 48.4 for pine, birch and alder whole-tree chips on arrival at a mill. Hakkila (1984) has recommended the solid content factors of 0.43 for pine, 0.39 for birch and 0.46 for alder in practice. Nylinder and Toernmarck (1986) have found the factors 0.39—0.43 for forest chips of oak and 0.42—0.48 for that of mixed tree species. Based on Nurmi's (1986) results, the approximate solid content for whole-tree and slash chunks is 0.33—0.35 and 0.40 for pulpwood chunks. Additional results have been presented by Gislerud (1974), Hovila (1981), Kalaja and Rantamaula (1982), Kuitto (1983), Metsola (1983), Pietilä (1984), Rantamaula (1981) and Uusvaara (1984).

The Finnish Forest Research Institute carried out a comprehensive research study on the factors affecting the solid content of forest chips in 1984—1985 (Uusvaara and Verkasalo 1987). The material consisted of 879 loads of chips comminuted by 10 different mobile chippers and of 10 kinds of chips. The solid content depended mostly on the chipper type and kind of chips (tree species and assortment), which accounted for 49.1% of the variation. The coefficient of determination (R-square) of the models to explain the variation improved only 5.4% units when other affecting factors (size and drying time of chip-wood, season of comminution, transport vehicle and distance) were included. The moisture content was also a significant factor, unexpectedly. This was mainly because of the varying solid content of fresh and seasoned chips.

The solid content factors measured were unexpectedly high compared with the former interrelation of the subject. This could explain the "shrinkage" of chipwood piles that have been observed in practice when comparing the solid volume results of scaling by loose volume method and pile method. The alternative explanation could be the wood loss during logging and transport, which is estimated to be 1—6%.

The recommendations on the estimation of solid content of forest chips were presented on the basis of the above and a supplementary study (Verkasalo 1987c) on measurement by loose volume at the delivery point (Table 2). The chip classification is based on chipper type, tree species and assortment of chipwood and season. The chipper type is defined by the comminution principle, which affects the chip particle size, and by the method of discharge.

In Finland a typical disc chipper with a blower at the back of the load is a TT 1500 LP and a typical drum chipper of that kind is a TT 910 R. Most of the mobile chippers comminuting chips for heating plants are disc chippers with a blower at the top of the load. The most popular makes are TT 1000 TU, Junkkari HJ 30 and Karhula 312 CS. TT 97 R and Erjo are drum chippers which have a similar loading method. Compared with, for instance, Sweden there are relatively few chippers that work on strip roads and unload the chips by tip-up to a multilift load. The TT 1000 TS disc chipper and the Bruks 1001 CT drum chipper are examples of this type of chipper. Three Lokomo MS 9 hammermill crushers, which have comminuted logging residues for the heating plants of the forest industries, have also been working in Southern Finland.

Scaling by loose volume is currently a standard method of scaling both forest chips for energy and for pulp and board production. The results are used to fix the definite purchase prices and the fees for comminution and transport of chips. In addition to problems with the conversion factors, the use of the method is hampered by the delay between the purchase and logging of chipwood and the delivery of chips.

Table 2. Recommendations on the solid content of forest chips by chipper type, treespecies and assortment in various seasons for scaling by loose volume at the delivery point.

Chipper type	Season	Wholetree				Tree length			Slash	
		Pine	Spruce	Birch	Alder	Pine	Birch	Alder	Fresh	Seasoned
		Solid content, m ³ solid/m ³ loose								
Disc chipper, blow from the back of the load	S	0.47	0.44	0.44	0.54	0.48	0.44	0.56	-	-
	W	0.50	0.44	0.46	0.54	0.51	0.44	0.56	-	-
Disc chipper, blow from the top of the load	S	0.48	0.44	0.45	0.54	0.49	0.43	0.56	-	-
	W	0.49	0.44	0.50	0.54	0.50	0.43	0.56	-	-
Disc chipper, tip-up	S	0.45	0.39	0.38	0.48	0.41	0.46	0.50	-	-
	W	0.48	0.39	0.43	0.48	0.42	0.46	0.50	-	-
Drum chipper, blow from the back of the loa	S	0.46	0.43	0.43	0.52	0.47	0.43	0.54	0.36	0.39
	W	0.49	0.43	0.44	0.52	0.50	0.44	0.54	0.38	0.41
Drum chipper, blow from the top of the load	S	0.41	0.39	0.40	0.52	0.42	0.40	0.53	-	-
	W	0.44	0.39	0.42	0.53	0.44	0.40	0.53	-	-
Drum chipper, tip-up	S	0.38	0.36	0.37	0.45	0.39	0.37	0.45	-	-
	W	0.40	0.36	0.39	0.45	0.41	0.37	0.45	-	-
Crush, belt conveyor	S	-	-	-	-	-	-	-	0.39	0.39
	W	-	-	-	-	-	-	-	0.39	0.3

The scaling of forest chips by weight

The aim in scaling chips by weight is to find out the dry material amount of the biomass delivered by weighing the chip loads and measuring the moisture content.

The loads can be weighed either with stationary equipment or with portable axle weight scales. An extremely good weighing accuracy of 0.5—1% is reached with stationary equipment, if the equipment is regularly calibrated and its surface is kept clear of ice and snow in winter. The ergonomomy is good as well, because no work out of doors is needed. Weighing with axle weight scales takes 6—40 minutes/load and the accuracy of the results is highly affected by external conditions (temperature, ground flatness) (Verkasalo 1987b). In addition, the ergonomomy is unsatisfactory in winter. Both the accuracy and the ergonomomy can be improved, if the weighings are done in a covered space, where the load cells have stationary places made of concrete, for example (Fig. 5). The low expenses are an considerable advantage: axle weight scales cost only 40 000 FIM/two load cells, which is only 1/10 of the purchase price of stationary equipment.

Electronic load cells installed below the loading spot of the timber truck have been introduced in the United States and France (Lewis 1987). Practical applications for chip transport might be possible, as well. A weighing unit costs approx. 20 000 FIM.

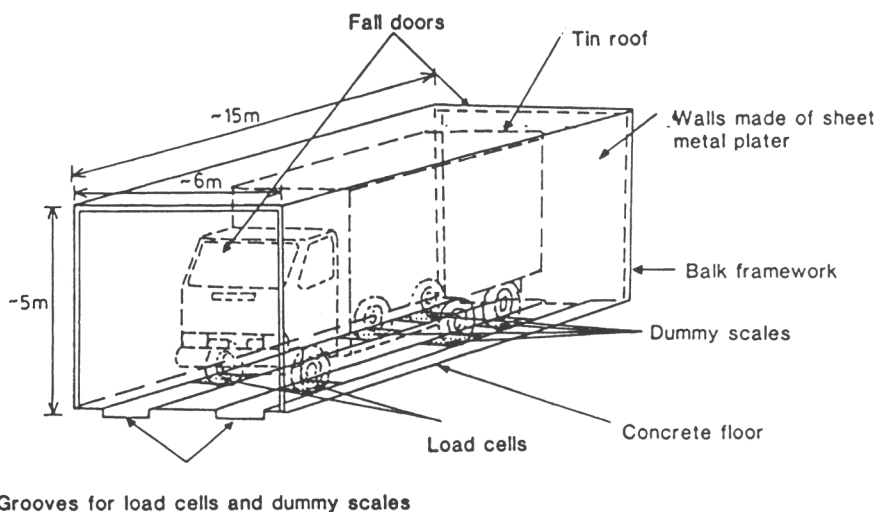


Fig. 5. An alternative to improve accuracy and ergonomcy for weight scaling with axle weight scales.

Weighing a chip sample in a box with a volume of 2 m³ has been tested to determine the green weight of a loose volume unit in the 1970's (Laine and Haapasalo 1981). In the box the weight per loose m³ was clearly lower than in the chip load and the ratio varied considerably. Therefore, the development of the method has been abandoned.

Moisture content in the chip load is measured by manual sampling. Because of the variation in biomass composition, ability to freeze, temperature, packing density and basic density, the continuous measurement of moisture content in a chip load by X-rays, infrared radiation etc. is not possible by currently used techniques. The number of sample units needed depends on the accuracy required and on the variation of chip properties (Table 3).

Table 3. The number of sample units needed per chip load to determine its moisture content by chip type and accuracy needed.

Chip type	Accuracy	required
	2%	5%
Number of sample units needed		
Fresh whole-tree and bole chips	3—9	1—2
Slash chips, seasoned whole-tree and bole chips	35—90	6—15

Reference: Verkasalo 1987a

In principle it could be possible to sample the chip loads by weighing and measuring the moisture content of a part of the loads for weight scaling of a chip lot. However, the variation in the basic density, and moisture content especially, of the chips comminuted of seasoned wood is so great that a sufficient accuracy cannot be reached by sampling. The question of minimum sample size, when the measurement lot is small, is also raised in connection with the feasibility of sampling. The smallest population for which the use of sampling would be profitable is at least 5 - 15, even 50 loads of chips comminuted of seasoned slash (Verkasalo 1987a).

The scaling of standing chipwood

Standing chipwood is scaled by a circular sample plot survey before felling. In this connection the DBH:s of all the marked trees, the heights and the crown lengths of the sample trees are measured. The timber cutter completes the scaling by noting the DBH classes of the trees felled by tree species. The solid volume of stem, tops and branches can be read in the tables, which have been drawn up separately for pine, spruce and hardwoods in Southern and Northern Finland (Kanninen et al. 1979)

The scaling of standing trees gives accurate results, at least of the stem volume. The basic information for setting contract prices for cutting work and haulage are obtained by chance. The scaling of standing trees is not naturally suitable for delivery cuttings. Some of the tops and branches also fall down during logging. This may result in an overestimation of 10—15% in the chip volume delivered.

Additional drawbacks in the scaling of standing trees are slowness and high cost, since despite the small spacing, the yield of chipwood per hectare is small. In the stands where whole-trees and tree lengths have been procured on the stump for fuel chips for heating plants the average yield was 41 m³ per hectare, the average timber volume being 245 m³ and the average area 6 hectares (Hakkila 1984). In general, the whole-tree stands for pulpwood procurement are more profitable.

The scaling of piled chipwood

The scaling of piled chipwood is conducted at a roadside landing by the measurement of frame volume and conversion to solid volume by a factor, solid volume percentage. In a technical sense the method is similar to that for pulpwood. However, the solid volume percentages are considerably smaller for chipwood piles than for pulpwood piles (Table 4).

The difference between the solid volume percentages is due to the branches, small diameter and excess length of the chipwood. These factors also cause an extremely great variation in solid volume percentage between the piles (Kanninen et al. 1979) Thus, the solid volume estimate is considerably more inaccurate than in scaling of standing trees and even in the scaling of chips by loose volume. However, the scaling of piled chipwood is a flexible and more inexpensive means than scaling standing trees. It is also suitable for delivery cuttings. The delay between the agreement and the measurement is clearly shorter than in the scaling of chips. That is why the scaling of piled chipwood is generally used to determine the advance and intermediate payments for the chipwood seller.

Table 4. Solid volume percentages according to various studies in Finland.

Assortment	Pine	Birch	Alder
	Solid volume percentage		
Pulpwood, length approx. 3 meters	63	54	54
Small-sized whole-trees, length 6—10 meters	28	23	14
Small-sized tree lengths, length 4 meters	50	44	41
length 3—5 meters	48	37	35
Manually stacked twigs, tops and branches		34—52	

Reference: Verkasalo 1988

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DRYING OF WOOD SAMPLES IN DRYING OVENS

INTRODUCTION

There is often a need of determining the amount of water in a wood material. The relation between the green weight and the oven dry weight of the material can be expressed as moisture content or dry matter content. The moisture content can be calculated on dry basis or on wet basis. One important use of these determinations is within the wood measurement where some assortments are paid according to their dry matter content. The wood samples are normally dried in drying ovens at 103°C. Properly working drying ovens and adequate drying times are essential for the result of wood measurement.

In this report drying of different assortments at different temperatures is studied. There are also temperature measurements done inside the drying ovens. The intention of the studies is to give some guidelines for the use of drying ovens in the wood measurement.

MATERIALS AND METHODS

Drying ovens, temperature measurements and wood materials

Temperature measurements were made inside eight drying ovens, four of them with an inner volume of 745 litres and four with an inner volume of 250 litres. The temperature was measured at five places and recordings were made every half hour.

The drying studies were made in the 745 litre ovens on the following assortments:

- * fresh sawmill chips from mixed softwoods
- * fresh spruce sawdust
- * fresh spruce bark
- * newly chipped two years old logging residues, 90% spruce
- * fresh drill shavings from tree sections, 80% spruce
- * fresh pine needles

The purpose of so many different assortments was to get different species, fractions and components represented in the studies.

* paper presented by

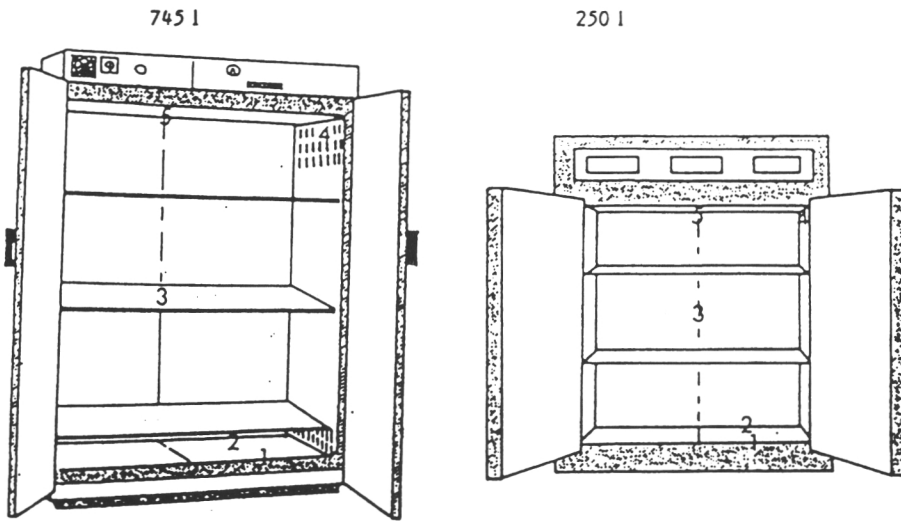


Figure 1. Five thermo elements were placed in each drying oven.

Drying tests

Standard procedure

Standard procedure means drying at 103°C. It was done with all assortments except needles. The samples were put in paper bags and control weighed every fourth hour. Each sample had a green weight of 300—400 g except for the sawdust samples which weighed 100 g each. Every standard procedure drying comprised a total of 60 samples, placed on three shelves in the drying oven.

An extra study was made with the samples in plastic cans instead of in paper bags. The comparison between paper bags and plastic cans is interesting since plastic cans are used at some scaling stations in Sweden.

Continuous drying

The continuous drying was started with 20 samples on the upper shelf. The samples on the middle shelf were put in after eight hours and the samples on the bottom shelf after another eight hours. This study was made with sawmill chips and drill shavings. All samples were dried in paper bags.

The intention of this procedure was to see if the drying is influenced when new fresh samples are put in the oven during ongoing drying.

High and low drying temperature

Two test series were made with drying temperatures 85°C and 120°C respectively. They were done with sawmill chips and with the same amount of, and size of, the samples as in the standard procedure. Two more studies with high temperatures were done by raising the temperature after concluded standard drying. Test temperatures were then 150°C.

Drying of needles

Needles contain more extractives than wood does. Needles may therefore be extra sensitive to wrong drying temperatures. A study was done where samples of 70 g fresh pine needles were dried at different temperatures. They were dried according to the following drying scheme:

Trial	1st 24h	2nd 24h	3rd 24h	4th 24h
	Drying temperature			
1	60°C	60°C	80°C	100°C
2	80°C	100°C	120°C	140°C
3	100°C	120°C	140°C	160°C
4	120°C	140°C	160°C	180°C

The purpose of 24 hours at each temperature was to reach a status of constant weight, which here means less than 0.1% weight loss per hour. At 60°C, 48 hours were needed.

Remoisturing

Two test series were done with the intention to see how quick samples take up moisture from the surrounding air when they are taken out of the drying oven. This is a potential error in DM-content determinations. Tested materials were sawmill chips and drill shavings.

RESULTS

Temperatures in the drying ovens

Results from the temperature measurements inside the ovens are shown in figures 2 and 3. Figure 2 shows three different temperature settings on the same 745 litre oven. The oven was filled with fresh (=moist) samples when starting the tests. Figure 3 shows four different 250 litre ovens. These were empty during the tests.

Figure 2 and 3 show that relatively big temperature differences can occur within the drying ovens. The temperature is as expected highest where the hot air comes into the oven which in these cases means at the bottom of the ovens. The highest temperature differences occur in the beginning of the tests when the samples are still moist. But even with completely dry samples differences of up to 10-15°C occurred. The preset temperature was normally closely related to the lowest temperature inside the ovens. It means that some of the samples might be dried at 10—15°C higher temperature than wanted.

Drying results

Standard procedure

Bearing in mind the knowledge about temperature differences inside the ovens, it might be interesting first of all to compare the drying on the different shelves on which the samples were placed. This is shown in figure 4.

From figure 4 can be seen that the quickest drying is on the bottom shelf. It is also closest to where hot and dry air comes into the oven. Figure 4 is about sawmill chips but the other assortments showed the same result. The difference in drying time between bottom shelf and

top shelf could be 4—8 hours. This means that one must be aware of where control samples are taken. Otherwise one might think that the drying is completed while there are still some moist samples at other places in the oven.

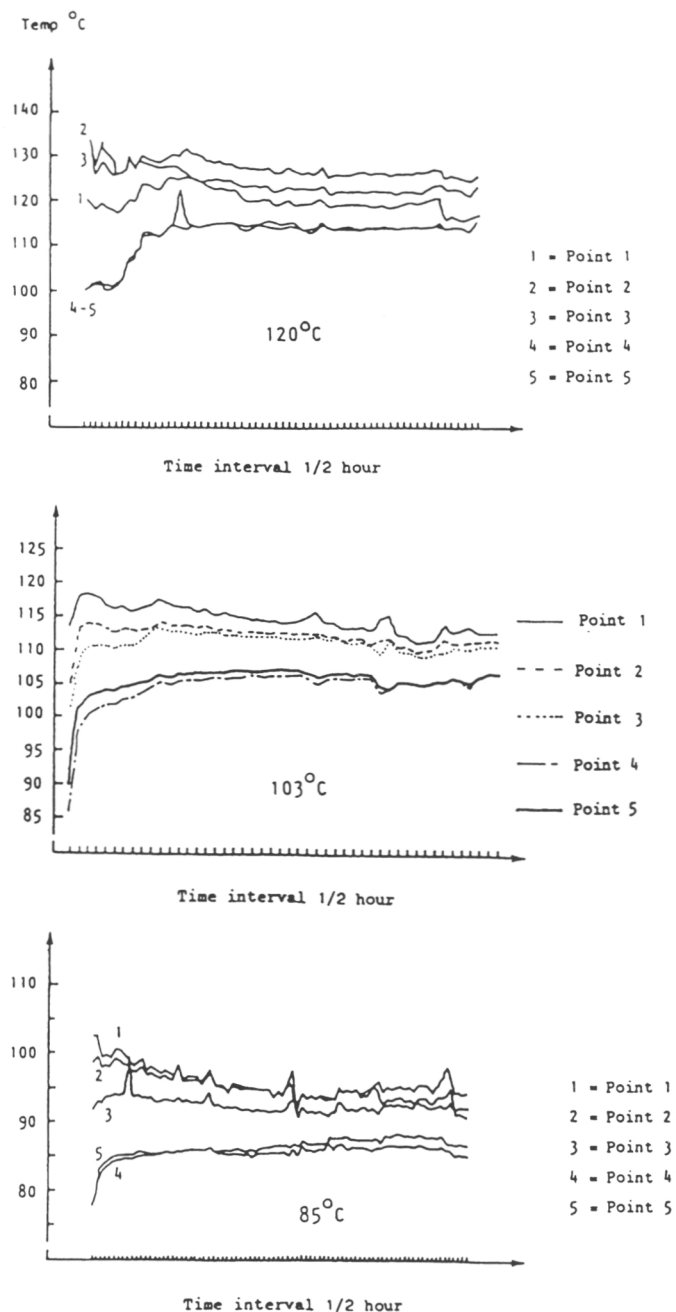


Figure 2. The temperature at five places inside the oven (see figure 1) and with three different temperature settings. A 745 litre drying oven filled with samples.

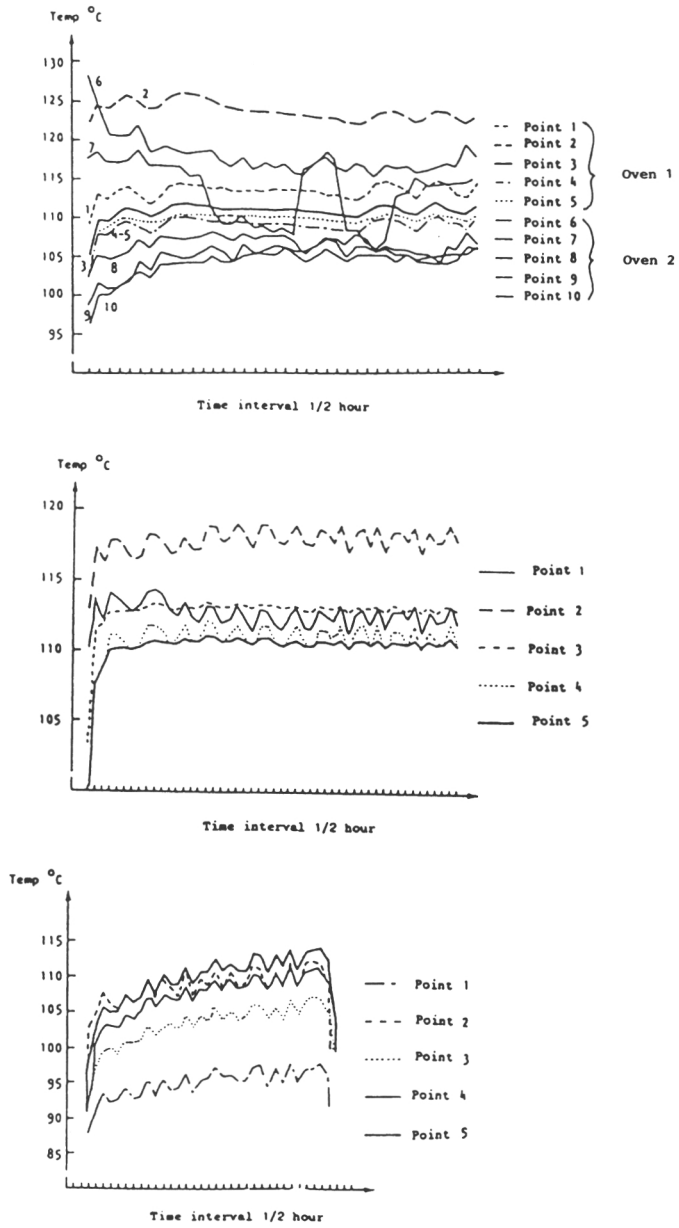


Figure 3. The temperature at the five measuring points in four different 250 litre drying ovens. Empty ovens and the temperature set at 103°C.

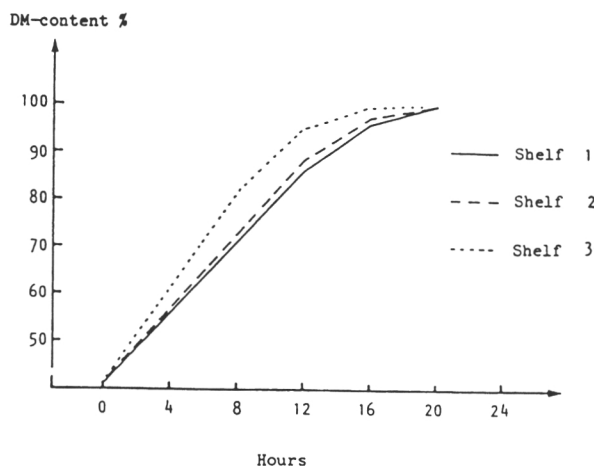


Figure 4. The drying on each of the three shelves in the drying oven. Average of ten samples on each shelf, sawmill chips.

As a result of this the following figures refer only to the top shelf (=the slowest one).

In figure 5 five different assortments are compared.

Drill shavings dried very rapidly but the samples were smaller than for the other assortments. Seen to the other assortments sawdust dried quickest, 16 hours, and logging residues slowest, 28 hours.

The comparison between drying in paper bags and in open plastic cans showed that plastic cans may well be used in routine measurements.

Continous drying

In this test series shelf two and three were filled with samples with eight and 16 hours delay respectively. The results are shown in figure 6.

Figure 6 shows that the drying on shelf one was not affected when new fresh samples were put in on shelf two and three. One reservation must however be made since there were four hours between the control weighings.

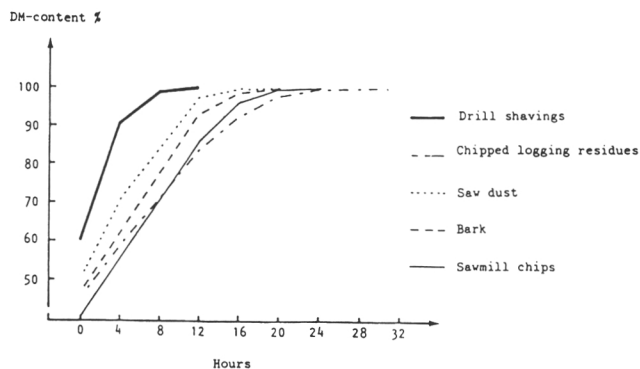


Figure 5. Drying times for five different assortments. Average of ten samples. Sample size 300—400 g except for drill shavings with 100 g.

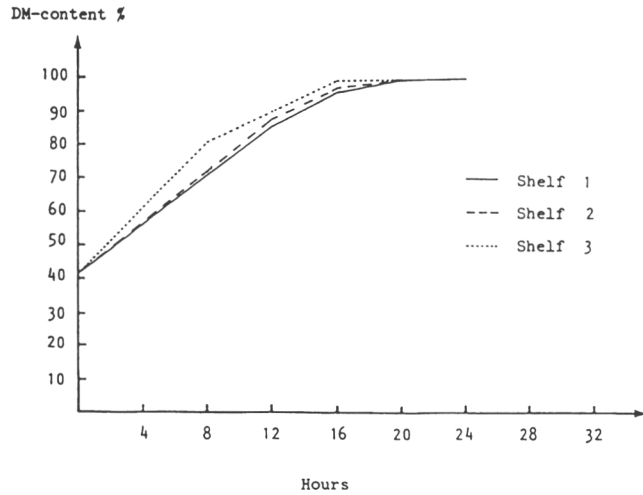


Figure 6. Continuous drying. Shelf two and three put in with eight and 16 hours delay respectively.

High and low drying temperature

Sawmill chips was dried at three different temperatures, 85°C, 103°C and 120°C. The results are shown in figure 7.

The temperature was, as can be seen in figure 7, very important for the drying time. At 120°C 16 hours were needed, at 103°C 20 hours and at 85°C 28 hours. Constant weight was reached at all three temperatures, it was only the time to reach it that varied.

Two studies were also made where the temperature, after standard drying, was raised to 150°C for eight hours. These studies were done on drill shavings and on chipped logging residues. The result was a very small extra weight loss compared to drying at 103°C, 0.3% and 0.5% respectively.

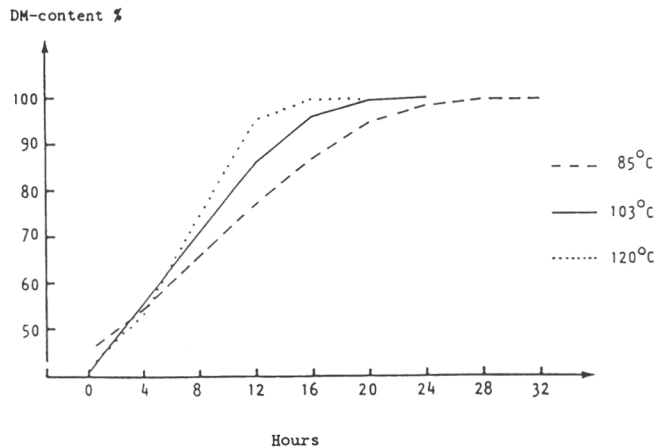


Figure 7. Drying of sawmill chips at three different temperatures.

Drying of needles

The results are shown in table 1 and figure 8. Relative DM-content 100% is defined as the result of 24 hours drying at 100°C. It corresponds to international standards and it is also the normal drying routine at many wood measurement stations.

Table 1. Relative DM-contents for needles after drying in different temperatures. DM-content after 24 hours in 100°C has been set to 100%.

Trial	1st 24h			2nd 24h			3rd 24h			4th 24h		
	°C	TH	K	°C	TH	K	°C	TH	K	°C	TH	K
1	60	92.0	-	60	98.9	+	80	100.1	+	100	101.5	+
2	80	99.7	+	100	101.0	+	120	103.2	+	140	105.4	+
3	100	100.0	+	120	102.1	+	140	104.1	+	160	107.5	-
4	120	103.2	+	140	105.9	+	160	110.8	-	180	118.7	-

TH= dry matter content in %

K = "constant weight" = less than 0.1% weight loss in one hour

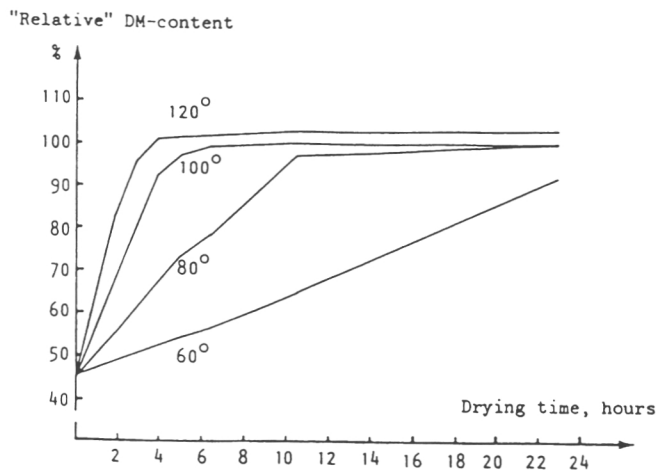


Figure 8. Drying during the first 24 hours, pine needles.

The following conclusions can be drawn from table 1 and figure 8:

- Constant weight is no guarantee for a correct DM-content. The study resulted in "constant weights" for relative DM-contents from 99% to 106%. It was only for temperatures above 140°C that constant weight was not obtained.
- Drying of needles at low temperatures give only small errors as long as the drying time is sufficient.
- Drying at too high temperatures gives overestimations of 2—3% at 120°C, of 4—6% at 140°C, of about 10% at 160°C and of about 20% at 180°C.
- When drying at 100°C a small time correlated weight loss can be seen. This weight loss is however so small that it does not exceed the definition of constant weight.

Remoisturing

Remoisturing, in normal indoor air, of sawmill chips and drill shavings is shown in figure 9.

Figure 9 shows that drill shavings gain moisture quicker than the sawmill chips. The study also shows that it is important to weigh the samples immediately when they are taken out of the drying oven.

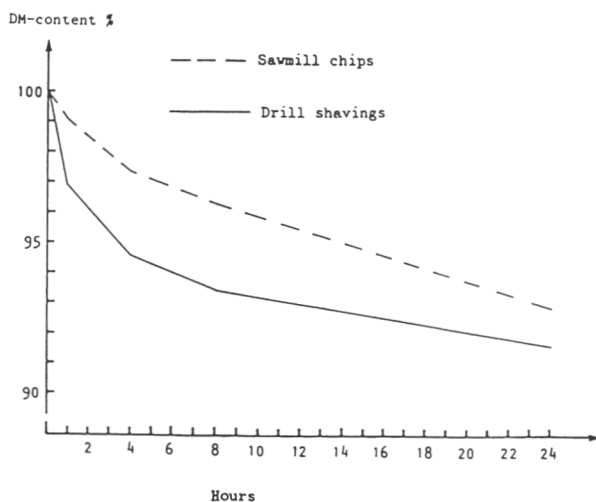


Figure 9. Remoisturing of DM-content samples. The samples were placed in normal indoor climate after being dried in a drying oven.

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**AN ASSESSMENT OF THE FLUIDISED BED
COMBUSTION OF CHIPPED FORESTRY WASTE****INTRODUCTION**

The Energy Technology Support Unit (ETSU) of the Department of Energy are assessing the potential for the utilisation of forestry wastes as a fuel in the UK. FEC Consultants have been engaged by ETSU to identify the technologies most appropriate for the industrial and commercial scale combustion of forestry waste as a partial or total replacement for coal in existing solid fuel combustion plant.

One possible method of utilising forestry wastes is to use fluidised bed combustion (FBC) technology. A short combustion trial was therefore carried out on an FBC test rig at the British Coal, Coal Research Establishment, which showed that forestry waste could be burnt satisfactorily in a suitably designed FBC boiler. However, further detailed investigation was required to analyse and refine various technical aspects in order that correct design data could be obtained.

This assessment of the fluidised bed combustion of forestry wastes examines the effects of variations in fuel quality, using computer simulation of FBC and boiler operation, based on Combustion and heat transfer models.

OBJECTIVES

The overall objectives of this theoretical study were:

- a) to investigate the effect of moisture content variations (in the range 20—60%) and the need for supplementary fuel firing or in-bed cooling for typical commercial FBC operating conditions.
- b) to investigate this effect of variations of over-bed versus in-bed combustion on the autothermicity for typical commercial FBC operating conditions.
- c) assuming a typical commercial coal fired FBC shell boiler design, to evaluate the effects of burning forestry waste on such a boiler.

METHODOLOGY

General

A typical dry basis forestry waste analysis was used throughout the study:

	%
Carbon	50.0
Hydrogen	8.0
Oxygen	39.2
Nitrogen	0.5
Sulphur	0.5
Ash	1.0
Cross Calorific Value	22 500 kJ/kg

The stoichiometric air: fuel ratios for the range of wood moisture contents studied are:

Wood Moisture Content	Stoichiometric air: fuel ratio
20%	5.69 kg/kg
30%	4.98 kg/kg
40%	4.27 kg/kg
50%	3.56 kg/kg
60%	2.845 kg/kg

In all cases, FBC performance was determined with an excess air level of 50%, due to the high oxygen content of the fuel. The above combustion air requirements fix the quantity of fuel which can be burnt per unit area of bed at the specific fluidisation velocity.

Autothermal Combustion

Autothermal combustion of a fuel in a fluidised bed is attained when the heat input from the fuel is sufficient to maintain the bed temperature at the fluid bed operating conditions, without supplementary fuel. Maintenance of bed temperature is important as it influences the efficiency with which the fuel is burnt, lower bed temperatures give lower combustion efficiencies.

The ratio of in-bed combustion is also a critical, and unknown, factor which affects Autothermal combustion of forestry wastes.

A computer programme that models the fluidised bed combustion system, by means of heat and mass balances, was used to predict the combustion performance of forestry wastes by varying the input data to allow for changes in fuel moisture content in-bed: over-bed combustion ratios and bed operating temperature.

The results of this simulation exercise are illustrated graphically in figure 1, which shows the limits of Autothermal and non-Autothermal operation for a range of bed operating temperatures, fuel moisture contents and levels of in-bed combustion.

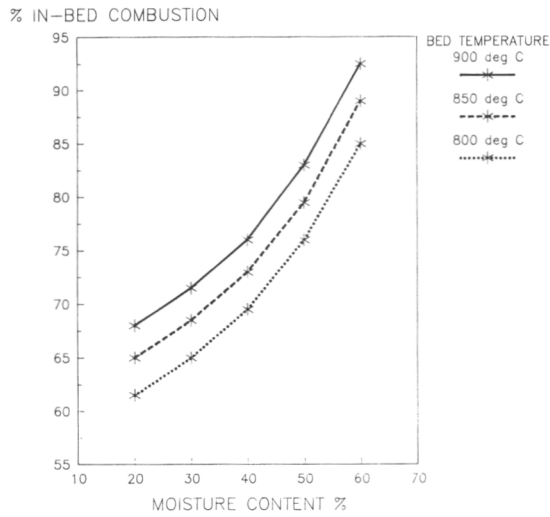


Fig. 1. Autothermal fluidised bed combustion of forestry waste.

In-bed Cooling/Supplementary fuel requirements

The same computer model was also used to predict the level of in-bed heat removal or supplementary fuel required for operation of an FBC at a constant bed temperature and fluidisation velocity over a range of fuel moisture contents and levels of in-bed combustion.

The results of this exercise are shown graphically in figure 2.

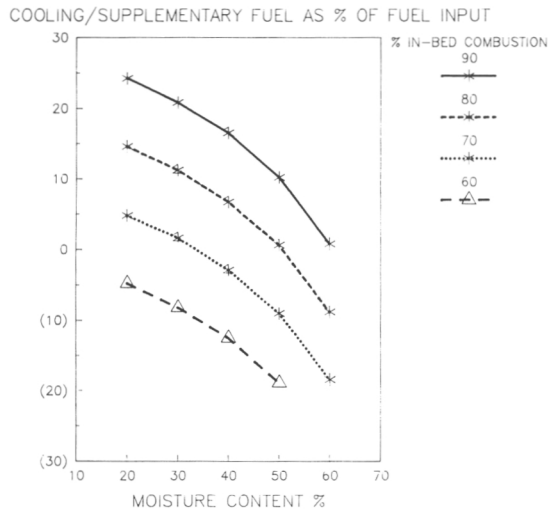


Fig. 2. Fluidised bed combustion of forestry waste in-bed cooling and supplementary fuel required.

Effect of Fuel Quality on Boiler Performance

General

As a basis for the evaluation, a coal fired fluidised bed boiler design was assumed, with a steam output of 5 000 kg/h and a fluidisation velocity of 2 m/s.

When considering burning forestry waste on such a boiler, there are certain aspects of the boiler design that are fixed and cannot be adjusted for a new fuel type. Other parameters are easier to modify in an economical manner and some parameters vary automatically as a result of the change in combustion conditions.

For the purpose of this study, it has been assumed that no major modifications to the original boiler design can be made. The only modification considered, is that of removing some of the in-bed cooling surfaces so that the bed temperature can be maintained for the lower grade wood fuel.

The following assumptions were therefore made:

- | | |
|--------------------------------------|---------------------------|
| • Bed Area | Fixed |
| • Convection Pass Heat Transfer Area | Fixed |
| • Fuel Firing Rate | Variable |
| • Steam | Variable |
| • Bed Temperature | Variable (between limits) |
| • In-bed Heat Transfer Area | Chargeable |
| • In-bed Heat Transfer | Variable |
| • Fluidisation Velocity | Variable |

Base Case Coal Firing

The following typical coal analysis and operating parameters were used:

	%
Carbon	67.0
Hydrogen	4.5
Oxygen	7.0
Nitrogen	1.2
Sulphur	1.6
Ash	6.7
Moisture	12.0
Cross Calorific Value	28 046 kJ/kg (as fired)
Stoichiometric Air: Fuel Ratio	9.02 kg/kg
Excess air level	30%
Combustion Efficiency	Bed Temperature
94.2%	800°C
95.2%	850°C
96.0%	900°C

The following assumptions were also used:

Steam Production Rate	5 000 kg/h
Boiler Efficiency	80 %
Bed Temperature	900°C
Fluidisation Velocity	2 m/s
Enthalpy of Steam	2 733 kJ/kg
Combustion Freeboard Temperature	900°C
Exhaust Gas Temperature	242°C

Based on the above data the following boiler design parameters were determined:

Coal firing rate	609 kg/h
Air flowrate	7 155 kg/h
Bed area (for 2 m/s fluidisation velocity)	3.302 m ²

Forestry Waste Firing

The computer model was first used to determine the maximum wood and air flowrates under autothermal combustion conditions for various wood moisture contents and combustion performance assumptions. Supplementary fuel firing was employed when the wood could not maintain autothermal combustion at the required bed temperature. The maximum fuel and air flowrates are limited by the fixed area of the bed.

The freeboard gas temperatures were then calculated. This freeboard gas temperature was then used to calculate the boiler exit gas temperature, using a shell boiler heat transfer model and the heat transfer area and configuration determined for the coal base case design.

The boiler exit gas temperature and combustion (determined by the combustion computer model) were then used to predict the overall boiler efficiency by the losses method, where

$$\% \text{ Gross Boiler Efficiency} = 100 \cdot A \cdot B \cdot C \cdot D$$

and

- A = % heat loss in dry products of combustion.
- B = % heat loss due to water.
- C = % heat loss through boiler casing.
- D = % heat loss through combustion inefficiency.

The gross boiler efficiencies and the maximum fuel input rates, determined earlier, were then used to calculate the actual steam production when firing forestry waste.

This simulation exercise was carried out for a range of moisture contents (20—60%), and levels of in-bed combustion (60—80%) for two fluidisation velocities (1 m/s and 2 m/s). The effects of forestry waste firing in the FBC boiler designed for coal firing are illustrated in figures 3 and 4.

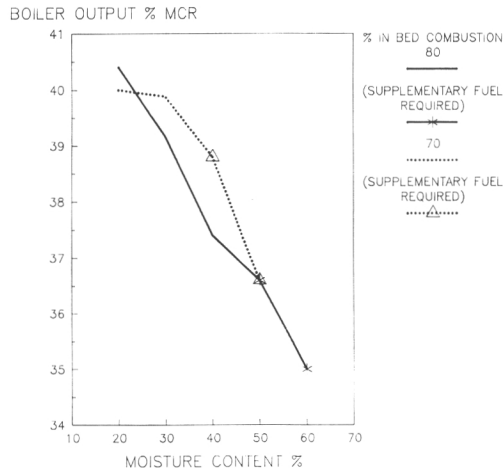


Fig. 3. FBC shell boiler outputs when firing forestry wastes.1 m/s fluidisation velocity.

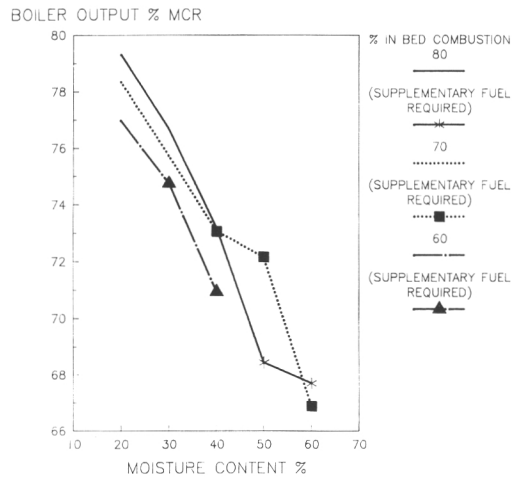


Fig. 4. FBC shell boiler outputs when firing forestry wastes.2 m/s fluidisation velocity.

CONCLUSIONS

Due to the fact that forestry waste is a lower grade fuel than coal, the degree of in-bed cooling required to maintain controlled bed temperatures is significantly less than for coal. Removal of the majority or all in-bed heat transfer area is required. In certain cases, supplementary firing of a premium grade fuel, in conjunction with the forestry wastes, is necessary to maintain satisfactory bed temperatures.

In all cases, both the boiler efficiency and output is lower than for the coal firing base case. Both boiler efficiency and output decrease with increasing moisture content and degree of over-bed combustion.

An FBC fired shell boiler specifically designed for forestry waste require both a greater bed area and convection pass heat transfer area than a coal fired FBC boiler design, to achieve a similar output and efficiency. Pre-heating of the combustion air may also be a sensible precaution to cater for high moisture contents and variables in the forestry waste fuel.

Additional Work Required

Further combustion test work is required in order to fully characterise fluidised bed combustion of forestry waste, particularly the effect of fuel moisture content and fluidisation velocity on the degree of in-bed combustion and also the effect of bed temperatures on combustion efficiency.

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AN INDIRECT METHOD FOR DETERMINATION OF FUEL ENERGY IN DISTRICT HEATING PLANTS USING WOOD AND PEAT

INTRODUCTION

In Finland there are more than 100 municipal district heating plants using wood and peat fuels. Forest chips are used as a fuel source to produce about 550 000 MWh per year in district heating plants. About 70 plants use forest chips as the main source of fuel. This means that a typical chip fired boiler is rather small (1—5 MW). Also wood wastes are used in district heating. The use of peat in district heating plants accounts for almost 1 500 000 MWh in 50 plants. Total use of the peat is about 10 500 000 MWh. Most of the peat is used in combined heat and power plants.

Conventionally fuel energy is determined by the direct method. By using the conventional method to determine fuel energy the weights of all fuel loads have to be measured and the fuel moisture content has to be analysed. Measuring fuel moisture content is very difficult because properties of fuel vary greatly. By using the conventional method to determine fuel energy many fuel samples have to be taken and also taken from the right place.

Because of the difficulties in determining fuel energy by the conventional method, a new method has been developed. In the new method fuel energy is calculated from produced energy and efficiency of the boiler. This new method to determine fuel energy is indirect.

FUEL ENERGY METHOD BASED ON PRODUCED ENERGY AND LOSSES OF THE BOILER

The new method is based on produced energy and on efficiency of the boiler. This is possible because of the development of digital process automation in district heating plant boilers. The advantages of the new method is that it is accurate, easy to use and also rather inexpensive.

The reliable use of this method requires that the conditions of the district heating plant are well known. First, the process automation of the boiler has to be digitally controlled. This makes it possible to gather enough information from the boiler. Secondly, the fuel has to come from only one fuel producer at a time.

By using this new fuel energy method the operation of the boiler is continually controlled by measurements from the process. Intentional falls in the efficiency of the boiler do not affect the price paid to fuel producer.

The efficiency of the boiler is based on DIN 1942 standard. In this standard losses are divided into the following groups:

- sensible enthalpy of flue gasses
- reaction enthalpy of flue gasses
- unburned in grate ash and fly ash
- losses by radiation and convection
- other losses

To determine the efficiency of the boiler the following entities are continuously measured from the heating process:

- output of the boiler
- flue gas temperature at balance limit
- temperature of combustion air
- temperature of fuel

In addition, the method naturally requires information about the boiler and the fuel. The analysis of the fuel has to give:

- elementary analysis (C, H, N, O, S)
- ash content
- moisture content
- heating value

The most important properties of the fuel are ash content, heating value and moisture content. This data has to be received from the fuel producer or seller and approved by the buyer.

The moisture content of the fuel can be analyzed and the result fed into the program. Small changes in moisture content are no cause for worry because small changes in moisture content do not seriously affect efficiency. If moisture content is measured continuously and reliably from the fuel, this measurement can be used in place of the manual system. Small changes in the elementary analysis (C, H, N) of the fuel do not have a considerable effect on the result.

Because losses in unburned grate ash and fly ash can not be measured directly these losses have to be measured by special testings. Also losses in reaction enthalpy of flue gasses have to be measured specially. Carbonmonoxide can also be directly measured and the losses calculated in the program.

The indirect method to determine fuel energy in district heating plant requires the following equipment:

1. Measuring equipment, from which computer can read measurements in given period.
2. A personal computer that has enough memory to collect data.
3. Programs for data handling and calculations.

COMPARING FUEL ENERGY METHODS

Methods differ from each other in principle — the conventional method is direct and the fuel energy method based on produced energy is indirect. In using the indirect method it is most important to measure produced energy as accurately possible. It is very important that all water circuits are included in the measurements.

In the conventional method both the weight and the moisture content of the fuel are very important for the accuracy of fuel energy.

The accuracy of flue gas temperature is usually measured at least to the nearest 2—5°C. The biggest errors in flue gas temperature usually occur when temperature is measured in the wrong place or equipment is poorly installed.

In district heating plants oxygen of flue gas is normally measured from wet gas. The most important factor is the placement of equipment for this measurement also.

Table 1 shows typical efficiencies of the boiler. The table shows that losses of sensible enthalpy of flue gas are largest.

By using the indirect method the accuracy of fuel energy is determined by combining errors in efficiency calculation and errors in produced energy. The efficiency of a boiler using peat and wood fuels can usually be determined with an accuracy of 1—2.5%. Normally the error in produced energy is less than 2%.

Table 2 shows accuracy of fuel energy determination in the method based on produced energy and on efficiency of the boiler.

Table 3 shows the accuracy of the conventional direct method.

In many cases, fuel energy can be determined with better accuracy by using the indirect method than by using the direct method.

Table 1. Typical efficiencies of the boilers.

Peat, grate combustion	
- efficiency	88—91%
- sensible enthalpy of flue gas	6—8%
- reaction enthalpy of flue gas	0.1—0.3%
- unburned in grate ash and fly ash	1—3.5%
- losses by radiation and convection	1.5—2.5%
Peat and wood, fluidized bed combustion- efficient	
- sensible enthalpy of flue gas	5—6%
- reaction enthalpy of flue gas	0.1—0.5%
- unburned in grate ash and fly ash	0.1—0.8%
- losses by radiation and convection	1.2—4%
Peat, grate combustion- efficiency	
- sensible enthalpy of flue gas	7—8%
- reaction enthalpy of flue gas	0.1—0.5%
- unburned in grate ash and fly ash	0.1—0.5%
- losses by radiation and convection	1—4%

Table 2. Accuracy of fuel energy using the indirect method.

Efficiency error, %	Produced energy error, %	Total error, %
1.0	1.0	1.4
1.0	1.5	1.8
1.0	2.0	2.2
1.5	1.0	1.8
1.5	1.5	2.1
1.5	2.0	2.5
2.0	1.0	2.2
2.0	1.5	2.5
2.0	2.0	2.8
2.5	1.0	2.7
2.5	1.5	2.9
2.5	2.0	3.2

Table 3. Accuracy of fuel energy using the direct method.

Error in weight %	Error in moisture %-unit	Error in heat value %	Total error %
1.5	0.5	1.1	1.9
1.5	1.0	2.2	2.7
1.5	1.5	3.4	3.7
1.5	2.0	4.5	4.7
1.5	2.5	5.6	5.8
0.2	0.5	1.1	1.1
0.2	1.0	2.2	2.2
0.2	1.5	3.4	3.4
0.2	2.0	4.5	4.5
0.2	2.5	5.6	5.6

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THE CHEMICAL COMPOSITION OF SMALL TREE BIOMASS IN FINLAND

INTRODUCTION

In 1987 the Finnish Forest Research Institute started a project in which the department of forest technology participates by researching the logging and technical qualities of small-sized tree biomass.

The pulp and paper industry views small-sized trees whose diameter at breast height is 4-12 cm as rather expensive raw material because of the proportion of bark and branches and above all because of high handling costs which arise as a result of traditional logging methods.

Small-sized trees could be more sensible utilized as raw material for energy purposes and in the chemical industry where the size of tree and the composition of biomass are not so important. However, at present the energy use of small-sized trees is unprofitable, although that may change in the future. Interest in chemical utilization and its development has recently increased.

MATERIAL AND METHODS

In the first phase research is being done to determine the quantitative amounts of the chemical main components of trees like cellulose, hemicelluloses, Klason-lignin, extractives and ash in different parts of the above-ground biomass of small-sized tree stands.

The study material was collected at Kannus in Ostrobothnia on the west coast of Finland. The examined tree species were *Pinus sylvestris* (Scots pine), *Picea abies* (Norway spruce), *Betula pendula* (European white birch), *Betula pubescens* (pubescent birch), *Populus tremula* (European aspen), *Alnus incana* (grey alder) and *Alnus glutinosa* (black alder). Two stems of each tree species were taken from mineral soil and in addition two stems of *Pinus sylvestris*, *Picea abies*, *Betula pendula* and *Alnus glutinosa* from peatland. The diameter at breast height was 10-12 cm.

Samples were taken from each tree as follows: stem at 20% height and 80% height, over 5 mm branches, under 5 mm twigs and foliage. Bark was removed from the samples. The outer bark was separated from the inner bark except for thin twigs. Two similar analyses were made from each sample.

Samples were kept in the refrigerator or freezer if it was not possible to debark them immediately after felling. Barked samples were dried at a temperature of 40-50°C and were chipped and homogenized into a fine powder (40 mesh).

The dry matter contents of the samples were measured before extraction. The results were

calculated as percent proportions of absolute dry matter. Because samples had to be stored for different lengths of time before extraction, the reliable analysis of monoterpenes (volatile oils) was not possible and they were therefore ignored.

Extraction was carried out successively in three organic and hot water solvents in the Soxhlet-apparatus in the order of increasing polarity of solvents: hexane-acetone-ethanol-water. The samples were dried overnight before the next solvent. After extraction the solutions were evaporated by rotavapor and dried in the oven before weighing.

The ash content of every sample was analysed by TAPPI standard n:o T211 om-85 (fired at 580°C for 3 hours).

The quantity of Klason lignin was analysed from extracted samples by the microlignin method (Efland 1977). The method correlates with the traditional Klason method but the size of sample needed is smaller (0.3 g).

The acid soluble lignin was analysed by UV-spectrophotometer using 205 nm wavelength (Tappi Standard 13-m54).

If the content of lignin in bark and foliage is determined only by Klason method the result will probably increase up to 70-80% of dry matter. This phenomenon is due to a lot of lignin type polyphenols and polyestolides (suberin) in bark and foliage which do not dissolve in 72% sulphuric acid and therefore disturb the analysis of Klason lignin. To get rid of these compounds study samples were extracted with a 3% KOH-solution. After extraction the Klason lignin content of alkali insoluble residue was determined by microlignin method (Efland 1977).

Cellulose and hemicellulose which are constructed of longpolysaccharide chains were determined by hydrolyzing the extracted samples with 72% sulfuric acid into monosaccharides. Hydrolyzed samples were neutralized with ion exchange resin (Dovex) and were chromatographed by HPLC which were equipped with Pb⁺⁺-ion exchange column and distilled water as eluent.

The disappearance of carbohydrates may happen during extraction when some parts of hemicelluloses could dissolve in ethanol or hot water. Watersoluble components of hemicelluloses are xylose and mannose units which include acidic acetyl groups. Disappearance of carbohydrates may be larger in hardwoods than in softwoods because of the greater amount of acetyl groups (Jensen 1977).

The heterogeneity of bark and foliage appears in the large variation of results. The difference is great at times even between parallel samples. To achieve exact results one should have several parallel samples and many trees taken from the same site. The results of this research are thus directional. After the quantitative stage, the focus of interest will be turned on the qualitative studies, using for example, a mass spectrometer.

RESULTS

The distribution of wood and outer and inner bark in different parts of tree species researched in this study are represented in Fig.1. The ratio between bark and wood matter is rather even except a couple of exceptions (spruce full tree, birch and aspen twigs).

Extractives

Organic and water solvents

The solvents (hexane, acetone, ethanol, water) used in the study were chosen mainly in order to get as varied a view as possible about the amounts of components soluble in different solvents. Secondly, we wanted the solvents to be relatively safe to handle.

The amount of extractives extracted from wood matter is relatively small if compared with the amount of extractives got from bark and foliage (Table 1). When the amounts of extractives are calculated as proportions of weight of different parts of tree biomass, we found that the amount of extractives that exist in wood matter is even larger than that in bark and foliage (Table 2).

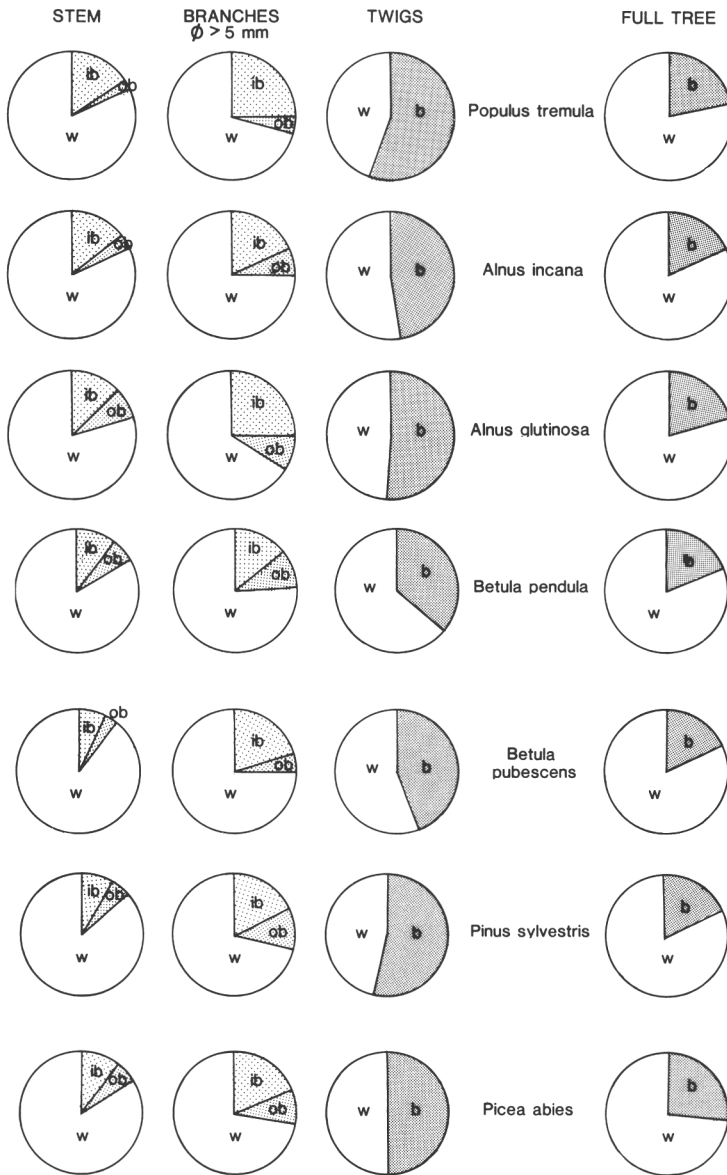


Fig. 1. The division of wood and bark in a different parts of tree.

Table 1. Organic and hot water extracts of different tree species.

Tree species	Stem 20% height			Stem 80% height			Branches >5 mm			Twigs	Foliage	
	Wood	Inner bark	Outer bark	Wood	Inner bark	Outer bark	Wood	Inner bark	Outer bark	Wood	All bark	
<i>Populus tremula</i>	3.2	18.7	24.4	4.5	20.5	25.2	8.6	18.9	19.8	14.8	19.5	25.4
<i>Betula pubescens</i>	4.4	21.3	33.2	5.8	23.7	29.6	6.8	29.0	24.1	9.1	23.9	32.5
<i>Betula pendula</i>	4.2	18.8	31.6	5.8	18.9	32.7	7.0	19.5	26.5	8.2	20.5	33.4
<i>Alnus incana</i>	4.4	20.4	27.8	7.5	38.2	39.0	7.3	21.3	22.7	11.3	22.5	28.3
<i>Alnus glutinosa</i>	4.8	17.9	14.3	5.5	20.4	22.4	6.2	24.2	24.6	7.2	21.1	27.6
<i>Picea abies</i>	3.5	37.4	23.4	5.4	38.7	20.9	6.0	30.5	17.0	9.6	26.4	43.3
<i>Pinus sylvestris</i>	5.0	39.5	15.9	5.6	44.4	23.3	9.1	43.4	28.4	14.1	39.9	40.6

Table 2. The content of extractives in different parts of trees in proportions to weight.

Tree species	Stem 20% height			Stem 80% height			Branches >5 mm			Twigs	
	Wood	Inner bark	Outer bark	Wood	Inner bark	Outer bark	Wood	Inner bark	Outer bark	Wood	All bark
extractives %											
<i>Populus tremula</i>	2.8	1.9	0.8	0.4	1.2	1.7	0.9	2.0	2.1	0.6	0.7
<i>Betula pubescens</i>	3.9	1.7	1.3	0.3	1.3	1.6	0.5	2.1	1.8	0.7	1.9
<i>Betula pendula</i>	3.8	1.3	0.9	0.4	1.3	2.2	0.2	0.5	0.7	0.2	0.4
<i>Alnus incana</i>	3.9	2.1	0.5	0.7	3.4	3.5	0.7	2.1	2.3	0.6	1.1
<i>Alnus glutinosa</i>	4.2	1.1	1.7	0.6	2.0	2.1	0.4	1.1	1.2	0.2	0.4
<i>Picea abies</i>	2.9	3.9	1.7	0.3	2.6	1.4	0.5	2.5	1.9	2.9	7.8
<i>Pinus sylvestris</i>	4.5	1.5	1.0	0.4	2.8	1.5	0.6	2.9	1.9	1.5	4.3

The difference between hardwood bark and softwood bark can be seen in the varied distribution of extractives (Fig. 2 a,b,c,d). The extractive content of the inner bark of softwood is remarkably larger than that in the outer bark while in hardwoods, except in birch, the extractive content both in the outer and inner bark is rather similar. On the other hand, the extractive content of birch outerbark is rather high compared with that of inner bark. This phenomenon is due to compound named betulinol (which accounts for even 30% of the dry matter of birch

outer bark). Betulinol is triterpene in structure and dissolves in hot organic solutions. The white colour of birch outer bark comes from betulinol (Jääskeläinen 1982).

Alkalic solvents

Suberin is a typical compound especially in the outer bark of *Quercus suber* and birch species (suberin content may be more than 50% of abs. dry matter). It is composed of several monocarboxylic and dicarboxylic aliphatic acids and in some species phenolic constituents may be part of suberin complex. On the other hand the suberin content of inner bark in birch and other tree species is only 2-5% of dry matter.

As mentioned earlier bark and foliage samples were extracted by alkalic solution before lignin analysis. The solution used was according to Ekman (1983) appropriate to the determination of suberin. In table 3 we observe that the results of the outer bark of birches, rich in suberin, differ clearly from the results of the outer and inner barks of other tree species.

Nurmesniemi et al. (1983) isolated a phenol fraction of 22% of abs. dry matter from inner bark of birch using 1%NaOH-solution. The alkali-insoluble fraction was further analysed by Klason method yielding 4,5% of lignin. There was no sign of any alkalisoluble lignin during the analysis. Another alkali extraction analysed from the inner bark of birch (Pulkkinen and Nurmesniemi 1980) yielded 25% of phenolic acids calculated from dry bark matter. The extractive solvent was 24% KOH but no lignin determination was carried out from the residues.

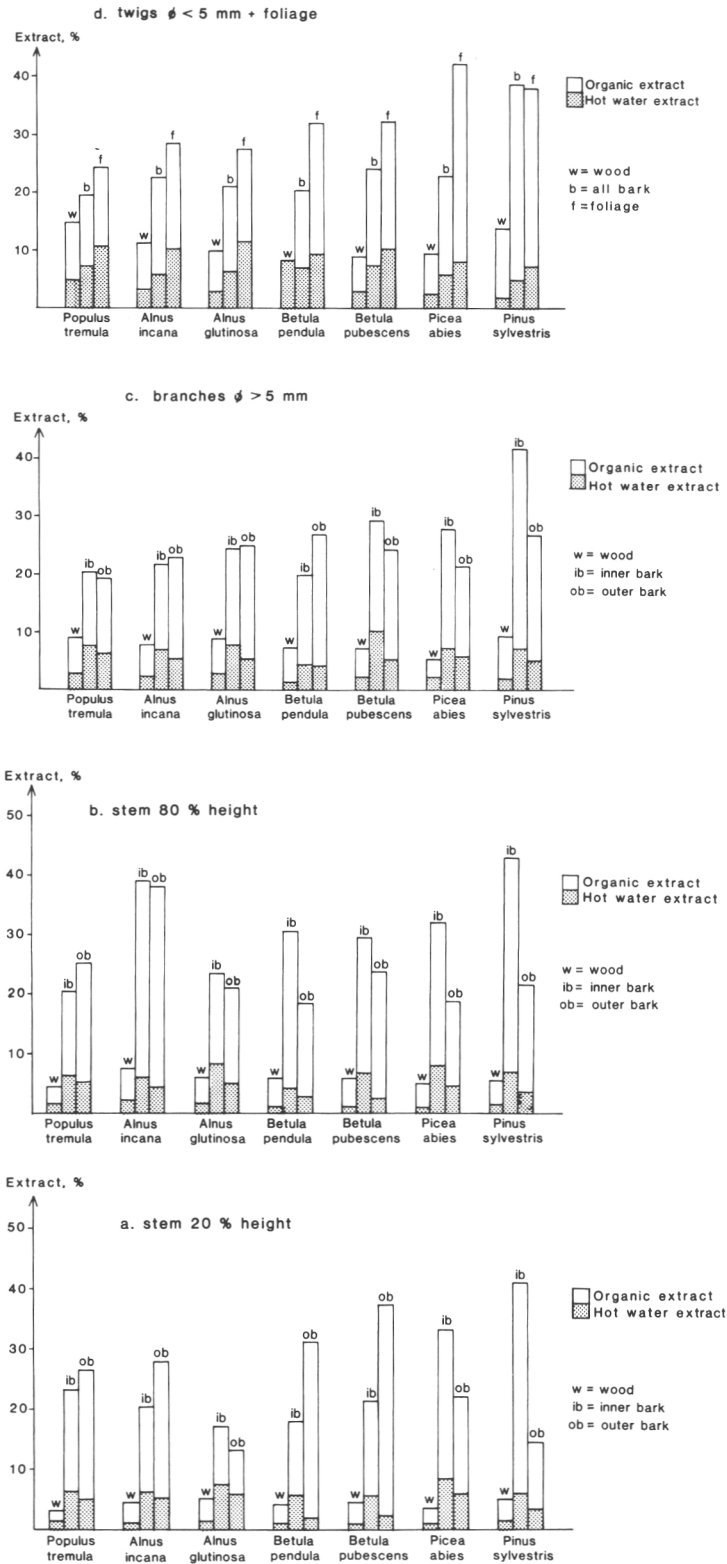


Fig. 2. The content of organic and hot water extracts in the different parts of small-sized trees.

The results of the alkalisoluble extracts of birch inner bark in table 3 are slightly lower than Nurmesniemi's. The difference may be the result of a lower pH of the alkalic solution used in this analysis.

Table 3. The proportion of alkalic extracts in the dry matter of bark and foliage.

Tree species	Stem 20% height		Stem 80% height		Branches > 5 mm		Twigs < 5mm	Foliage
	Inner bark	Outer bark	Inner bark	Outer bark	Inner bark	Outer bark	All bark	
alkalic extracts %								
<i>Populus tremula</i>	26.9	22.6	16.7	25.5	26.1	26.0	22.5	28.1
<i>Betula pubescens</i>	15.3	55.0	15.5	57.0	17.7	54.7	36.6	25.6
<i>Betula pendul</i>	14.1	46.3	14.5	45.6	18.5	44.6	33.0	23.9
<i>Alnus incana</i>	14.2	20.5	19.5	36.9	24.1	37.5	29.9	25.2
<i>Alnus glutinosa</i>	16.4	24.0	14.5	32.2	18.2	34.4	29.9	22.8
<i>Picea abies</i>	15.2	18.8	17.6	16.0	24.5	18.3	19.7	13.0
<i>Pinus sylvestris</i>	18.8	18.9	19.2	26.7	21.1	30.7	24.4	17.7

Because of the heterogeneity of bark, many different factors have an effect on its chemical composition, for example growth site, season, storing circumstances, age of tree, etc. Acetyl groups connected with hemicellulose molecules may increase the yield of alkalisoluble extracts. These groups can split off from the polysaccharide molecules affecting a hydrolysis where some of polysaccharides will turn into monosaccharides, which then will dissolve in alkalic solution. In this research alkalisoluble carbohydrates did not cause any loss in polysaccharide content because carbohydrates were analysed only from samples extracted with organic and water solutions.

Lignin

Lignin is polyphenolic-type polymeric compound, complicated in structure. We can find it in the secondary layer and middle lamella of the cell wall. Lignin has a very close relationship with hemicellulose by acting as a kind of glue which fixes the bunches of cellulose chains in plant tissues together, in this way giving mechanical strength to the plant stem (Levin and Repyah 1984).

The Klason method is universally used in the quantitative analysis of lignin. It is not suitable in qualitative analysis because 72% sulfuric acid decomposes and changes the structure of lignin compounds.

The content of Klason lignin in wood, barks and foliage is represented in table 4.

Compression wood increases the lignin content of branches in softwoods. This effect can be seen in table 4 in the lignin contents of spruce and pine branches. Tension wood on the contrary decreases the lignin content in the branches of hardwood.

Softwood lignin is constructed of guajasy units, whereas hardwood lignin contains syringyl-guajasy units. This difference in their structure can be seen in the amounts of acid soluble lignin (Fig. 3). Only 1 percent of softwood lignin dissolves in acid whereas even 10 to 20 percent of hardwood lignin seems to be acid soluble.

Table 4. The Klason-lignin content of different parts of trees (percent of absolute dry matter).

Tree species	Stem 20% height		Stem 80% height		Branches >5 mm		Twigs		Foliage			
	Inner Wood	Outer bark	Inner Wood	Outer bark	Inner Wood	Outer bark	Inner Wood	Outer bark	All Wood	All bark		
Klason-lignin%												
<i>Populus tremula</i>	20.1	14.8	16.9	19.8	15.1	12.5	18.4	14.9	17.0	21.2	17.5	18.9
<i>Betula pubescens</i>	18.8	24.2	6.2	19.8	21.9	6.3	20.1	17.7	11.2	20.6	14.1	14.6
<i>Betula pendula</i>	21.6	21.6	11.7	22.2	20.2	7.9	22.1	16.8	10.1	22.0	14.5	18.5
<i>Alnus incana</i>	21.0	26.7	26.0	23.5	16.4	11.7	22.0	21.9	18.9	28.5	19.0	21.5
<i>Alnus glutinosa</i>	21.0	28.4	32.0	22.1	24.6	19.6	22.4	23.5	21.4	25.5	22.0	25.0
<i>Picea abies</i>	27.8	7.7	22.9	28.2	9.2	23.9	31.7	7.2	24.7	30.2	18.7	11.5
<i>Pinus sylvestris</i>	25.5	5.3	29.5	27.0	7.2	17.9	29.7	7.1	15.7	27.8	10.5	9.8

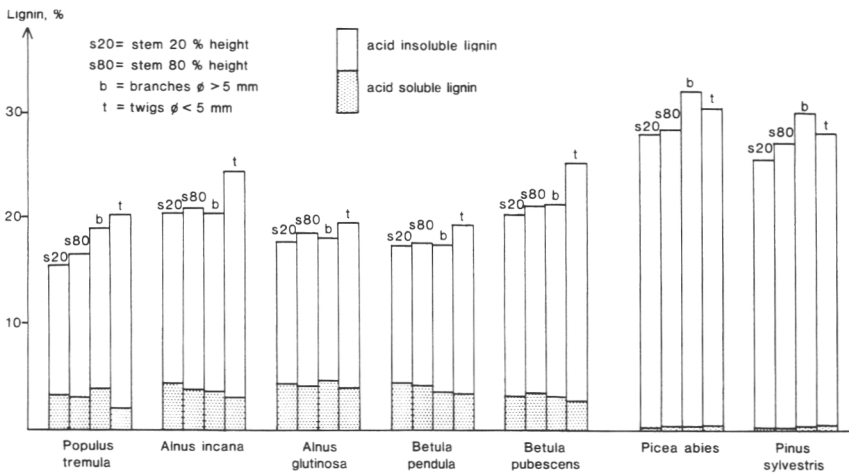


Fig. 3. The Klason lignin content of wood of different tree species.

The Klason lignin determinations of bark and foliage were made from an alkali-insoluble sample residue. In table 4 we can see that a lot of alkalisoluble matter in the outer bark of birch has disappeared during the alkali extraction. The same phenomenon can be seen in the results of softwood innerbark. In the case of birch outer bark dissolved matter is mostly suberin and in the case of softwood innerbark there are a lot of alkalisoluble phenolic acid compounds.

Because the lignin and alkalisoluble matter of bark consists of very complexed compounds which in some cases can be rather similar in structure we cannot be sure (without some qualitative analysis) that the Klason lignin results are pure lignin and we cannot also say that there are no lignin residuals in the alkalisoluble extracts. This research method gave these results other methods may give different results.

Carbohydrates

The cellulose molecule consists of several glucose units which are bonded together into a long chain. The chain of hemicellulose molecules consists of different combinations of glucose, xylose, arabinose, galactose and mannose units.

The main hemicellulose in softwoods is galactoglucomannan. Two types of that compound exist, one with a low galactose content and another with a higher galactose content. The amount of the former compound in softwoods is 10-15% of dry matter and the amount of the latter 5-8%. On the basis of the results represented in table 5 it seems that the type richer in galactose exists mainly in the branchwood. The other noticeable hemicellulose compound in softwoods is arabinoglucuronoxylan, which accounts for 7-10% of dry wood matter.

In hardwoods the main hemicellulose component is glucuronoxylan, usually called simply xylan. The xylan content is 15-30% of dry wood matter. In addition the hemicellulose compound glucomannan rises to 2-5% of dry hardwood matter (Sjöström 1977).

Table 5. The monosaccharide content of wood and bark in different parts of trees.

Tree species	Stem 20% height		Stem 80% height		Branches >5 mm		Twigs		Foliage			
	Inner	Outer	Inner	Outer	Inner	Outer	All					
	Wood	bark	Wood	bark	Wood	bark	Wood	bark	Wood	bark	%	
monosaccharide %												
Populus tremula												
Glucose	53.6	25.9	14.6	49.2	32.4	20.9	48.1	31.8	23.1	39.9	26.0	12.2
Xylose	17.4	8.4	4.9	18.8	9.9	6.7	16.2	9.8	6.8	14.5	8.7	3.9
Galactose	0.7	1.4	1.3	0.8	1.1	1.0	1.0	1.4	1.3	1.1	1.3	1.6
Arabinose	0.2	5.1	3.9	0.3	5.8	3.9	0.4	3.8	4.0	0.7	2.7	3.5
Mannose	2.9	0.8	0.7	2.4	0.6	0.7	1.9	0.9	0.7	1.3	0.8	0.7
Betula pubescens												
Glucose	43.8	20.1	2.8	40.1	17.9	2.9	40.1	18.0	3.9	38.1	13.0	12.3
Xylose	22.8	11.9	0.9	23.5	10.9	1.2	21.5	7.2	1.0	20.1	4.6	2.6
Galactose	0.8	1.0	0.5	1.0	1.1	0.5	1.4	1.4	0.7	1.6	1.0	2.7
Arabinose	0.3	3.4	1.5	0.4	3.3	1.5	0.4	3.6	1.6	0.6	2.7	1.9
Mannose	1.8	0.5	0.2	1.4	0.4	0.3	1.1	0.5	0.3	0.8	0.5	0.6
Betula pendula												
Glucose	41.8	24.1	3.5	37.0	18.0	3.9	36.6	21.4	7.4	35.5	14.6	14.7
Xylose	22.4	14.1	1.6	23.8	11.2	0.9	23.5	12.8	2.9	19.8	5.5	3.1
Galactose	0.6	1.3	0.5	0.9	1.3	0.5	1.2	1.8	1.0	2.2	1.5	2.1
Arabinose	0.3	3.2	1.7	0.4	3.2	1.6	0.6	3.9	2.2	1.0	3.1	2.0
Mannose	2.6	0.6	0.2	1.5	0.6	0.3	1.3	0.7	0.5	0.9	0.6	0.4
Alnus incana												
Glucose	41.5	17.3	9.8	35.5	14.2	6.5	38.2	18.3	8.6	31.7	16.4	15.1
Xylose	21.2	9.2	5.5	20.8	7.7	2.3	21.2	8.5	3.6	19.5	7.0	1.4
Galactose	0.7	1.7	1.2	1.0	1.9	1.2	1.5	2.1	1.3	1.5	1.5	1.4
Arabinose	0.3	3.0	2.6	0.3	3.8	3.2	0.5	4.3	3.2	0.6	2.6	2.0
Mannose	1.6	0.7	0.5	1.1	0.4	0.3	1.0	0.7	0.3	0.8	0.5	0.5
Alnus glutinosa												
Glucose	46.3	22.3	11.4	43.0	21.9	10.5	37.8	19.3	8.3	34.0	13.6	15.4
Xylose	17.8	8.3	5.5	20.0	10.1	5.0	19.4	9.0	3.8	19.5	6.6	3.4
Galactose	0.6	1.8	1.6	0.8	1.5	1.5	1.0	1.8	1.2	1.5	1.6	1.7
Arabinose	0.2	5.1	4.7	0.4	5.0	3.8	0.5	5.0	3.8	0.9	3.8	2.5
Mannose	1.7	1.0	0.9	1.5	0.8	0.8	1.1	0.7	0.6	0.9	0.6	0.8
Picea abies												
Glucose	52.7	29.9	19.4	48.4	27.4	21.4	40.2	30.8	17.4	35.1	20.6	18.0
Xylose	5.7	2.1	3.4	6.2	1.7	4.7	6.8	2.0	3.8	5.7	2.9	2.0
Galactose	1.9	2.2	1.5	2.5	2.0	1.5	6.8	2.5	1.5	7.1	2.0	1.6
Arabinose	1.0	9.3	3.2	1.2	8.3	3.3	1.4	9.1	3.4	2.1	4.2	2.7
Pinus sylvestris												
Glucose	46.3	26.2	20.1	42.0	18.5	19.7	32.9	18.9	18.2	28.1	15.4	23.4
Xylose	5.7	2.2	2.5	6.6	1.7	2.6	7.2	1.7	2.4	5.7	1.7	1.6
Galactose	2.3	2.8	3.2	4.1	2.1	2.8	6.5	2.1	2.2	5.9	1.7	2.6
Arabinose	1.4	10.6	5.3	1.7	12.1	5.9	2.5	12.3	6.9	3.6	9.2	2.5
Mannose	13.7	1.7	3.2	11.1	1.3	3.8	7.3	1.4	3.0	5.9	2.1	7.3

Wood matter also contains arabinogalactan (1-2%), uronic acids which are mainly bonded to xylan, acetyl groups bonded to xylan (in hardwoods) and mannan (in softwoods). Uronic acids are important in the metabolism of trees but they are not technically interesting (Jensen 1977). Uronic acids account for 3-5% and acetyl groups about 5% of the carbohydrate content of wood (Sjåström 1977).

The structure of polysaccharides in wood, bark and foliage is rather similar but the content of different compounds vary according to different parts of the tree.

The relatively high content of arabinose and galactose seems to be characteristic for bark and foliage (table 5), whereas the mannose content in bark is smaller than in wood. Due to the influence of compression wood in softwood branches free galactan can exist, which in turn increases the galactose content of branchwood (Sjåström 1977).

There are also some lignin-carbohydrate bonds which do not break off during hydrolysis. As a result some of the hemicellulose molecules may remain undetermined by the methods used in this research.

Several researchers have studied lignin-carbohydrate bondings. Matsumoto et al. (1984) used the ozone-method in determining the carbohydrate residue remaining in the lignin molecules of spruce and birch wood. The total carbohydrate content in spruce was 0.75% of the lignin amount and in birch 0.95%. In a spruce carbohydrate residue largest monosaccharide component was glucose (36% of the whole residue) in birch xylose (50% of residue) was the main component. Simonsen (1974) also found a lot of xylose (88% of carbohydrate residue) when he determined the lignin-carbohydrate bondings of birch. The proportion of other monosaccharides was 1-3%. Eriksson and Lindgren (1977) and Iversen (1985) analysed carbohydrate residues in the lignin-carbohydrate bondings of

spruce and found mainly mannose (45% of residue), xylose (about 22%) and glucose (18%) were also found.

A careful examination of the results verifies that either the chemical constitution of wood is truly inconstant or research methods are unreliable. The lignin-carbohydrate bondings in bark and foliage are obviously more complicated and more difficult to examine than those in wood matter.

The carbohydrate content in foliage is lower than that in wood and inner bark but a little higher than that of outer bark. The greatest difference is in the results of glucose and xylose. The total content among hardwood species is rather similar. The typically high mannose content raises the total monosaccharide content of softwood foliage to over 30% of dry matter (table 6).

Table 6. The monosaccharide content of foliage in different tree species.

Tree species	Glucose %	Xylose %	Galactose %	Arabinose %	Mannose %	Total %
<i>Populus tremula</i>	15.2	3.8	1.6	3.5	0.7	24.8
<i>Betula pubescens</i>	12.3	2.6	2.7	1.9	0.6	20.1
<i>Betula pendula</i>	14.7	3.1	2.1	2.0	0.4	22.3
<i>Alnus incana</i>	15.1	1.4	1.4	2.0	0.5	20.4
<i>Alnus glutinosa</i>	15.4	3.4	1.7	2.5	0.8	23.8
<i>Picea abies</i>	18.0	1.9	1.6	2.7	7.5	31.7
<i>Pinus sylvestris</i>	23.4	1.6	2.6	2.5	7.3	37.4

Ash

The ash of wood, bark and foliage consists of minerals and some other inorganic elements. If we compare different components of the tree, wood matter has the lowest ash content. Ash accounts for under 1% of abs. dry matter in Finnish tree species. Foliage has a content approaching even 10% of dry matter. The content of ash in outer and inner bark is somewhere between that of wood and foliage (Table 7).

The main minerals in the ash of trees are potassium (K), calcium (Ca), magnesium (Mg) and phosphorus (P). In addition lower concentrations of zinc (Zn), sulphur (S) manganese (Mn), copper (Cu) and boron (B) exist. Quantities of different elements vary according to tree species and biomass composition.

Table 7. The ash content of different parts of tree.

Tree species	Stem 20% height		Stem 80% height			Branches >5 mm			Twigs	Foliage		
	Inner Wood	Outer bark	Inner Wood	Outer bark	Inner bark	Outer Wood	Inner bark	Outer bark	Wood	All bark		
	ash %											
<i>Populus tremula</i>	0.4	5. 11.1	0.5	4.9	10.2	0.7	5.5	6.8	2.0	5.2	8.7	
<i>Betula pubescens</i>	0.3	2.0 0.5	0.4	1.8	0.5	0.5	3.2	0.9	0.7	2.4	4.2	
<i>Betula pendula</i>	0.3	2.7 0.7	0.4	2.3	0.6	0.7	4.6	2.0	1.1	3.4	4.9	
<i>Alnus incana</i>	0.4	3.2 2.4	0.6	3.2	1.7	0.7	2.9	2.0	1.0	2.2	5.4	
<i>Alnus glutinosa</i>	0.3	2.5 1.4	0.4	2.1	1.5	0.5	2.0	1.5	0.7	2.1	4.8	
<i>Picea abies</i>	0.3	3.5 3.3	0.5	3.0	2.6	0.5	5.1	3.9	1.0	2.9	4.2	
<i>Pinus sylvestris</i>	0.3	1.2 1.0	0.3	1.8	1.2	0.4	1.9	1.5	0.7	1.8	2.2	

The ash content in the inner and outer bark of aspen (*Populus tremula*) is remarkably high compared to ash content of other tree species:

<i>Populus tremula</i>	bark	4—10%	of abs. dry matter
Other hardwoods	- " -	0.5—5%	- " -
Softwoods	- " -	1—5%	- " -

The high ash content of aspen bark is due to the calcium and potassium contents which can be more than 5 times higher in the bark of *Populus tremula* than in other tree species.

The potassium content of hardwoods is much higher than in softwoods when measured from wood matter. Hardwood and spruce foliage contains similar amounts of potassium but pine foliage contains only a third of that amount. The manganese content of stem softwood is even five times higher than that of hardwoods (Hakkila and Kalaja 1983).

External factors like impurities which have accumulated during logging and transportation may increase the mineral content of foliage and bark. Poorly cleaned samples may contain remarkable amounts of sand and other impurities which also increase the ash content.

DISCUSSION

When we examine the different chemical components in different parts of different tree species we can see that in wood matter the two largest components are glucose (over 90 percent comes from cellulose) and Klason lignin. These components are followed by xylose (comes from xylane) in hardwoods and by mannose in softwoods which comes from galactoglucomanan.

On the contrary the chemical composition of bark and foliage is much more varying. Glucose is not the main component, the extracts (organic, hot water and alkalic) may even equal the amount or even exceed to higher quantities than glucose.

The amount of glucose in hardwood bark varies a lot between different tree species. For example the glucose content in aspen (*Populus tremula*) outer and inner bark is much higher than in other hardwoods:

		glucose	
Populus tremula	inner bark	25—32%	of abs. dry matter
Betula sp.	- " -	17—24%	- " -
Alnus sp.	- " -	14—22%	- " -
Populus tremula	outer bark	14—23%	- " -
Betula sp.	- " -	3—7%	- " -
Alnus sp.	- " -	6—11%	- " -

The glucose content of softwoods are nearly the same as in aspen bark:

Pinus sylvestris	inner bark	18—26%	of abs. dry matter
Picea abies	- " -	27—30%	- " -
Pinus sylvestris	outer bark	18—20%	- " -
Picea abies	- " -	17—21%	- " -

A typical monosaccharide compound in bark and foliage is arabinose. The amount of this compound in inner bark is nearly twice the amount in outer bark and foliage and ten times higher than in wood.

Galactose which is the smallest group of monosaccharides in most parts of tree species (under 2% of abs. dry matter) is a typical compound in softwood branches where its content may rise over 6% of abs. dry matter.

The cellulose and hemicellulose content of foliage is nearly the same as in outer bark of both in softwood and hardwood species. However, the distribution into different chemical components varies between hardwood and softwood foliage. The lower content of alkalic extracts and Klason lignin in softwood foliage is compensated with higher contents of monosaccharides and organic and hot water extracts.

Softwoods	alkalic extracts	13—17%	of abs. dry matter
	Klason lignin	9—11%	- " -
Hardwoods	alkalic extracts	22—28%	- " -
	Klason lignin	14—25%	- " -
Softwoods	monosaccharides	31—37%	- " -
	extractives	40—44%	- " -
Hardwoods	monosaccharides	20—24%	- " -
	extractives	26—34%	- " -

The amount of biomass available in a stand at the first commercial thinning stage is remarkab-

ly smaller than that in the final felling stand. Logging and transportation costs are high compared to the collected raw material. That is why the utilization of small-sized trees is a problem of high costs for the wood manufacturing industry.

Because of its high bark content unbarked small-sized timber is not a very suitable raw material in the pulp and paper industry. The applicability of bark in energy use comes from the high calorific values which for example within birch outer bark are over 50 % (MJ/kg) higher than those of the wood matter (Nurmi 1989). Nevertheless, the utilization of bark need not be limited to only energy use, although it does not serve as a proper fiber material for the pulping industry.

Betulinol, in the outer bark of birch species, and its utilization has been studied by several researchers, mainly polymerchemists. The outer bark of birch contains on the average 315 g/kg triterpenoids and betulinol accounts for about 77 percent of that amount (Ekman 1983). Betulinol has been used as a raw material in PVC plasticizers and polyurethanes. It has also been used as a suitable emulsifier in vaseline as well as in cosmetics, i.e. hair conditioners (Jääskeläinen 1982).

The amount of another significant component, suberin, in the outer bark of birch, is on the average 322 g/kg (measured from a fresh bark sample) (Ekman 1983). One possible area of utilization is as a source of carbon which forms when bark is decomposed by means of microbes.

It has been calculated that about 1012 tons of hemicellulose exist in nature and the annual renewal of that is 1010 tons. One important compound of hemicellulose is xylose which is nowadays an important raw material in the sugar industry. Also other hydrolyzation products of hemicellulose, mainly sugars, are used for instance in the production of organic acids, sugar alcohols and solvents used in different biotechnical and chemical processes. In addition the Technical Research Centre of Finland is investigating methods to convert xylose into other useful products like ethanol, acetone, lactic acid, xylan acid, butanol and butanediol. Today, however, it is still cheaper to convert glucose into these products (Kairamo 1987).

Foliage has been an important raw material in the USSR for a long time already. A significant product of foliage is chlorophyll-carotene paste which is used as a raw material in the medical and cosmetic industries. In addition that paste is an important livestock feed supplement (Levins and Daugavietis 1986).

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**THE EFFECT OF CHEMICAL AND PHYSICAL CHARACTERISTICS
OF FEEDSTOCK ON WOOD LIQUEFACTION BY STEAM/WATER PYROLYSIS****INTRODUCTION**

Wood has been used by man as a building material and a fuel for thousands of years. The art of charcoal making led to the use of wood-derived carbon as a reducing chemical for smelting ores. For centuries the cellulosic component of wood has been used for paper making. More recently, vanillin, a flavouring has been produced from lignin wastes. However, against the background of the petroleum age, wood was not seriously considered as a large scale feedstock for fuels and chemicals.

However, the events of the early 1970's changed that, and as a result several groups initiated research with the objective of converting wood to high yield of organic liquids by thermal processes.

The dry "distillation" of wood does yield a distillate, which is rich in certain chemicals such as methanol (wood alcohol), but the yield of liquid is not large. The advantage of liquid products is that they can be pumped and transported from one chemical engineering process to another, as in a petroleum refinery, and thus be upgraded.

The revived liquefaction research divided early on into water-based and non-water based processes. The latter are pyrolysis processes in which thermal energy alone is used to depolymerise the biopolymers. Three major reactor types have developed from this research. These are fluidised beds (Piskorz et al. 1988), vacuum pyrolysers, in which the feed passes down through grates of increasing temperature (Roy et al.) and ablative pyrolysis in which the feed is contacted with a heated wall as it spirals through the reactor (Diebold and Scahill). Temperatures are usually in the region of 500°C or more. In all three cases the residence time of the products in the reactor is fairly short.

The water-based processes make use of the chemical intervention of water, which is aided by the heat transfer from the high pressure steam formed under the reactions conditions. Most of the water-based research initially used catalysts and reducing gases with the objective of removing oxygen from the substrate. For example, the U.S. Bureau of Mines process used sodium carbonate solutions and carbon monoxide (Elliott 1980). The same system was used in the screw feeder reactor at the University of Saskatchewan (Eager et al. 1981). At the University of Toronto early studies involved the use of nickel metal and hydrogen. As a result it was identified that the purpose of the nickel/hydrogen system was to stabilize any liquid products which were formed by thermal and hydrolytic processes. It was shown that if powdered poplar, in water, was heated to 350°C in about two minutes and the reaction quenched, then only gas, water soluble organics and oil (acetone-soluble material) were formed (Boocock and Sherman 1985). It was shown that poplar sticks (6.6 mm square) could also be converted under the same conditions (Boocock and Porretta 1986). Quenching experiments demonstrated that in the liquefaction process water enters the wood and swells it. The wood then physi-

cally disintegrates and depolymerises with the result that the absorbed water is released (Boocock and Porretta 1986). Scanning electron microscopy of the outer and inner surfaces of the poplar wood has been used to identify changes at the cell level (Boocock and Kosiak 1981). Initially on the surface of the wood, the middle lamella separates. This is followed by matrix flow which merges cell walls and engulfs the cell cavities. Any debris on the surface of the wood also "melts". Inside the wood, spherical structures, which represent the most depolymerised material, form, particularly on the insides of the vessels. The cell structure breaks down and flowing matrix fills the irregular cavities so formed. Acetone extraction removes the spherical structures from the wood whereas chloroform extraction only disrupts and agglomerates them. Ether extraction causes no visible change. This is significant because the latter solvent usually removes only monomeric material, while chloroform and acetone dissolve successively higher molecular weight material.

More recent experiments have shown that the oil derives almost equally from the lignin and cellulosic fraction of the wood although some contribution from the hemicellulose is not ruled out (Allen et al.).

Most of the early research on the non-catalytic liquefaction of wood in water was done using small tubetype reactors which were successively heated in a fluidised sand bath and then quenched in water. An internal thermocouple measured the temperature profile and from it the reaction severity parameter, as defined by Overend et al. (1988), could be calculated. This parameter R_o , which has the form

$R_o = \exp ((T-373)/14.75) t$,
where T is the reaction temperature
and t is the reaction time

is kinetic in nature and assumes that there is no heat transfer resistance to the inside of the wood. Experiments showed that there was very little resistance to heat transfer when dry poplar sticks with a 6.5 mm square cross section were used as feed.

THE REACTOR

On the basis of this work a larger reactor, in which initial heating was provided by steam injection, was built. It was originally intended that the reactor should operate in a semi-continuous mode and that cylindrical baskets containing the feed would be passed successively through a cylindrical reactor. However, cost considerations for the necessary inlet and outlet high pressure valves precluded this and therefore, the design was such that the feed basket was introduced and retrieved through the inlet valve. A schematic diagram of the reactor system is shown in Figure 1.

The cylindrical reactor is vertically oriented and has an internal diameter of 3.8 cm. The total internal volume is 640 mL. On the top there is a 3.8 cm diameter inlet ball valve. At the base there is a 1.8 cm diameter outlet ball valve attached to a cooling lock. On one side of the reactor are three steam inlet ports connected to a steam generator. The reactor is heated externally with a heating element wound helically around the body. The whole is insulated with ceramic brick which has been cut to fit the exterior dimensions of the reactor.

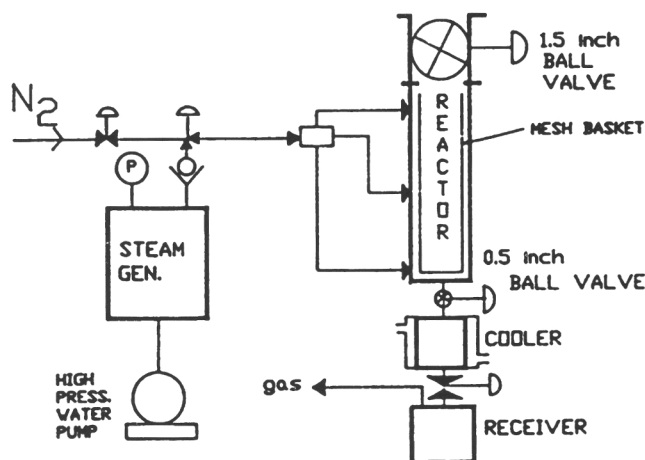


Fig. 1. Schematic diagram of wood liquefaction unit.

The feed, contained in a cylindrical mesh basket, is quickly introduced to the nitrogen-purged pre-heated reactor through the inlet valve. The valve is quickly closed and the steam lines opened (usually for 7 s). After a suitable reaction time the outlet valve to the cooling lock is opened, and shortly thereafter the products are discharged. The reactor is then opened and the basket immediately retrieved through the inlet valve using a hook.

Hybrid poplar wood, varying in size and shape from chips up to 3.1 cm diameter dowels has been the major feedstock. The poplar was provided by the Ontario Ministry of Natural Resources and usually had a moisture content of about 7 percent.

The major problem with the reactor is that it is non-isothermal. In particular, the base of the reactor can not be overly heated because of the pressure and temperature ratings of the outlet valve. There is also heat loss by conduction and radiation at both the top and bottom valves even though they are lagged. Typically in a liquefaction run the upper and middle reactor temperatures at the wall are over 400°C whereas the base temperature is about 300°C. Another problem is that the temperature of the steam entering the reactor is not exactly known. The steam generator has a relatively small volume (1L) and the expansion of steam when it enters

the reactor drops the temperature somewhat. Steam generator temperatures in the range of 330—350°C are usually employed with the upper temperature being most common.

THE PRODUCT

Typically, 100g of poplar wood chips can be totally converted in 60 s or less. Most of the “oil” is removed from the bottom of the reactor along with water. This oil solidifies and can be filtered from the water. It usually contains up to 20 per cent of trapped water but the latter phase separates if the oil is heated to about 75°C. More acetone-soluble material can be removed from the reactor after it has cooled.

The oil yield, which includes all acetone-soluble material, is typically 40—45% on a dry mass basis. However, close to 60% of the wood carbon is in these oils. This is possible because the oxygen content of the oil is in the range 20—25% whereas that in the wood is close to 45%. The aqueous phase contains about 30% of the carbon and another 6% is in the gas phase as carbon dioxide and carbon monoxide in a molar ration of 9:1.

The aqueous phase ejected from the reactor has not been extensively investigated for organic content. However, the aqueous phase from the small tube type reactors contains acetic acid and other aliphatic acids, furfural, 5-methylfurfural, 5-hydroxy-methyl furfural, phenol (including guaiacol, syringol and alkyl derivatives) and levulenic acid, as well as many unidentified compounds (Kallury et al. 1987).

THE OIL

As mentioned previously, the “oil” is actually solid at room temperature and softens around 75°C. It has a polystyrene-equivalent number-averaged molecular weight of about 800. Protein and C-13 nmr spectra clearly shows the retention of lignin methoxyl groups. The same analytical technique also shows the non-alkane character of the oil. Fast pyrolysis oils are notoriously thermally unstable and at temperature not much above 100°C they reactively decompose to produce materials which can be crushed easily to fine powders. The same phenomenon was observed with those oils produced using nickel/hydrogen/water systems. The oils produced in this reactor are much more stable and at temperatures below 220°C polymerise only very slowly. The rate of polymerisation, as well as the free radical concentrations of thermally treated oils, is currently being investigated. This is important since the oils will certainly require upgrading to change both their molecular weights and chemical compositions. Catalytic deoxygenation of the oils and model compounds has been studied by several groups (Various papers... 1988). It has been shown that those catalysts which are used to hydrodesulphurise petroleum will also hydrodeoxygenate wood oil components.

PHYSICAL CHARACTERISTICS OF FEEDSTOCK

Poplar wood chips, sticks and dowels of different diameters have all been used as feedstock. The sticks referred to here are rather thin and are longitudinal offcuts from the dowel making operation.

Figure 2 shows the mass conversion of chips, sticks, 2.5 cm diameter and 3.1 cm diameter dowels as a function of time for a steam temperature of 350°C. It should be noted that except for the larger dowels, when the feed load was 160g, the feed loads were in the range of 80—100g, and usually close to 100g. It can be seen that there is an initial fast conversion, the rate of which is different for each feedstock but larger for the smaller feedstocks. This is followed by

a slower mass conversion rate which is the same for all feedstocks, at least after 60 s. For the larger dowels, and perhaps also the 2.5 cm diameter dowels, there is also an intermediate transition rate which precedes the slower rate.

The observations can be explained with the following simple model. When the steam is injected the resistance to heat transfer, and therefore the reaction rate, is limited only by the surface area of the feed. However, after this, the heat transfer through the reactor walls and water to the feed becomes limiting, and thus the rate becomes constant. For the 3.1 cm dowels another effect comes into play. The dowels are only just slightly smaller than the internal diameter of the reactor. The condensed water is forced higher into the narrow annulus between the dowel and the wall and the conductive heat transfer is therefore much better. The radiative heat transfer is probably also important in this case.

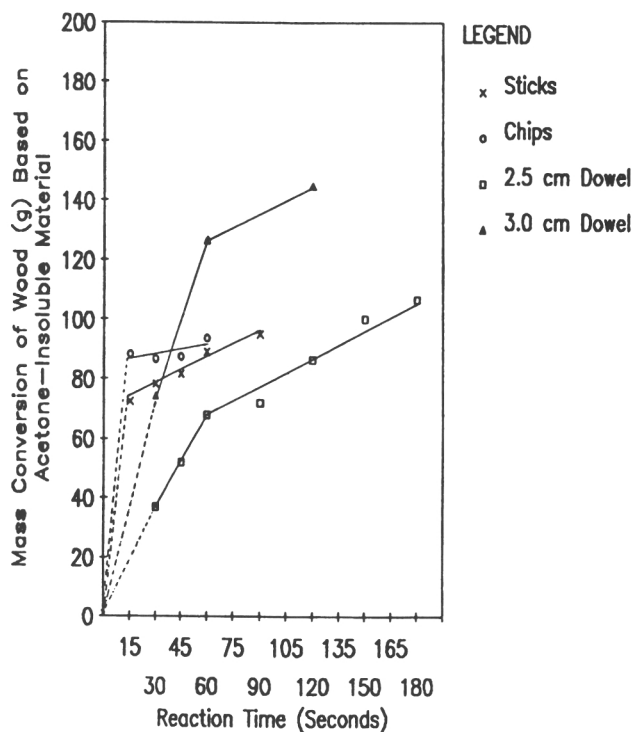


Fig. 2. Size study, total conversion (g) of chips, sticks, 2.5 and 3.0 cm dowels as a function of reaction time (steam is at 350 °C).

It can now be seen why ideally the initial mass of feed should be the same in all runs. The initial mass conversion rate is controlled by the surface area of the feed, and this is directly proportional to the mass of the feed for a particular feed forms. Some experiments were made using three dowel sizes. (1.3, 1.75 and 2.5 cm diameter). Only 50g of the two smaller dowel sizes were used whereas 100g of the larger dowels. Therefore conversion in per cent was plotted against the surface area/volume ratio for a 30 s reaction time and 350°C steam (see Figure 3). The plot, based on total acetone insolubles, if projected, passes almost through the origin. This was somewhat surprising given that at 30 s all three feeds have progressed beyond the initial reaction phase (see Figure 2). However, the conversions at 30s are still dominated by the fast initial rate.

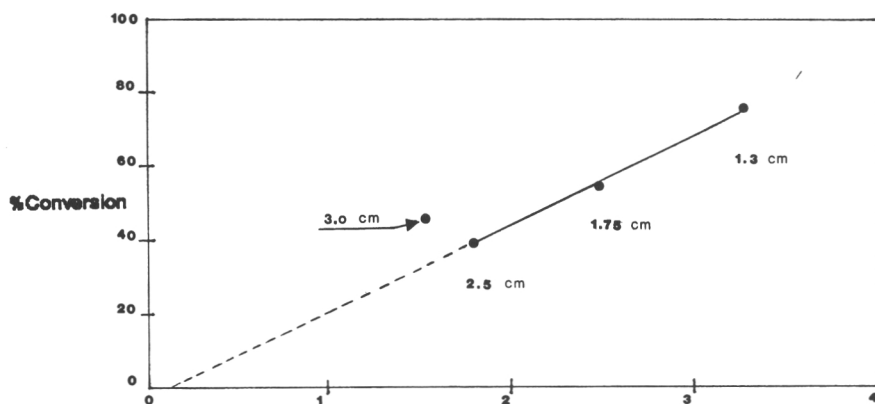


Fig. 3. Conversion vs. surface area/volume ratio for dowels reacted with 350°C steam (30 s reaction time).

The above model has important implications. The first is that the initial fast reaction controls the liquefaction of feed such as chips. Therefore the ease with which the steam can penetrate the wood may determine how fast the reaction proceeds. Thus the lack of vessels, which are present in poplar, the presence of water, which can occupy cells and vessels, and the presence of bark can all impede the steam penetration. It is already known that softwood, which lacks vessels, converts much less easily than poplar. There is also evidence that wet poplar converts less easily than dry material and studies on one and two-year old willow, indicate that their green bark may seriously impede liquefaction. On the other hand the results suggest that finely divided lignin, which has not been chemically modified during the isolation, may liquefy easily and in high yield. Lignins from alcohol pulping processes may well be suitable candidates for investigation as feedstock.

CHEMICAL CHARACTERISTICS OF FEEDSTOCKS

It has already been mentioned that the oil which is formed during the aqueous liquefaction of wood derives largely from the cellulose and lignin. This is important because it may dictate subsequent uses of the oil. We had noted that the hybrid poplar yielded significant amounts of phenol and that some poplar clones consistently gave more phenol than others. We showed that this phenol derived exclusively from the lignin under liquefaction conditions. Although a yield as high as 24%, based on lignin, has been reported, upper yields now seem to be around 10% and the former figure should be viewed with suspicion. Agblevor in our group isolated hybrid poplar lignins by a combination of solvent extraction and enzymatic methods (Agblevor and Boocock 1989). In some clones base hydrolysis of the lignin at 150°C produced amounts of phydroxy-benzoic acid (4% by weight) equivalent to the phenol (3% by weight) produced by the liquefaction (see Figure 4). Hydrolysis at a higher temperature (180°C) yielded phenol at the expense of the p-hydroxybenzoic acid (PHBA). In addition when PHBA was subjected to the liquefaction conditions it quantitatively decarboxylated to phenol. It is therefore proposed that the poplar lignins contain PHBA units esterlinked to the lignin via the carboxyl group.

In some poplar clones, more phenol is produced from the liquefaction of the lignins than would be expected from the hydrolysis. This occurs when the PHBA yields from the lignin are in excess of 4%. Liquefaction of the hydrolysed lignins did indeed show that more phenol could be produced. Alkaline nitrobenzene oxidation of these lignins (Agblevor 1988) yielded almost the same molar amount of PHBA as the phenol produced in liquefaction (see Figure 5). Since

the nitrobenzene oxidation will cleave oxygen functionalities at the alpha and beta positions of the lignin propane units then we believe that in certain lignins some PHBA units are ether linked (through the phenolic OH) to these positions. It is not clear why this only appears to happen above a certain PHBA content. However, it is clear that those lignins which contain the most of these units derive from clones which are cross-breeds of *Pinus nigra*. The *Pinus nigra* lignin has a relatively high PHBA content (6.2%).

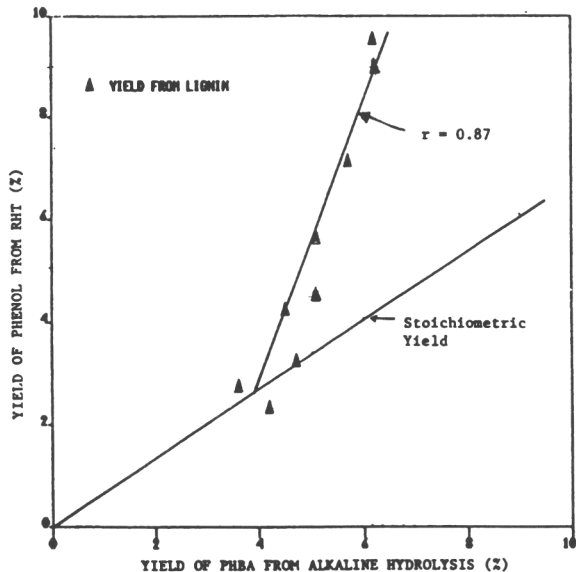


Fig. 4. Relationship between phenol produced by rapid hydro-thermolysis and p-hydroxybenzoic acid produced from the alkaline hydrolysis of hybrid poplar lignins.

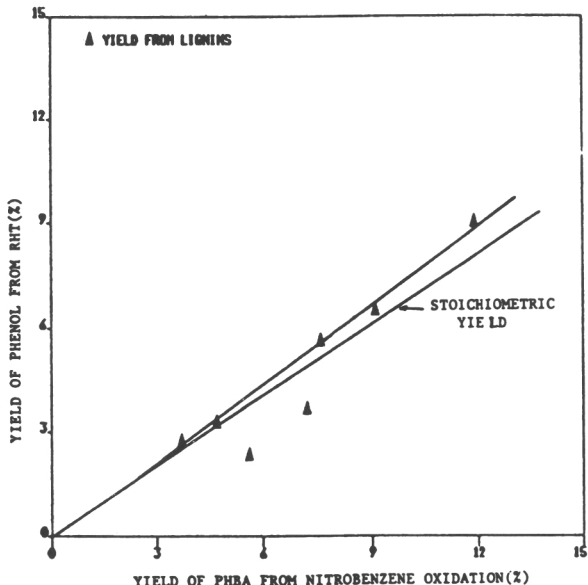


Fig. 5. Relationship between phenol produced by rapid hydro-thermolysis and p-hydroxybenzoic acid produced from the alkaline nitrobenzene oxidation of hybrid poplar lignins.

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