# WORKING PAPER

**WOOD QUALITY IN PINE STANDS DAMAGED BY INDUSTRIAL POLLUTANTS IN POLAND**

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July 1988
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PUBLICATION NUMBER 77 of the project:
Ecologically Sustainable Development of the Biosphere

IIASA
International Institute for Applied Systems Analysis

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## ABOUT THE AUTHORS

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## FOREWORD

Within IIASA's Environment Program, the Project on Ecologically Sustainable Development of the Biosphere seeks to clarify the policy implications of long-term, large-scale interactions between the world's economy and its environment. The Project conducts its work through a variety of basic research efforts and applied case studies. One such case study, the Forest Study, has been underway since March 1986, and is focusing on the forest-decline problem in Europe. Objectives of the Forest Study are:

(a) to gain an objective view of the future development of forest decline attributed to air pollution and of the effects of this decline on the forest sector, international trade, and society in general;

(b) to build a number of alternative and consistent scenarios about the future decline and its effects; and

(c) to identify meaningful policy options, including institutional, technological and research/monitoring responses, that should be pursued to deal with these effects.

The spatial limits of the Forest Study encompass the entire continent of Europe. For practical purposes, this means that the spatial resolution must be at the level of small countries, or provinces/regions in large countries. Yet there is much heterogeneity in forest-sector phenomena below this level of resolution. To examine the importance of this heterogeneity, in 1987 the Study entered into a research agreement with the Faculty of Agricultural and Forest Engineering at the Agricultural Academy of Warsaw. Under the terms of the agreement, the Polish collaborators are producing a series of technical background papers exploring the extent of forest decline in Poland, potential future courses for the decline, and various environmental and socio-economic consequences of continued forest decline. This paper examines the effects of air pollutants on the quality of wood from Polish pine stands, pine being the dominating species in the country. Other papers in the series will look at the extent of forest decline in Poland in the context of the forest inventory, future wood-supply prospects, promising silvicultural regimes for stands under the influence of air pollutants, the harvest-machinery implications of continued forest decline, and the consequences of a changing wood supply on the forest-products industry.

R.E. Munn
Leader
Environment Program

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## ABSTRACT

Information on the impact of industrial air pollutants on forest stands and consequences on wood quality are a little mixed up and misleading. Some experiments made on pines 130-230 years old did not reveal serious changes of wood quality. In this work, we present results of investigations on wood from 60-year-old pine trees which were under the influence of air pollutants for about 40 years.

Such pine stands, of an age near the mean for the present forests in Poland, were the basis for some evaluations of financial losses in Poland due to the effects of air pollution on forests. Detailed data on the properties of the pine wood, which were the basis of the above-mentioned calculations, are also presented. The factors influencing economic losses are given based on the findings presented.

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## 1. INTRODUCTION

Many theories have been elaborated in recent years to explain the phenomenon of forest decline (e.g., acid rain, ozone, ecological stress, mycorrhizal dysfunction and others). The report on the state of Polish forests (Anonymous, 1986) does not regard any theory as exclusively true, but scientists and practitioners gathered at the Forest Decline Workshop in Wakefield, Quebec, in October 1986, adopted the ecological-stress theory presented by Wargo (1986). We are inclined to adopt the ecological stress theory as compatible with the principles of infectious plant diseases of Gauman (1959), because forest decline is accompanied by the spread of infectious diseases of woody plants (diseases which until now are poorly known) and insect infestations (Splawa-Neyman, 1984).

If we take into account that, in the lowlands of west and central Poland and also in northern Poland, plantations of pine (Pinus silvestris L.) prevail (amounting to 71.5% of the total area of Polish forests), we must take the situation as very serious. Two main factors are of basic importance: first, coniferous trees are more sensitive to industrial emissions than deciduous trees; and second, the planted pine has a tendency to accreate by roots, enabling diseases to spread throughout biogroups (Ejtingen, 1950). Such a situation supports the opinion of Kuusela (1987) that a conclusive role in forest decline is played by environmental stress.

The quality of wood from damaged areas, according to some authors (e.g., Fruhwald et al., 1986; Liese, 1987), does not differ across a range of properties from wood from areas free of industrial emissions. These authors have not found defects associated with the occurrence of emissions and their influence on wood. Thus, it can be assumed that while a tree in a polluted area is living, its tissues will be similar to normal ones. After tree death, processes of degradation occur in damaged as well as undamaged trees. Apart from epidemic occurrence of tree fungal diseases and insect infestations, roundwood and timber ought not to reveal special defects. But the above-mentioned authors agree that reductions of annual growth of forest stands and individual trees have occurred in polluted areas. That which occurs in Poland is estimated at 3.0 million $m^3$ annually (Anonymous, 1986).

The decrease of annual-ring width causes an equalization of the anisotropic stucture of wood. Such an effect can be obtained by pruning the crowns of young pine trees; after some years, changes in the mechanical properties and quality of wood from such pruned trees can be seen (Pazdrowski, 1981). However, published data of investigations of wood from trees from damaged forest areas often pertain to rather old stands. For example, Fruhwald et al. (1986) conducted analyses of wood from trees 130-230 years old. Taking into account natural decreases of growth of such old trees, the results become a little doubtful. Therefore, we concluded that the proper way to undertake such investigations under Polish conditions is to determine quality of wood from trees in damaged forests of about 60 years of age, i.e., the age of full growth. Thus, we assume that fast-growing, younger pine trees react more strongly to degradation of the natural environment by industrial emissions (Splawa-Neyman and Wojciechowski, 1987).

## 2. LABORATORY INVESTIGATIONS OF WOOD PROPERTIES

### 2.1 MATERIALS AND METHODS

#### 2.1.1 Characteristics of the Forest Stands from which Material for Investigation was Taken

We chose four pine stands of the so-called long-rotation harvesting course from among the Fresh Forest stands on site classes III/IV. The question of site class is doubtful due to the degradation of the natural environment and decrease of tree height. The soils in every case were deep sands of the podzol type.

The plots where trees were felled were positioned 5, 10 and 15 km from a known air-pollution emitter (zones III, II, I, respectively -- Figure 1). For a control, we chose a pine stand 50 km south-east from the same emitter. These forest stands in the Central Poland lowlands represent average conditions. Extreme conditions can be found in the mountain terrains (Karkonosze), but spruce is the main species occurring there.

#### 2.1.2 Emitter Characteristics

The main emitter in the study area is a phosphoric fertilizer plant producing sulphuric acid, simple superphosphate, aluminium fluoride and hydrogen fluoride. There is one chimney equipped with an electrofilter. Emissions include:

- dusts, at an average 30.2 kg/h
- CO, 56.0 kg/h
- $N_2O$, 9.2 kg/h
- $SO_2$, 33.6 kg/h.

Zone III begins 400 m from the works and extends 5 km away, while zone II is 10 and zone I 15 kilometers away, respectively (Figure 1). Considering the results of investigations by Molski (1987), this area represents average conditions with respect to the sulphur content of the pine needles -- approximately 0.121-0.150% S.

#### 2.1.3 Scope and Range of Investigations

Sample material from nine trees in each plot area were taken according to the Urich I method (Pazdrowski, 1981). For each measured property, 20 to 30 samples were taken. The following measurements were made on the wood samples taken to the laboratory:

1. Structural properties:

   (a) length of tracheids;
   (b) external diameter of tracheids;
   (c) internal diameter of tracheids;

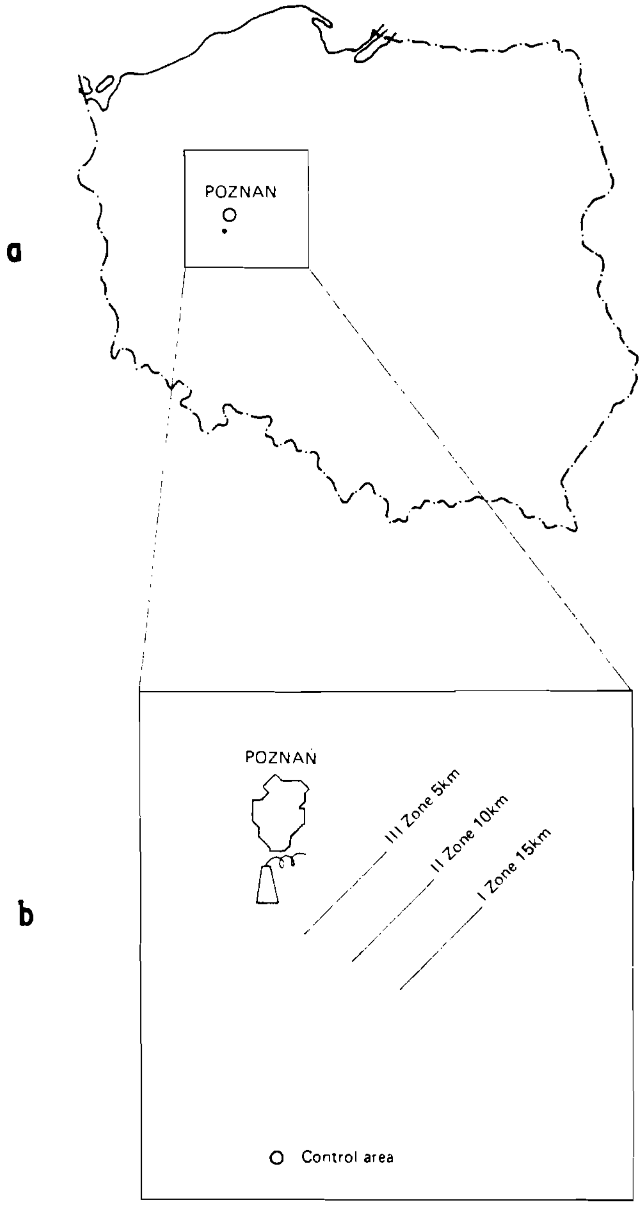


Figure 1. Location of the study area (a) and the pollutant emitter (b) in Poland.

(d) thickness of cell walls; and
(e) joint thickness of two cell walls.

2. Physical/mechanical properties:

(a) moisture content;
(b) wood density;
(c) shrinkage of cross-section surface;
(d) absorbability;
(e) static bending strength;
(f) modulus of elasticity at static bending;
(g) compression strength along the grain at moisture content $W = W_r$ and $W > W_n$,
where $W_r$ = wood equilibrium moisture content, and
$W_n$ = wood in a state of fiber saturation point;
(h) stress at bending on the proportional limit;
(i) deformation at static bending on the proportional limit;
(j) maximum deflection at static bending.

3. Chemical properties:

(a) solubility in cold and hot water;
(b) solubility in alkali -- 1% NaOH and 10% KOH;
(c) solubility in ethanol-benzene mixture;
(d) cellulose content according to Kurchner-Hoffer (see Stamm, 1964);
(e) percentage of alpha-cellulose in K-H cellulose (see Stamm, 1964);
(f) cellulose according to Seifert (see Stamm, 1964);
(g) lignin according to Saward (see Stamm, 1964);
(h) whole-sugar contents (see Stamm, 1964);
(i) pentosane content;
(j) ash content;
(k) pH of wood according to Grey (see Stamm, 1964).

## 2.2 RESULTS AND DISCUSSION

### 2.2.1 Anatomical Investigations

Determinations of the anatomical properties of wood did not show essential differences in comparison with results obtained from control material. The length, diameter and slenderness of tracheids were very similar for all zones; in zone II they were even a little higher, explainable perhaps by the "fertilization effect" (e.g. Fraser et al., 1985) which could result from the phosphorite dusts and nitrogen compounds emitted by the fertilizer works.

Only joint thickness of two walls (Figure 2) and thickness of tracheid walls (Figure 3) of late wood were higher at distances exceeding 5 km from the emitter. Data described elsewhere for this factor, e.g., 0.18 for early wood and 0.76 for late wood (Owczarzak, 1987), were in this case greater. These observations and measurements suggest that disturbances at the level of cell-wall and wood substance are probably occurring, in accordance with our hypothesis that younger trees react more strongly to environmental pollution than old trees.

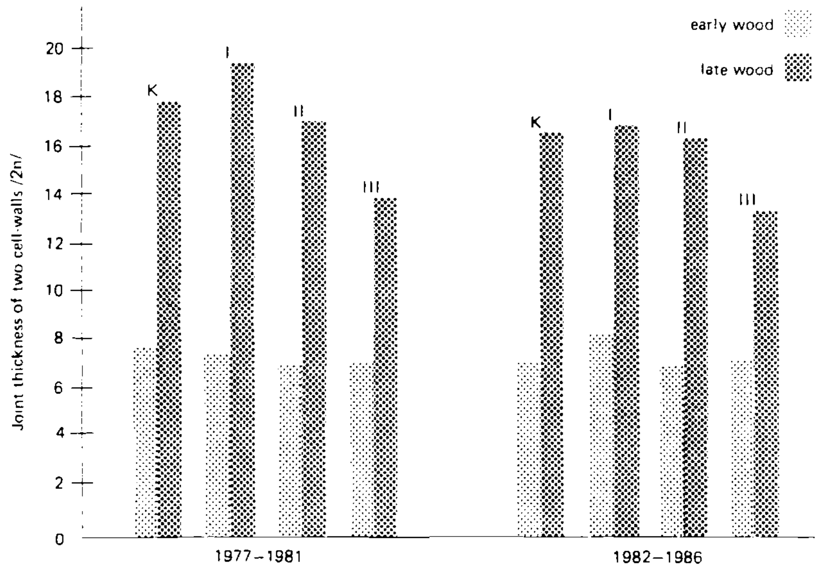


Figure 2. Joint thickness of two cell-walls (2n) of early and late pine wood from areas in central Poland polluted by industrial emissions.

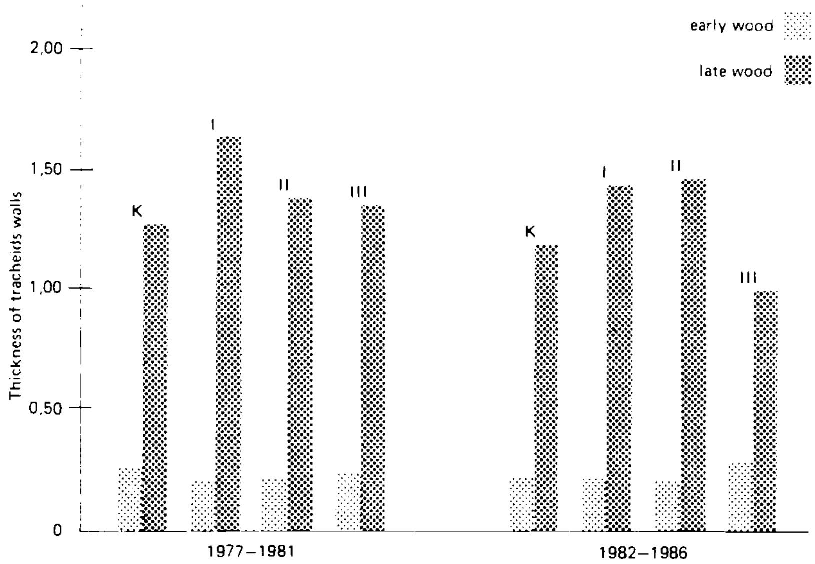


Figure 3. Thickness of tracheid walls from early and late pine wood from areas in central Poland polluted by industrial emissions.

### 2.2.2 Physical and Mechanical Properties of Pine Wood

Determinations of physical and mechanical properties (presented in Tables 1 and 2 in relative values) showed some changes which can be explained only by the changes of chemical composition of wood. For the analysis, we also calculated a strength quality coefficient accordingly to the formula

$$J = \frac{\text{compression strength along the grain}}{\text{density}}$$

(see Table 3).

Our conclusions from this part of the investigation are as follows:

- industrial emissions have had negative effects on some properties of wood contrary to data from the literature (e.g. Liese, 1987) indicating otherwise; and

- this influence was greater for strength and adsorbability the closer was the distance from the emitter (taking into account the prevailing direction of winds and disregarding long-range pollution transport).

### 2.2.3 Chemical Investigations

Statistical analyses of the chemical data indicated that the industrial emissions influenced wood chemical composition to a rather small extent (Table 4). In some cases, differences between small, medium and large diameter trees were noted (Wroblewska, 1987). There was no relationship between chemical composition of pine wood, i.e., cellulose, lignin and pentosane contents, with distance from the emitter. However, wood from the areas close to the emitter contained higher amounts of sugars, solubles in alkali solutions and not water, extractives, and ash (Table 4).

Wood from the emission zones was characterized by distinctly lower contents of alpha-cellulose compared to the control wood. Air-dry wood from the emission zones also had lower equilibrium moisture content and higher wood pH than control wood.

The findings here are in accordance with results of several studies in FRG, e.g., Fruhwald et al. (1984), Koltzenburg and Knigge (1987), Liese (1987) and Puls and Rademacher (1986).

## 3. TECHNICAL EVALUATION OF REDUCED WOOD QUALITY

The above results pertain to wood which has grown during the last 40 years in conditions of exposure to dust, liquid and gaseous pollution, and reveal that properties of the wood were negatively effected. Now we consider what negative effect these changes could have on the forest-products industry and utilization of such wood, that is, on its technical properties. An economic evaluation of those quality changes will be given afterwards.

### 3.1 Changes in Roundwood

The decrease in tree diameter observed in central Poland for 60-year-old trees was about 25%, i.e., 5.7 cm for trees on site class III/IV. This

Table 1. Properties of pine wood from damage zones I, II and III and from control area with statistical data.

| Property | Statistical Coefficient | Measurement Unit | Control Area | Wood from Damage Zones I | II | III |
|---|---|---|---|---|---|---|
| Moisture Content | x | % | 9.1 | 9.6 | 10.5 | 9.7 |
| | | % | 0.6 | 0.7 | 0.8 | 0.7 |
| | v | % | 6.1 | 6.8 | 7.8 | 7.6 |
| | n | pcs | 2 | 2 | 3 | 4 |
| Density | x | $kg/m^3$ | 552 | 548 | 572 | 556 |
| | | $kg/m^3$ | 52.0 | 42.1 | 44.9 | 50.7 |
| | v | % | 9.4 | 7.7 | 7.8 | 9.1 |
| | n | pcs | 4 | 3 | 3 | 4 |
| Shrinkage of Cross-Section Area | x | % | 14.1 | 14.2 | 13.5 | 13.0 |
| | | % | 1.1 | 1.0 | 2.1 | 2.4 |
| | v | % | 7.9 | 7.4 | 15.3 | 18.8 |
| | n | pcs | 3 | 3 | 10 | 14 |
| Absorbability | x | % | 91.1 | 92.7 | 93.1 | 97.4 |
| | | % | 14.2 | 9.6 | 13.9 | 11.2 |
| | v | % | 15.2 | 10.3 | 14.9 | 11.5 |
| | n | pcs | 10 | 5 | 9 | 6 |
| Static Bending Strength | x | MPa | 108.4 | 108.0 | 103.0 | 97.4 |
| | | MPa | 19.7 | 18.0 | 19.7 | 16.8 |
| | v | % | 18.2 | 16.7 | 19.1 | 17.2 |
| | n | pcs | 13 | 12 | 15 | 12 |
| Modulus of Elasticity at Bending | x | GPa | 10.9 | 10.4 | 9.7 | 9.1 |
| | | GPa | 1.6 | 1.6 | 1.9 | 1.9 |
| | v | % | 14.9 | 15.3 | 19.1 | 21.1 |
| | n | pcs | 9 | 10 | 15 | 18 |
| Compression Along the Grain at Moisture Content $W = W_r$ | x | MPa | 62.0 | 61.6 | 57.1 | 56.3 |
| | | MPa | 9.4 | 7.9 | 7.8 | 8.7 |
| | v | % | 15.1 | 12.8 | 13.7 | 15.5 |
| | n | pcs | 10 | 7 | 8 | 10 |
| Compression Along the Grain at Moisture Content $W > W_r$ | x | MPa | 20.3 | 18.7 | 19.4 | 18.2 |
| | | MPa | 3.0 | 2.9 | 2.4 | 3.6 |
| | v | % | 17.0 | 15.3 | 12.3 | 19.6 |
| | n | pcs | 12 | 10 | 7 | 16 |
| Bending Stress on the Proportional Limit | x | MPa | 57.3 | 57.8 | 55.7 | 50.1 |
| | | MPa | 9.4 | 10.4 | 8.5 | 8.9 |
| | v | % | 15.1 | 17.9 | 15.3 | 14.9 |
| | n | pcs | 15 | 13 | 10 | 8 |

Table 1. (continued).

| Property | Statistical Coefficient | Measurement Unit | Control Area | Wood from Damage Zones I | II | III |
|---|---|---|---|---|---|---|
| Deformation at | x | cm | 0.24 | 0.26 | 0.27 | 0.26 |
| Static Bending on | | cm | 0.03 | 0.03 | 0.04 | 0.04 |
| the Proportional | v | % | 11.3 | 12.5 | 16.3 | 13.6 |
| Limit | n | pcs | 6 | 7 | 11 | 8 |
| Maximum Deflections | x | cm | 0.76 | 0.73 | 0.81 | 0.80 |
| at Static Bending | | cm | 0.10 | 0.15 | 0.25 | 0.20 |
| | v | % | 14.8 | 20.1 | 18.7 | 19.5 |
| | n | pcs | 9 | 16 | 14 | 16 |

Remarks:

Each damage zone and control wood was represented by 9 trees (thick, medium, thin) chosen according to the Urich method. From each tree, 20 samples were taken for each investigated property. The data presented are calculated for 180 samples.

x = mean value (for 180 samples)
  = standard deviation
v = coefficient of variation
n = indispensable (statistically) number of samples

Table 2. Relative values of pine-wood properties from damage zones I, II, and III in relation to control wood. Figures are percentages of the results for control wood.

| Property | Control Wood | Wood from Zones of Damage I | II | III |
|---|---|---|---|---|
| Moisture Content | 100 | 105 | 115 | 107 |
| Density | 100 | 99 | 104 | 101 |
| Shrinkage of Cross-Section Area | 100 | 101 | 96 | 92 |
| Absorbability | 100 | 102 | 102 | 107 |
| Static Bending Strength | 100 | 100 | 95 | 90 |
| Modulus of Elasticity at Bending | 100 | 95 | 89 | 83 |
| Compression Along the Grain at Moisture Content $W = W_r$ | 100 | 99 | 92 | 91 |
| Compression Along the Grain at Moisture Content $W > W_n$ | 100 | 92 | 96 | 90 |
| Bending Stress on the Proportional Limit | 100 | 101 | 97 | 87 |
| Deformation at Static Bending on the Proportional Limit | 100 | 108 | 113 | 108 |
| Maximum Deflection at Static Bending | 100 | 96 | 107 | 105 |

Table 3. Strength quality coefficients of pine-wood from damaged zones I, II and III determined at compression along the grain. W is the actual moisture content; $W_r$ is the equilibrium moisture content; and $W_n$ is the fiber saturation moisture content.

| Conditions of Testing | Strength Quality Coefficient: Control Wood | Wood from Damaged Zone I | II | III |
|---|---|---|---|---|
| Compression Strength Along the Grain at $W = W_r$ | 11.2<br>100% | 11.2<br>100 | 10.2<br>91 | 10.1<br>90 |
| Compression Strength Along the Grain at $W > W_n$ | 3.7<br>100% | 3.4<br>92 | 3.4<br>92 | 3.3<br>89 |

Table 4. Chemical composition of pine-wood from the three damage zones and the control zone.

| | Control Wood | | Wood from Zones of Damage | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | III | | II | | I | |
| | % | g/100cm³ | % | g/100cm³ | % | g/100cm³ | % | g/100cm³ |
| Moisture Content | 5.80 | 3.20 | 6.70 | 3.32 | 5.10 | 2.90 | 4.83 | 2.70 |
| Solubles in - Cold Water | 1.40 | 0.77 | 1.37 | 0.75 | 1.17 | 0.67 | 1.75 | 0.97 |
| - Hot Water | 3.38 | 1.85 | 3.98 | 2.17 | 3.50 | 1.99 | 4.37 | 2.43 |
| - 1% NaOH | 13.54 | 7.43 | 14.83 | 8.09 | 16.37 | 9.21 | 15.27 | 8.52 |
| - 10% KOH | 22.56 | 12.41 | 22.18 | 12.12 | 24.47 | 13.92 | 24.43 | 13.61 |
| - Ethanol-Benzene Mixture | 3.35 | 1.83 | 3.72 | 1.92 | 5.14 | 2.92 | 4.52 | 2.51 |
| Cellulose acc. Kurchner-Hoffer | 54.35 | 29.97 | 54.17 | 29.64 | 53.37 | 30.41 | 53.44 | 29.84 |
| Alpha-cellulose (% of cellulose K-H) | 72.43 | | 71.09 | | 69.33 | | 66.09 | |
| Cellulose acc. to Seifert | 43.98 | | 44.30 | | 44.06 | | 43.16 | |
| Lignin acc. to Saward | 26.26 | 14.48 | 26.45 | 14.48 | 26.91 | 15.33 | 26.96 | 15.06 |
| General Sugars | 75.37 | 41.57 | 76.28 | 41.72 | 74.81 | 42.60 | 75.75 | 42.30 |
| Pentosanes | 9.52 | 5.25 | 10.08 | 5.54 | 9.38 | 5.35 | 8.94 | 5.00 |
| Ash | 0.26 | 0.14 | 0.21 | 0.12 | 0.29 | 0.17 | 0.29 | 0.16 |
| pH | 4.4 | | 4.5 | | 4.6 | | 4.6 | |

will affect the yield of sawn timber generally. There will be necessary changes of machinery and equipment for more economic processing in the primary conversion enterprises, requiring increased investments. In addition, storage of roundwood from stands damaged by industrial emissions will demand obligatory application of wood-preservation methods. As shown by Splawa-Neyman (1984), wood from damaged stands incurs increased amounts of defects such as those caused by insects (e.g., Tomicus piniperda, Ips sexdentatus, Trypodendron lineatus and others from the family Cerambycidae) and fungi (e.g., Armillaria mellea, Phellinus pini, Heterobasidion annosum, Stereum sanguinolentum, Poria species, Ceratocystis species, Discula pinicola, Discula brunnectingens, Sclerophoma pityophylla). As observed also by other authors (e.g., Schmidt, 1985) roundwood sap stain has in this case serious consequences during the conversion of such wood.

## 3.2 Changes in Sawnwood

Increased attacks of roundwood by insects and fungi increase the risk of occurrence of so-called "inside sap stain" as described by Tarocinski (1970). Such a situation demands two treatments in the saw mill -- antiseptic dipping of timber, and thermal sterilization of the wood. Without these treatments, there is a risk of depreciation of such wood into lower quality classes by a minimum of one class. Such treatments will be costly and expensive in view of the energy, chemicals and labor requirements.

There are also other economic effects resulting from changes in wood tissues caused by industrial emissions. There is a decrease of strength at compression up to 10% and decreases of modulus elasticity at static bending up to 15%, 10% and 5% in damage zones III, II and I respectively. Such distinct decreases we assume result from lower alpha-cellulose content. In such a situation, criteria of visual grading of wood will be unreliable, and this could induce application of stress-grading systems and machines from this purpose. There can also be an increase of square surfaces of loaded beams in wooden structures. It is estimated that presently about 1 million $m^3$ is used annually in Poland for structural purposes.

In summary, the following factors ought to be taken into account in estimating the economic losses that may result from forest damage and its impact on the forest-products industry:

- a decrease of diameters of saw logs (5.7 cm in our findings for 60-year-old stands); here we should also consider utilization of wood of lower age classes, considering the sanitary and age structures of forests in Poland;

- losses of material during conversion of roundwood of smaller diameters (loss of about 5% of the wood mass),

- material losses during storage of roundwood (about one quality class lower);

- increases of investment costs in the wood-processing industry for new machines, chemicals and protective treatments;

- losses of about 5% of sawnwood quality and increase of costs of production due to the obligatory treatments and sterilization;

- decrease of strength of sawnwood by about 10%, and increased costs of production by about 10-15%; and

- average changes of about 10% in the chemical composition of wood, implying increased use of glues and lacquers (with higher absorbability of such wood, and with the production of wood-cement materials) by about 10%; increases of mineralizing chemicals in wood-cement bonded materials by about 5% will be required (for 1 $m^3$ of cement-bonded particle board, 700 kg of cement and 22 kg of mineralizing chemicals are used).

## 4. ECONOMIC EVALUATION OF REDUCED WOOD QUALITY AND QUANTITY

Research conducted at the Forest Research Institute in Warsaw on the economic effects of damages caused by biotic and abiotic agents revealed that losses in annual growth of forest stands throughout Poland amounts to about 3 million $m^3$ of wood annually, valued at 25 milliard zlotys (zl). It is assumed that in future (after 1990) those losses could even reach 90 milliard zl. Pine of lower quality was estimated at about 37 milliard zl annually (Anonymous, 1986).

On the basis of our empirical investigations on the range of quality and properties of wood from areas damaged by industrial emissions, economic losses can be estimated. The estimates are rather uncertain due to the hypothetical character of assumed losses caused by industrial emissions. The calculations below incorporate our estimates of decreased technical properties of wood, present amounts of harvested roundwood and production, and current prices and costs.

It was stated above that wood harvested in the near future from damaged areas, despite protective treatments, will yield sawn materials of 15% lower quality. The mean difference of prices between wood quality classes amounts to about 6,600 zl/$m^3$. Therefore, the decrease of sawnwood value due to loss of quality will average 990 zl for 1 $m^3$. For all the roundwood processed in Poland (ca. 6.5 million $m^3$ annually) and sawnwood obtained from that quality of roundwood, joint losses will be about 4,290 million zl annually. Wood harvested from terrain damaged by abiotic agents, in addition to the decrease of quality, is more susceptible to further quality degradation caused by easier spread of fungi and insects. Thus, there will be an obligatory need for protective treatments of pine round- and sawnwood by proper chemical treatments such as sprays, antiseptic dipping and sterilization. It was calculated that the cost of spraying roundwood will be about 165 zl/$m^3$, resulting in costs of protecting all sawlogs of about 1,072 million zl annually. Similarly, protective treatment ought to be applied to all sawn materials. There are two possible ways: antiseptic dipping, and high-temperature sterilization of wood. For calculations, we consider protective treatments by dipping. Taking about 370 g of the proper chemical for one cubic meter of wood, a labor cost of 130 zl/$m^3$, and 2 million $m^3$ of sawnwood, it was calculated that additional costs will be about 288 million zl annually.

It was stated above that we expect a decrease of mean diameter of processed pine trees of about 5.7 cm. This means a decrease of sawlog supply for the sawmilling industry. Additional calculations based on results of other research at the Wood Technology Institute showed that the decrease of diameter of sawlogs is accompanied by losses of material yield when they are processed. The quality yield decrease is disregarded in these calculations. It was determined that a one-centimeter decrease of mean diameter of saw logs causes a loss of yield of sawnwood of about 0.5%. Thus the total loss of material yield to be expected is about 2.8%, or a decrease of production of sawn material of about 182,000 $m^3$. Taking actual prices into account, the loss of production value is 2,912 million zl annually. A decrease of mean diameter of sawlogs of 5.7 cm means that sawmills, in efforts to maintain present levels of production, will be compelled to convert much greater numbers of logs with smaller diameters than at present. Thus there will be a need to increase or to create greater production capacity. There will be ample opportunity for application of new technologies tailored to the smaller sawlogs. An attempt to estimate the increase of conversion costs showed that with actual costs of conversion of saw logs reaching about 3,300 zl/$m^3$, and an increase in the number of saw logs about 15%, the joint increase of costs of conversion will be 3,217 million zl annually.

Our technical tests and investigations showed that wood from damaged forest stands has about 10% less strength. This means that in future structural applications, we will be forced to increase by the same percentage the amount of sawnwood used in structures to maintain the strength properties of erected structures. That will increase the use of wood and labor. Limiting our calculations only to increases of sawnwood used for structural purposes, and taking 1 million $m^3$ for such purposes, the losses in the national economy will reach 1,850 million zl annually.

It is known from our investigations that the changes in wood chemical structure will have some influence on its chemical, physical and mechanical conversion. Without doubt this will result in increased costs due to greater use of glues, lacquers, varnishes and other chemicals. To illustrate this problem, we consider the production of particleboards. We assume an increased expense of 10% for binding agents (chemicals). Taking into account the present level of production of particleboards of about 1.2 million $m^3$ annually, additional expenses for 9,600 kg of glues will increase costs of production by about 384 million zl.

In summary, our estimates of annual economic losses which could arise during conversion of wood depreciated by industrial emissions, based on the actual levels of production, prices and costs, include the following:

| | |
|---|---|
| Decreased quality of sawnwood | - 4,290 million zl |
| Increased costs of protective treatments of roundwood | - 1,072 million zl |
| Increased antiseptic treatments of sawnwood | - 288 million zl |
| Decreased diameter of sawlogs | - 2,912 million zl |
| Increased costs of conversion of thinner roundwood | - 3,217 million zl |
| Decreased strength properties of sawnwood | - 1,850 million zl |
| Increased costs of additional materials (glue) in production of particleboards | - 384 million zl |

This evaluation, which does not take all aspects of losses into account, suggests that expected annual losses in current prices are estimated at about 14 milliard zl, which is a loss of about 1,650 zl/$m^3$ of sawlogs and raw material for board production. The estimates presented are only the part of the total losses. There are losses in the use of energy in paper mills, fiber and particleboard factories due to losses of material which is more soluble or which creates more dust than usual. Therefore, losses are actually much greater than indicated in this paper; their relative value could be estimated roughly at 50% of total losses.

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