Studies on the barrier properties of exterior wood coatings

Jan Ekstedt
Doctoral Thesis
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ABSTRACT

Coatings for exterior wood have two basic functions. One is to give an aesthetically acceptable surface appearance and colour. The other is to provide protection against wood degradation by microbiological or physical attack. These protective properties, often called the barrier properties, play an important role in the selection of proper material for supreme durability. The assessment of these barrier properties is of great importance. Within the CEN Technical Committee 139, Working Group 2, Coatings for exterior wood test methods and performance specifications have been established. For assessment of water protection efficiency a standard test procedure, EN 927-5, has been launched. The present work has focused on its applicability in assessing water protection efficiency in relation to the degradation of coatings during exposure.

Assessments according to EN 927-5 is shown to give significant differences in water absorption values for different types of coatings on wood. The proposed performance specifications in ENV 927 - 2 for the water absorption values for coatings to be used in different constructions seem to be set at acceptable levels. It has been shown that there is a good correlation between the level of water absorption and practical experience of the performance of paints in Scandinavia. However, it has also been shown that the combination of a standard procedure for water absorption measurement and an artificial weathering procedure gives more information regarding expected durability and long-term performance than a single measurement of water absorption on fresh, unweathered coated wood. A combination of water absorption measurement and artificial weathering could become a useful tool in product development as well as in benchmarking. Together with statistical tools, such as reliability-based service life prediction methodologies for predicting the service life of coating systems a reduction in testing times may be achieved.

Surface-active substances in coatings have a negative effect on the coatings ability to prevent water ingress, which most probably is due to the hydrophilic character of these substances. The presence of these substances, which are common in waterborne coatings, alters the moisture sorption characteristics of wood. Considering that these substances occur in waterborne coatings, may be mobilised during and after film formation and accumulate at the coating/substrate interface, there is a great probability that these substances change the moisture sorption characteristics of the wood substrate in an unfavourable way and create unexpected dynamic moisture conditions at the coating/wood interface.

Computerized tomography has been found to be a valuable, non-destructive tool for visualising the spatial moisture distribution of water and moisture in coated wood panels. The method is suitable for recurrent testing of a specimen exposed to a series of processes of wetting, drying. This thesis shows that high moisture contents occur locally at and around cracks. In these areas there is an increased risk of internal tension and stress resulting in crack initiation and propagation and that high moisture contents may occur in the first few millimetres under waterborne coatings despite intact coating films. Even with good barrier properties of the coating, moisture may accumulate by water-vapour
absorption in air gaps behind the cladding thus causing favourable conditions for microbiological colonization.

The work that has been carried out regarding assessment of the water protection efficiency shows promising results regarding the possibility to use reliability-based service life prediction methodology for the assessment. The aim of future work will be to establish more reliable techniques and protocols for assessing service life expectancy and durability, especially for waterborne coatings with special focus on tendencies to early failure and robustness of the coating systems.

Keywords

Coatings, surfactants, water absorption value, EN 927, paint, additives, moisture dynamics, absorption, desorption, artificial weathering, artificial exposure, computerized tomography, MRI.
PREFACE

The work that is presented in this thesis is the result of different research projects that has been carried out at Trätek – Swedish Institute for Wood Technology Research with special focus on improving the durability of coated exterior wood. During the past ten years two especially large projects have been launched. In 1992 a project, “Träkvalitet”, was started by The Swedish Council for Forestry and Agricultural Research (SJFR), which included the research project “Relation between paint system composition and durability of wooden facades”. Some of the work presented in this thesis was included in that project and became part of the development of the quality assured wooden siding, “Kauna-panel”. Between 2000 and 2002, The Association for Swedish Wood Products Research (Träforsk) financed a research project “Environmental friendly coatings for exterior wood”. The objective was to develop waterborne coatings for wood with similar or better performance than the previously used solventborne coatings. Some parts of the work in this thesis has been closely linked to work done in association with my engagement in the European standardisation committee CEN TC 139/WG 2 “Coatings for wood” during the past ten years.

I would like to thank my supervisors Assoc. Prof. Ove Söderström, Assoc. Prof. Folke Björk and Prof. em. Kai Ödeen at the Royal Institute of Technology, Stockholm for their encouragement in the completion of this thesis. Their assistance is kindly acknowledged. The technical assistance of Mrs Katarina Nordman-Edberg, Mr Tommy Sebring and Mr Kjell Sjöberg has really been one of the foundations on which this thesis stands. Their assistance and efforts are very gratefully acknowledged. I would like to thank all my colleagues at Trätek for discussions and co-operations on different matters in wood technology during my years at Trätek. Especially I would like to thank my past and present colleagues in the wood durability group, Prof. em. Julius Boutelje, Dr. Finn Englund, Lic. Ingvar Johansson, Dr Ralph Nussbaum, Dr Mats Westin and Dr Magnus Wålinder for stimulating discussions on scientific as well as non-scientific matters. Mrs Laila Gunnare and Mrs Anna Nilsson are kindly acknowledged for their valuable literature services, Mrs Eva Lindqvist for her editorial revision and service on the manuscript. Special thanks go to my co-authors Mrs Gunilla Östberg at Alcro-Beckers, Stockholm and Ass. Prof. Nasco Terziev at the Swedish University of Agricultural Sciences, Uppsala for stimulating discussions and co-operation.

I would also like to express my sincere thanks to all my friends and colleges in the coatings and wood industries and research institutes with whom I have had the pleasure of discussing different aspects of coating science and technology through the years.

Special thanks go to all my past and present colleagues in CEN TC 139/WG 2 and EU Cost Action E 18, which have formed different forums for discussions on exterior wood coatings during the past decade. The work in those groups are important parts of the development of European standardization on wood coatings and also play an important role initiating coating research in Europe.
The work that is presented in this thesis has been financed though the years, wholly or partially, from different sources. The following organisations are gratefully acknowledged for financial support. The Swedish Wood Exporters’ Association (STEF), The Swedish National Board for Industrial and Technical Development (Nutek), The Swedish Council for Building Research (BFR), The Swedish Council for Forestry and Agricultural Research (SJFR), The Association for Swedish Wood Products Research (Träforsk), The Institute of Research and Competence Holding AB (IRECO), The Swedish Wood Association (Svenskt Trä), Dekkbeisfondet, Norge and the European Commission 5th framework program (Quality of Life program).

Stockholm in November 2002

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<table>
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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CEN</td>
<td>Comité Européen de Normalisation</td>
</tr>
<tr>
<td>CPVC</td>
<td>Critical Pigment Volume Concentration</td>
</tr>
<tr>
<td>CT</td>
<td>Computerized Tomography</td>
</tr>
<tr>
<td>EN</td>
<td>European Norm</td>
</tr>
<tr>
<td>ESEM</td>
<td>Environmental Scanning Electron Microscope</td>
</tr>
<tr>
<td>FOV</td>
<td>Field of view</td>
</tr>
<tr>
<td>FSP</td>
<td>Fibre Saturation Point</td>
</tr>
<tr>
<td>HEUR</td>
<td>Hydrophobically-modified, Etoxylated Urethane.</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standardization Organisation</td>
</tr>
<tr>
<td>LMW</td>
<td>Low Molecular Weight</td>
</tr>
<tr>
<td>LWA</td>
<td>Liquid Water Absorption</td>
</tr>
<tr>
<td>MC</td>
<td>Moisture Content (%)</td>
</tr>
<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>NMR</td>
<td>Nuclear Magnetic Resonance</td>
</tr>
<tr>
<td>PVC</td>
<td>Pigment Volume Concentration</td>
</tr>
<tr>
<td>RH</td>
<td>Relative humidity (%)</td>
</tr>
<tr>
<td>SD</td>
<td>Standard deviation</td>
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<tr>
<td>$T_g$</td>
<td>Glass transition temperature</td>
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1. SCOPE OF THE THESIS

The scope of the present thesis is to focus on the assessment of the barrier properties of organic coatings by means of standard testing procedures and to show how these assessments can be useful in predicting performance by means of reliability-based service life prediction technology. The influence of the composition of coatings on the performance regarding water protection is addressed. Special focus is placed on surface-active substances, which are commonly used in waterborne coating systems. Although both liquid water transport and water vapour transport occur when coated wood is subjected to water in its different forms during its service life, the focus of this thesis is directed to the action of liquid water. The reason for this focusing is that liquid water often produces more serious problems than action of water vapour on wooden constructions. Furthermore, the thesis concentrates on water acting on coated lateral surfaces in contrast to water acting on end-grain, the latter will not be covered by this thesis.
2. **INTRODUCTION**

Coatings for exterior wood have two basic functions. One is to give an aesthetically acceptable surface appearance and colour. The other is to provide protection against wood degradation by microbiological or physical attack. For decorative purposes, the coating should be durable and retain its gloss and colour for an extended period of time, and either be unchanged by solar radiation or be degraded in a smooth and uniform way. For protective purposes, the coating should be durable and retain its physical (e.g. protective) properties as long as possible in order to extend the interval between maintenance. These protective properties often called the barrier properties play an important role in the selection of proper material for supreme durability. The assessment of these protective, or barrier properties is of great importance. Ingress of water or moisture into wood causes dimensional changes which may result in cracking and checking of the film, and hence a loss of durability.

More elaborated methods are needed for assessing physical and chemical properties and durability. These methods are needed if durability and life cycle assessments will become useful methods for predicting service life expectancy. These methods are becoming more and more important as the time required to develop and introduce new products onto the market has become a crucial competitive issue, as Louis Floyd concluded in his 1997 Mattiello Memorial Lecture (Floyd 1998):

“It is essential that we find some reliable means to predict both performance and longevity of new products based on short term laboratory tests. Until now, this has been a largely unsuccessful effort on the part of the paint industry.”

One very important property of coatings for wood, is the ability to protect against unacceptable absorption and desorption of moisture in wooden constructions, which, if present will inevitably lead to dimensional instability. Two results of dimensional instability are jammed windows and cracking of claddings causing economical loss for the end-user. The ingress of water into a wooden construction goes through lateral surfaces (tangential and radial) and through the end-grains. The durability and lifetime expectancy of a coated exterior wood construction depends on its ability to resist the degradation processes that act on the coating and the wood substrate. The degradation processes are caused by the action of radiation, moisture, pollutants and microbiological activity. One of the most important degradation processes for coated wood panels in our climate is degradation by fungal activity. The essential factors for fungal growth are:

- heat
- moisture
- biodegradable matter
- fungal spores
- oxygen
In an exterior wooden construction, the only factor that can be controlled is the supply of water and moisture. Therefore, one important role of the coating is to protect the construction from moisture. Moisture contents in the construction should be kept below a level where the risk for decay by fungi can occur. This level can be described as a probability function, with gradually increasing risk of decay by fungi with increasing moisture content (Viitanen 1996).

Figure 1 shows a schematic presentation of part of a coated wooden panel. Water and moisture acting on the coating causes transport of water through the coating. Diffusion or capillary flow conducts this transport. Ingress of water (i.e. absorption) into the substrate induce dimensional changes (=moisture movements). These dimensional changes induce mechanical stress at the interface between the coating and the substrate, which may lead to loss of adhesion or blistering. Therefore, the coating needs to have enough flexibility to follow dimensional changes in the substrate. Otherwise cracking of the coating may occur, resulting in open pathways for liquid water ingress. Ultraviolet radiation degrades the coating, thus often causing a loss of its protective ability.

The interface between coating and wood is shown in Figure 2. The porous structure of wood is evident. The coating is seen as the black layer in the upper part of the picture. To the left is the porous structure of earlywood and to the right is the more dense latewood.
Fig. 2  
*Environmental Scanning Electron Microscopy (ESEM) image of coated wood.* The image is a cross-section of wood perpendicular to the longitudinal direction of the wood cells. Coating layer at the upper part of the image. Earlywood is seen to the left and latewood to the right. The horizontal white bar represents 300 µm.

From Figure 2 it is obvious that the structural differences in wood (earlywood and latewood) may have an impact on the supporting ability for the coating. The point of intersection between coating, earlywood and latewood is often susceptible to crack initiation and propagation (Stehr and Östlund 2000).

For a wooden construction, a balance between absorption and desorption of moisture is of crucial importance. If absorption is higher than desorption over an extended period, a continuous accumulation of moisture will occur in the construction. If this accumulation reaches high levels there is a risk of coating failure by physical causes like blistering or cracking or by biological causes like attack by blue-stain fungi or rot fungi.

The use of different types of coatings have gone through different stages depending on factors such as raw material availability, environmental legislation and end-user preferences. With the exception of the special Swedish Red Paint (Falu rödfärg) solventborne coatings were the most common type of coating until the 1960's. First, vegetable oils, (e.g. linseed oil, stand oil) were used as binders, but with the introduction of alkyds, in the 1950's, the main drawbacks of linseed oil paints were partly overcome. Unfortunately, both the linseed oil paints and the alkyd paints suffer from, more or less, severe chalking due to their susceptibility to degradation by UV light. In the 1960's, the
concern for environmental pollution by solvents and occupational health aspects caused a great demand for more environmentally friendly coating systems. With the introduction of waterborne paints, mainly based on acrylic polymers dispersed in water, it was believed that this concern was met. Another advantage of acrylics compared to linseed oil and alkyds was better resistance against degradation by UV radiation. The acrylics, therefore, constitute a more durable coating. These waterborne systems are much more complex than the solventborne systems. In a waterborne system, the binder is dispersed as small droplets in the water phase by different additives. Furthermore, the composition of the coating has an influence on the film formation. The mechanism of film formation of waterborne coatings is much more complicated than film formation of solventborne coatings thus causing risk of bad performance due to improper film formation. In the 1970’s, commercial coatings based on alkyds, emulsified in water or water/solvent mixtures, were introduced. In view of the environmental concern, much attention has been drawn towards the wide use of waterborne coatings. Although fundamental research in polymer science and other relevant areas find their way into the coating business, a great proportion of coating formulation is still done on an empirical basis.

Despite the good durability of the waterborne coatings, damage of wooden claddings by microbiological degradation (e.g. rot or blue-stain colonization) has been detected in exterior wooden facades in Scandinavia (e.g. Hjort 1989, 1993; Mohn Jensen 1989) when these types of coatings are used. The reported bad performance of exterior coatings in Scandinavia initiated a comprehensive national survey to study the relationship between coating composition and performance. The objective was to investigate if, or to what extent, differences in blue-stain colonization, adhesion to wood substrate, penetration of coatings into wood and moisture dynamic characteristics could be correlated to coating composition. As parts of this national survey, Bardage (1998) has reported work regarding the susceptibility of painted wood to colonization by blue-stain fungi (Aureobasidium pollulans). Bardage and Bjurman (1998) have reported work regarding adhesion of waterborne paints to wood and Nussbaum et al. (1998) have reported studies of penetration of coatings into wood.

3. COATINGS

3.1 Introduction

The performance of a coating is directly related to its chemical composition (e.g. type of binder and solvent) and physical state where parameters like glass transition temperature \( T_g \), pigment volume concentration (PVC) and critical pigment volume concentration (CPVC) have large impact on performance (e.g. Nagata 1976; Thomas 1991; Ahola 1993 and Dickie 1994).

The glass transition temperature \( T_g \) is the temperature where a polymer changes from a glasslike structure to a more amorphous structure. This transition in state has great impact on the barrier properties of the polymer. \( T_g \) often slowly increases with time for polymeric materials. Absorption of water normally reduces \( T_g \) due to plasticization of the
polymer. Exposure to sunlight may induce chemical reactions in the polymer that can increase or decrease $T_g$.

The pigment volume concentration (PVC) is defined as the fractional volume of the pigment in a unit volume of a given pigment/binder mixture and can be expressed as

$$PVC = \frac{V_p}{V_p + V_b}$$

(1)

Where $V_p$ and $V_b$ represent the volumes of pigment and binder respectively. At the critical pigment volume concentration (CPVC) there is just enough binder in the unit volume to completely fill the voids between the pigments. Above CPVC there exist voids not filled with the binder. The performance of a coating is to a great extent affected by the presence of such air-filled voids in the coating film.

3.2 Coating composition

Coatings for exterior wood normally consist of a physical mixture of substances from the following categories:

- **Pigments**
  (insoluble inorganic or organic pigments giving the coating hiding power, colour and good resistance against abrasion)

- **Binders**
  (polymeric substances, adhering pigment particles together and to the substrate)

- **Solvents**
  (water or organic solvents giving the coating a suitable viscosity for easy application)

- **Additives**
  (improve ease of manufacturing, dispersing agent for pigments, give the coating improved in-can stability and applicability, improve film formation and service life performance). Although the amounts of additives in the coating formulations are often rather low, their influence on coating performance can be very pronounced due to their chemical properties. For instance, surface active chemicals (*i.e.* surfactants) have a tendency to accumulate at interfaces.

Below follows a more detailed presentation of different binders for architectural finishes. The most common binders used in architectural finishes for exterior use are drying oils, alkyd resins and acrylic resins.
**Oils**
Different vegetable oils are used in architectural finishes. They are often in the form of triglycerides (*i.e.* esters of glycerol and fatty acids). Common examples are linseed oil, stand oil (*i.e.* polymerized linseed oil) and tung oil.

**Alkyd resins**
Alkyd resins are crosslinked polyesters synthesised from polyfunctional monomers. The principal raw materials involved in the manufacturing of alkyd resins are polyhydric alcohols (polyols) and dibasic acids (or corresponding anhydrides) together with the modifying oil (or corresponding acids). The modifying oils can be either drying oil, containing a high proportion of unsaturated acids, or non-drying oil, which are based mainly on saturated acids. The unsaturated oils give the alkyd cross-linking ability, thus giving the possibility to form three-dimensional polymeric networks. Raw materials from the three different categories can be used in different combinations thus forming a variety of different alkyds with large differences in physical and chemical properties. Common raw materials are:

- **Polyols:** *e.g.* glycerol, pentaerythritol, trimethylolpropan.
- **Dibasic acids and anhydrides:** *e.g.* phthalic anhydride, maleic anhydride, isophthalic acid.
- **Modifying oils:** *e.g.* linseed oil, tall oil, soybean oil, oiticica oil.

The properties of alkyd resins depends to a large extent on the nature and amount of modifying oil incorporated in the polymer. Therefore alkyds are often classified according to the type of oil they contain. Alkyds with higher amount of modifying oils, so called long oil alkyd resins, are more flexible than short oil alkyd resins.

**Acrylic resins**
Acrylic polymers are often used as binders for waterborne wood coating. The term “acrylic binders” is commonly applied to polymers of homo- and copolymers of esters of acrylic acid and methacrylic acid. The acrylic polymers are used as binders because of their superior properties of water resistance, film clarity and UV resistance. Most acrylic monomers can be polymerised and will copolymerise well with each other in either emulsion form or in a suitable solvent. The film properties of acrylic polymers may be altered substantially by varying the monomer composition.

The commonly used monomers can be divided into three categories, backbone monomers, modifying monomers and functional monomers.

Backbone monomers provide the principal film forming characteristics of the polymer and the basic adhesion properties. Most commonly used is methylmethacrylate (MMA), which has a high $T_g$ and exhibits excellent toughness, light fastness and chemical resistance properties. Other monomers are styrene and vinyl acetate. Modifying monomers are used to soften and flexibilise the polymer and/or to modify the solution properties. Acrylates and methacrylates of lower glass transition temperature ($T_g$) are used. Normally used acrylic modifying monomers are butyl acrylate (BA) and 2-ethyl hexyl acrylate (2-EHA) adding flexibility and improving adhesion. Functional monomers
are used at relative low levels to introduce specific properties such as cross-linking or external cross-linkability. Commonly used are carboxyl containing monomers like acrylic acid (AA) or hydroxyl containing monomers like hydroethyl methacrylate (HEMA). Different monomers like tri-n-butyltin methacrylate (Ghanem et al. 1981) and pentachlorophenol acrylate (Pittman et al. 1982) have been polymerised into acrylics to improve fungicidal effect.

For architectural finishes oils and alkyds may be dissolved in a solvent and used in solventborne coatings or emulsified in water and used in waterborne coatings. The acrylics are normally dispersed in water to be used in waterborne coatings. The use of surfactants is essential for controlling the colloidal stability of the dispersion during synthesis, storage, application and film formation. In waterborne coatings, surfactants are used for different reasons as reviewed by Heilen et al. (1994). Pigments are dispersed by surface-active dispersion aids, the emulsions and dispersions are stabilised by surfactants, and foaming tendencies are depressed by surfactants. Anti-settling agents are also normally surfactants. Both dispersions and emulsions need surfactants to develop stable products. Typical concentrations of surfactants in waterborne coatings are in the range of 0.5 to 5 % (by weight) of the amount of resin. Even if the emulsion system is optimised with respect to emulsion stability, some 25 % of the non-ionic surfactant can be found in the continuous phase (i.e. water phase) due to the hydrophilic/hydrophobic character of the surfactants (Hofland and Schaal 1990). The use of surfactants in coatings has been reviewed by Hellgren et al. (1999). During film formation, phase separation occurs and these surfactants in the water phase may be mobilised and transported into the wood substrate. The surfactants can also be released by rain after film formation and, either washed away, or transported into the wood substrate. The chemical nature of surfactants, with a hydrophilic and a hydrophobic part in the molecule, causes them to accumulate at interfaces, where high concentrations may occur. Bradford and Vanderhoff (1972) noticed the exudation of incompatible surfactants during ageing of latex films. They investigated nonyl phenol-ethylene oxide adducts of varying chain length. The long-chain, hydrophilic, compounds were found to exude towards the film surface, whereas the short-chain, lipophilic surfactants remained in the film. Migration of surfactants has also been reported by Zhao et al. (1989). They showed that accumulation of sodium dodecyl sulphate was enhanced at both interfaces as a result of film ageing. The presence of surfactants in latex films has been shown to strongly influence the adhesion properties (Charmeau et al. 1996). A literature survey on the role of emulsifiers in latex films has been carried out by Bindschaedler et al. (1987). The water absorption properties of different types of rheology modifiers (i.e. thickeners) have been studied by Shay et al. (1996). They found that there is a high degree of water vapour sorption differentiation between different types of thickeners. Their study was performed on pure substances and not in combination with any coating or substrate. Tzitzinou et al. (1999) found that anionic surfactants are always present at the surface of the acrylic latex films, regardless of the film-forming conditions.

Comprehensive outlines of the composition of coating systems is given by Turner (1980) and Paul (1985). Reviews of polymers for waterborne coatings have been published by
Wilson et al. (1990) and Padget (1994). Waterborne alkyd emulsions and alkyd emulsion coatings have been reviewed by Hofland (1994) and Beetsma and Hofland (1998). High solids alkyd paints for decorative coatings have been reviewed by Lindeboom (1998).

The water resistance of a coating is not only a function of the nature of the binder but, also, of the other components of the formulation. All components in a formulation contribute to the hydrophilicity of the coating. The concept of “hydrophilic budget” has been introduced and defined as the total hydrophilicity of a film or coating above which the coating will fail a specific water resistance test (Bassett 2001).

### 3.3 Film formation

The film formation processes for coatings depends to a large extent on the physical state of the coating, *i.e.* whether it is a solventborne, waterborne or solvent-free coating. The film forming process for solventborne coatings is a relatively straightforward process. The polymers, that constitute the binder in a solventborne coating, are solubilized in a solvent. They exist as discrete molecules or molecular aggregates. Upon drying the solvent evaporates forcing the polymer molecules to make contact with one another. Polymers used as binders in solventborne architectural coatings have chemically active sites in the molecule acting as sites for bonding to adjacent molecules thus forming a polymeric network. The mechanism of film formation of waterborne coatings is much more complicated than film formation of solventborne coatings. Theories for the film forming process for waterborne coatings have developed during the past decades (Sullivan 1975; Wicks, Jr. 1986; Croll 1986; Eckersley and Rudin 1990; Joanicot 1990; Wilson et al. 1990; Winnik et al. 1992; Hoy 1996; Vandezande and Rudin 1996; Schultz 1996; Hagedus et al. 1996; Keddie 1997; Tzitzinou et al. 2000; Weissenborn and Motiejauskaite 2000a, 2000b; Visschers et al. 2001 and Provder and Urban 2001).

To summarise, the film formation of waterborne coatings can be regarded as a three-step process:

**Step 1.** Water evaporation and subsequent packing of the polymer particles. When most of the liquid phase is evaporated, the emulsion particles coalesce to an almost solid film. This coalescence is controlled by film forming aids in the coating. The liquid phase of waterborne coating consists of water and film forming aids in specified proportions to achieve optimal film forming.

**Step 2.** Deformation of particles due to capillary and surface forces, sometimes referred to as sintering.

**Step 3.** Interdiffusion of polymer chains from one particle to another. This interdiffusion only takes place above the minimum film forming temperature (MFFT) which is the lowest temperature polymeric solution forms a homogeneous film. Film properties like mechanical strength and permeability are altered during this step.
Climatic conditions, for example relative humidity, influence the evaporation process. The rate at which water evaporates from the latex is dependent on the vapour pressure in the air and, therefore, on the relative humidity. It can also change the order in which the different solvents and water evaporate. A cosolvent \( i.e. \) a film forming aid) may be lost by evaporation before it becomes effective if high humidity has slowed down the evaporation of water relative to the cosolvent. The effect of humidity and other ambient conditions on evaporation of aqueous solvent blends has been reported \( e.g. \) Sullivan 1975; Rocklin 1976; Hansen 1982). The film forming process will thus sometimes deviate from that which can be considered ideal, due to non-optimal film forming conditions. Non-optimal film forming processes \( i.e. \) insufficient coalescence of latex particles) will lead to inferior barrier properties of the coating.

Surfactant migration and enrichment at coating interfaces have been reported. Juhue et al. (1995) have shown that addition of a coalescing aid to a latex dispersion greatly enhances surfactant migration. Torstensson et al. (1990) found using ESCA spectra that a lacquer film containing 1\% (by weight) of a monomeric surfactant my have an average surface surfactant concentration of around 50\%. Zhao et al. (1989) have shown that enrichment of sodium dodecyl sulphate (SDS) in acrylic latex films occur at both interfaces (film/air and film/substrate) but is more pronounced at the film/air interface. Roulstone et al. (1992) concludes that the type and concentration of surfactant used can significantly influence the water permeability of latex films. Higher concentration of surfactant results in higher permeability due to phase separation in the film. There are five possible regimes of deposition of the surfactant during film formation; it dissolves and migrates into the polymer, it is excluded to the latex film surface, independent volumes rich in surfactants are formed and these may or may not be located at the interstitial voids between the particles, continuous network of surfactant is formed and it may remain adsorbed on the particle surface as a monolayer.

3.4 Film morphology

The best barrier properties are usually obtained in latex films when the particles are well ordered prior to the final stage of film formation, when polymer chains interdiffuse, to achieve maximum density without voids or defects (Roulstone et. al. 1992). The highest degree of packing order within the film is usually achieved when the latex particles have a monolayer of surfactant (Juhué and Lang 1994).

During application of coatings on a substrate, air may be entrapped in the coating layer. This phenomenon is often found in waterborne coatings. To some degree this is a result of the presence of surface-active substances in the coating. Figure 3 (left) shows the dried surface of a waterborne acrylic coating. Figure 3 (right) shows an ESEM image of a cross-section through the same acrylic coating showing the presence of craters at the coating/wood interface. These entrapped air bubbles make the coating porous with a less “effective” film thickness. This fact may have some impact on the water protection efficiency as the “effective” film thickness is less that the “nominal” film thickness and the water protection efficiency is a function of the film thickness.
When the coating is applied on a porous substrate the binder may penetrate into the substrate during application resulting in a decrease in binder level. Such a decrease would increase the PVC of the film, a fact that can significantly change the permeability of the coating film (Perera and Selier 1973). Surface structures have been studied extensively during the past decades with the introduction of atomic force microscopy (e.g. Butt 1995; Hellgren 1998; Weissenborn and Motiejuskaite 2000b).

Fig. 3  
Left: Coating surface of a waterborne acrylic opaque coating showing pores. FOV: approx. 2 x 1.5 mm.

Right: Environmental scanning electron microscopy (ESEM) image of a cross-section of the acrylic opaque coating showing entrapped air bubbles generated at the application. White bar = 200 µm.
4. PERFORMANCE TESTING

4.1 Introduction

The ultimate goal of research on coatings for wood is extended service life. Service life represents a significant economic concern. A systematic assessment of a coating system consists of the syntheses of information from different sources of experience. This information is merged into a predictive model for the prediction of performance of a system. These sources can be summarised as follows:

- Material science
- Practical use
- Field tests (natural weathering)
- Accelerated tests (artificial weathering)

Performance tests consist of three elements:

- Experiments
- Evaluation of the degradation state or measurement of physical property
- Mathematical analysis of the data

Information, gained from practical use is, in fact, the only information that really reflects the actual performance of the systems in question under realistic conditions. This information has, of course, the disadvantage of not being especially useful for comparison between different systems tested at different locations and at different times. The conditions that act on one object are not easily transferable to other objects. This disadvantage is, in part, reduced by studying the systems under more controlled conditions in field tests, where the environmental conditions are the same for all observed systems. The field tests play two important roles in the evaluation of a predictive model. One is as a reference against which the results of laboratory test can be compared. The other role is as a source of information on modes of failure. Testing of exterior wood coatings by natural weathering, in field tests, is considered as a very useful tool for gaining information about outdoor performance and lifetime expectancy. The studied factors could be combined in a more scientific way, for example in factorial designed experiments. This gives a more reliable background for statistical evaluations of the performance of the coatings. The disadvantage with field tests is that the exposure times are usually very long before any significant changes occur, at least when studying high performing systems with good durability. To enhance the degradation processes, and shorten the time to failure, different methods for accelerated tests have been designed to accelerate the degradation processes to obtain relevant assessments in shorter times. Factors usually enhanced are UV-radiation, action of liquid water and high humidity and freeze/thaw exposure.

The introduction of "acceleration shift factors", as outlined by Simms (1987), is an attempt to improve the model of correlation between natural weathering and accelerated tests. Extensive work in refining and adopting accelerated methods to the field of coatings.
on wood is done within the European Committee for Standardization (CEN) and the International Standardization Organisation (ISO). However, development of an effective and reliable accelerated test must be based on the understanding of the fundamental processes involved in the degradation of the coating and the substrate, and the modes of failure. Knowledge about these processes is gained from the material sciences. The material science approach incorporates such disciplines as polymer physics, polymer chemistry, surface and colloid chemistry, wood anatomy, adhesion and interfacial sciences, coating formulations, moisture dynamics and statistics. A main objective of performance tests is to screen out bad products or to compare novel products to products having long performance history. Natural exposure testing is often regarded as the ultimate and most reliable tests of performance.

A fundamental concept in all performance testing is reproducibility and repeatability. In order to be useful in comparing results from measurements in different occasions and at different times, procedures need to be reproducible and repeatable. Although natural field exposure tests resemble the condition the coating will face in its intended use, field studies lack both reproducibility and repeatability (Martin 2002). Furthermore, the degradation is not linear over exposure time but rather occurs more rapidly during certain “critical” times. He has reviewed the literature to find support for natural exposure to be useful for comparing durability when exposure is made at different occasions and at different times. He concludes that testing is not repeatable for tests that are performed at the same site, at the same angle of exposure, at the same time of the year and for the same duration, but exposures begin on different years. Furthermore, if exposures begin at different times of the year, for different duration, at different exposure angles and at different exposure sites neither repeatability nor reproducibility was found. This is supported by the fact that it has been difficult to develop climatic indexes to be used for comparing field exposure at different locations. One approach has been taken in EN 927-3 when using a reference coating (Internal Comparison Product, ICP) to assess the exposure conditions at field-testing sites (EN 927-3, 2000).

The traditional way of performing assessment of durability for a system is to expose the specimens to some climate (natural or artificial). When using an artificial and accelerated exposure schedule it is of utmost importance that the chemistry involved in the artificial exposure does not differ from the chemistry that is involved in natural weathering. Otherwise the exposure testing results do not reflect the durability in real life applications.

In conventional durability assessment, the performance is assessed for one or more parameters after a specified time that is regarded to be an indicator of durability, for example cracking, blistering or water absorption. This is exemplified by the vertical line at exposure time =35 weeks in Figure 4 where the water absorption value vary between 500 and 800 g/m². The result of the assessment after week 35 will be reported as mean value, sometimes supplemented with the standard deviation.
In reliability-based service life methodology (Martin et al. 1996; Martin 1999), the time to reach a pre-set value for the water absorption value is measured. In Figure 4 the pre-set “critical performance value” is set to 300 g/m². The time for a replicate to reach the “critical performance value” is called “time-to-failure” and in Figure 4 shown to be between 17 and 27 weeks. These “time-to-failure” values can be used to calculate life expectancy distributions (Martin et al. 1996). The methodology of reliability-based service life prediction techniques is briefly described in Chapter 5. In Paper IV, reliability-based service life methodology is used to exemplify how water absorption measurements may be used in assessing the water protection efficiency of a coating system. In EN 927, there is a performance standard, ENV 927 - 2 proposing "Limit values for performance criteria" for coatings intended for different end uses, for example coatings for windows (stable substrate), for cladding (semi-stable substrate) or for fences (non-stable substrate). The proposed maximum accepted water absorption value for coatings or coating systems for "stable constructions” is 175 g/m² and for "semi-stable constructions” 250 g/m².

4.2 Artificial exposure testing

The European standard EN 927-5, “Assessment of liquid water permeability” contains a clause for optional testing of weathered panels. Clause 6.3 states: "If required, coatings may be subjected to a weathering test before or after measurement of liquid water permeability”. (EN 927-5, 2000). However, the standard does not specify any defined weathering procedure. A procedure for artificial weathering has been developed at Trätek.
This artificial testing procedure is used in Papers I, II and IV and outlined in Table 1. Artificial weathering was used because it offers acceleration and control over the weathering conditions.

**Table 1. Artificial weathering schedule used in Paper I, II and IV. Duration 840 hr (= 5 weeks).**

<table>
<thead>
<tr>
<th>Step</th>
<th>Function</th>
<th>Temperature</th>
<th>Duration</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Floating on water&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20°C</td>
<td>72 hr</td>
<td>In a conditioning room at 20°C/65% RH</td>
</tr>
<tr>
<td>2</td>
<td>Freezing</td>
<td>-18°C</td>
<td>24 hr</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Light/water spray&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Black panel temp. 63±3°C</td>
<td>72 hr</td>
<td>Atlas Weather-Ometer&lt;sup&gt;®&lt;/sup&gt; Ci65</td>
</tr>
<tr>
<td>4</td>
<td>Floating on water&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20°C</td>
<td>72 hr</td>
<td>Same as for Step 1</td>
</tr>
<tr>
<td>5</td>
<td>Cooling</td>
<td>+3°C</td>
<td>24 hr</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Light/water spray&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Black panel temp. 63±3°C</td>
<td>72 hr</td>
<td>Same as for Step 3</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td>Step 4 – 6 repeated 4 times</td>
</tr>
</tbody>
</table>

N. B.  
<sup>a</sup> = floating the test panels on the surface of water in a filled container with the coating under test facing downwards.

<sup>b</sup> = exposure to light and water spray in an Atlas Weather-Ometer<sup>®</sup> Ci65 (WoM) with a 6500 W xenon arc lamp. Spectral irradiance: 0.35 W/m²/nm at 340 nm. The WoM was programmed for 102 minutes of light followed by 18 minutes of light and water spray according to ISO 11 341:1994, method 1, wetting cycle A.

Before the artificial weathering and after 5, 10, 15, 20, 25, 30 and 35 weeks the test samples were conditioned to constant weight in 20°C and 65% RH and then subjected to measurement of the water absorption value according to EN 927 - 5. In Paper I and II, the weathering was performed for 15 weeks and in Paper IV for 35 weeks. The time for the conditioning step was normally 3 to 4 weeks. The Atlas Weather-Ometer<sup>®</sup> with xenon arc lamp was used in the weathering schedule because the xenon arc lamp shows similar spectral distribution to natural sunlight (see Figure 5).
Fig. 5  Relative irradiance of filtered xenon-arc radiation (black graph) used in the Atlas Weather-Ometer and normal sunlight (grey graph). (Atlas Electric Devices Co.)
5. RELIABILITY-BASED SERVICE LIFE PREDICTION METHODOLOGY

The methodologies and system approach for predicting the service life of coating systems that have been used in this thesis have been exhaustively outlined by Martin, Saunders, Floyd and Wineburg (1996). Their approach is based on reliability-based methodologies for the assessment of service life prediction for organic coatings. In a life test, a number of replicates are randomly selected from a population and are subjected to a certain stress. With increased time of exposure, the replicates start to degrade or change performance in relation to the applied stress. This degradation can result in either a serious failure or a drift out of tolerance or specification of a critical performance property. This change in the performance characteristics over time can be described by some function \( \eta(t) \), called a sample function. The sample function that was found to be the best fit for the measured water absorption values for coating system 2 in Paper IV had the form

\[
WAV(t) = a + bt + ct^2
\]  

(2)

where \( WAV(t) \) is the water absorption value at time \( t \), and \( a, b \) and \( c \) are coefficients.

Coefficients for System 2 are reported in Paper IV.

The lifetime of a specimen is defined as the time at which its sample curve reaches a preset limit or failure criterion. The user-defined tolerance or maximum or minimum value for a certain stress is called critical value, \( H_{\text{crit}} \) and the time at which a replicate fails is called its time-to-failure, \( t_n \). In Paper IV the critical value, \( H_{\text{crit}} \) was set to a water absorption value of 300 g/m\(^2\) and the time for each replicate to reach that critical value was expressed in weeks. If all of the replicates start the test at the same time, then the observed or calculated time-to-failure are arranged in ascending order. If \( t_i \) is the \( i \)-th observed or calculated time-to-failure, then

\[
t_1 \leq t_2 \leq \ldots \ldots \leq t_j \leq \ldots \ldots \leq t_r
\]  

(3)

where \( r \) is the number of replicates which have failed at the time when the test is terminated, \( n \) is the total number of replicates and \( r \leq n \).

Sometimes the tests are terminated before all replicates have failed; i.e. only replicates 1 to \( r \) have failed. The other replicates (\( t_{r+1} \) to \( t_n \)) that have not failed or exceeded the critical value, \( H_{\text{crit}} \), are said to be censored. For each replicates the following points are plotted as shown in Figure 6:

\[
\begin{align*}
\text{x-axis} & : t_1 \quad t_2 \quad t_3 \quad \ldots \ldots \quad t_n \\
\text{y-axis} & : (1-0.5)/n \quad (2-0.5)/n \quad (3-0.5)/n \quad \ldots \ldots \quad (n-0.5)/n
\end{align*}
\]

where \( n \) = number of replicates.
Figure 6 shows the calculated time-to-failure ($t_1$ to $t_5$) for the five replicates for System 2 in Paper IV together with the life distribution function $F(t)$ that best fits the observed time-to-failure.

![Weibull Distribution](image)

$F(t) = 1 - e^{-\left(\frac{t}{\beta}\right)^{\alpha}}$

where $F(t)$ is the time-to-failure distribution
$\alpha$ is the shape parameter
$\beta$ is the scale parameter

From the ordered time-to-failure, a cumulative distribution function can be fitted to these values. In life time studies the Weibull distribution $F(t)$ is frequently used and has the form:

$$F(t) = 1 - e^{-\left(\frac{t}{\beta}\right)^{\alpha}}$$  \hspace{1cm} (4)

The Weibull reliability function $R(t)$ is given by:

$$R(t) = 1 - F(t)$$  \hspace{1cm} (5)
and its probability density function $f(t)$ is given by:

$$f(t) = \frac{\alpha}{\beta} \left( \frac{t}{\beta} \right)^{(\alpha-1)} \exp \left[ -\left( \frac{t}{\beta} \right)^{\alpha} \right]$$  \hspace{1cm} (6)

The hazard rate, $h(t)$ for the Weibull distribution is found by dividing Equation (6) by Equation (5):

$$h(t) = \left( \frac{\alpha}{\beta} \right) \left( \frac{t}{\beta} \right)^{(\alpha-1)}$$  \hspace{1cm} (7)

Solving Equation (4) for time $t$, the maximum service life, $t_{sl}$, at the exposure conditions, can be calculated:

$$t_{sl} = \beta \left[ -\ln(1 - \Phi) \right]^{\frac{1}{\alpha}}$$  \hspace{1cm} (8)

where $\Phi$ is the fraction of the specimens failed after time $t$.

The question arises as to which time to failure should be regarded as the service life of the product. For coatings and coating systems, end-users are often more concerned with the premature failure than the half-life of the population. Using Equation (8) on the test results for coating system 2 in Paper IV with $\Phi$ set to 0.05 (i.e. only 5% of the samples are supposed to have failed), $\alpha$ and $\beta$ are 6.63 and 22.8 respectively, the $t_{sl}$ is calculated to be 14.6 weeks. This calculated $t_{sl}$ can then be compared with $t_{sl}$ for other coatings thus making performance comparison possible.

For some products early failure are frequent and often referred to as “infant mortality” or “freak failure”. Reasons for this are for example design flaws, manufacturing errors, inadequate preparation of substrate or bad coating application. Most product liability claims occur during this interval (Floyd 1998). By using reliability theory and life testing analysis, it is possible to compare different coating systems and to compare novel products to products having long performance history. Comparison can be made not only for the difference in overall performance and durability but also the performance for the first percentage of failure, i.e. premature failure.
6. MOISTURE DYNAMICS IN COATED WOOD

6.1 Introduction

The movement of water through coatings on wood can be described by different mechanisms, Siau (1984):

1. Liquid water transport, through the coating, into the wood substrate (water absorption)
2. Water vapour transport, through the coating, into the wood substrate (water vapour absorption)
3. Water vapour transport, through the coating, from the wood substrate (water vapour desorption)

The first step (1) involves several sub-steps (Thomas 1991):

- absorption into the film surface
- solubilization into the polymeric matrix
- diffusion through the matrix due to a concentration gradient, and
- desorption from the film into the interfacial region between the film and the substrate.

Fick’s first law of diffusion states that during steady state diffusion, moisture flux is proportional to the gradient in moisture content, making concentration gradient the driving forces for diffusion (Crank 1975).

For one-dimensional transport Fick’s first law yields

\[
g = -D \cdot \frac{d(MC)}{dx}
\]

where
- \(D\) = transport coefficient
- \(MC\) = moisture content (mass of moisture/dry mass)

The value of \(D\) is dependent on the corresponding potential.

Assuming that diffusion of moisture into wood obeys Fick’s second law in one-dimensional flow and neglecting the dimensional changes, one gets:

\[
\frac{\partial MC}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial MC}{\partial x} \right)
\]

where
- \(MC\) = moisture content
- \(x\) = distance along the direction of flow
- \(t\) = time
- \(D\) = diffusion coefficient
When the diffusion coefficient is a function of the moisture content the solution of Equation (10) is cumbersome. Siau (1984) proposed an approximate solution to solve Equation (10) by using a mean diffusion coefficient, $\overline{D}$, for parallel-sided test bodies:

$$\overline{D} = \frac{\pi E^2 L^2}{16t}$$  \hspace{1cm} (11)

where $\overline{D} =$ mean diffusion coefficient, m$^2$ s$^{-1}$  
$E =$ fraction of final water absorption at time t, dimensionless  
$L =$ sample thickness, m  
$t =$ time, s

This graphical solution, Equation (11), has been used in Paper III to calculate moisture diffusion coefficients for uncoated spruce and spruce treated with coating additives.

The rate of permeation depends on two parameters, the solubility of the water in the polymer and the diffusivity of the water (Thomas 1991). The permeability is defined as:

$$P = D \cdot S$$  \hspace{1cm} (12)

where $P =$ permeability coefficient  
$D =$ diffusivity coefficient  
$S =$ solubility coefficient

In coatings having both crystalline (or areas with high cross-link density) and amorphous areas, water solubility will occur only in the amorphous areas. Presence of substances with plasticizing effects will increase water solubility (Hare 1997a). Polymers with hydrophilic groups will show stronger affinity with water than polymers with hydrophobic groups thus making them more water sensible. However, areas with polar structures may reduce the rate of water diffusion due to lower mobility due to hydrogen bonding. Mills and Mayne (1981) showed that most cross-linked polymeric films have areas of higher and lower cross-link density. The substrate under low cross-link density areas was more affected by water than under high cross-link areas.

Transport of liquid water in organic polymers is mainly controlled by diffusion (e.g. Bagda 1990). The diffusion through the matrix due to a concentration gradient can be of two different mechanisms, activated diffusion through the homogenous polymer matrix, and non-activated diffusion through pores and defects (i.e. sub-microscopic pathways). In non-porous films water transport occurs through activated diffusion whereas in porous films capillary transport occurs to a larger extent resulting in higher permeability. This may be the reason waterborne coatings with more porous films often show higher permeability.
Adding pigments to a polymer matrix (i.e. opaque coating) will lower the permeability since normal pigments are inorganic substances with “non-permeable” properties, as long as the pigment volume concentration (PVC) is below the critical pigment volume concentration (CPVC). Well dispersed, non-hydrophilic, impermeable pigments reduce the diffusion of water through the coating by increasing the volume fraction of impermeable substances in the coating (Hare 1997b). In practice the reverse may occur. If incomplete dispersion, flocculation, irregular distribution, poor bonding between pigment and resin or non-ideal pigmentation, (e.g. hydrophilic pigments) exist, these non-ideal conditions can even lead to an overall increase in moisture transport through the coating with increasing PVC (van der Wel and Adan 1999). Some pigments are hydrophilic in nature and some degree of flocculation may occur due to improper dispersion. Adding surfactants, which in turn may coat the pigments with water-sensitive layers, normally solves flocculation. The work by Michaels (1965) indicates that the water absorption through the interfaces between pigment and polymer matrix is substantially greater than the water transport through the polymer matrix. The use of chemically surface-modified pigments may, in part, solve this problem.

The diffusion in the homogenous polymer matrix can be divided into three basic cases (Blahnik 1983):

- Case I or Fickian diffusion, where the speed of diffusion is much smaller than the speed of relaxation in the polymer
- Case II diffusion, where the speed of diffusion is very fast in comparison with relaxation processes
- Non-Fickian diffusion, which appears when the speed of diffusion and relaxation are comparable

The change from one diffusion mechanism to another may take place when the polymer changes its physical state, for example passes the glass transition temperature where relaxation processes change considerably. Absorption of substances that plasticizes the polymer film has also been found to increase the diffusion coefficient. Michaels (1965) concludes that for polymers capable of absorbing less that about 5% of water, the diffusion coefficient for water is essentially independent of water content or relative humidity. For polymers absorbing more than 5% of water, the diffusion coefficient tends to increase rapidly with water content due to the fact that water itself gives swelling and plasticization to the polymer. Deviation from Fickian diffusion may be due to the fact that certain penetrant molecules bind to certain active localities in the polymer matrix and thus become more immobile.

Numerous studies have been reported in the literature regarding moisture transport through paint films (Holbrow et al. 1972; Bagda 1988; Ahola 1993; Davies and Bassi 1994; Nilsson and Hansen 1981; Hora 1994; Ekstedt 1995a, 1995b; Derbyshire and Miller 1996, 1997a, 1997b; de Meijer and Millitz 2000, 2001; de Meijer 2002). Review articles on water and moisture behaviour in coated wood have been published (Huldén and Hansen 1985; Graystone 1998; van der Wel and Adan 1999). Theoretical calculations
of moisture conditions in coated wood have been carried out (e.g. Hjort 1998 and Derbyshire and Robson 1999). Due to the anisotropic character of wood some parts of a wooden construction are more susceptible to water ingress than others. The importance of end-grain sealing on moisture protection has been addressed (Miller and Boxall 1984, 1987; Miller et al. 1987; Raaschou Nielsen and Lindberg 1987; Lawther et al. 1992). Many reports in the literature deal with the moisture dynamic properties of free films. A more realistic approach is to measure these properties of coatings on wood. Nguyen et al. (1995) review the literature regarding water permabilities for coatings applied to a substrate and water permeability for free films. They conclude that several papers report higher water uptake in applied films than in free films while the opposite sometimes also is reported. Huldén & Hansen (1981) report that the measured permeability of water and moisture through coatings on wood is normally higher than the measured permeability through free films. They report the following reasons for this discrepancy:

- When the thickness of the coating is calculated, based on the amount of coating applied, the effective thickness will be less because some of the coating will penetrate the substrate
- The uneven swelling of the wood substrate compared to the swelling of the coating
- Fibres from the substrate penetrate the coating film, thus reducing the net thickness
- The interface between the coating and the wood is larger than its geometrical surface
- The surface of the wood is more hydrophilic than the coating
- Cracks and inhomogenity of the coating on wood are difficult to control

6.2 Methods for assessment of water uptake in coated wood

Several techniques have been used for measuring the liquid water transport through coatings. There are basically two different approaches, steady-state methods and sorption methods.

Steady-state methods measure the permeability as the amount of penetrant transported through a defined area in a specified time when there is a one-dimensional, constant driving force over the test sample. Sorption/desorption methods measure the change in weight of a test sample when the surrounding condition changes. Sorption curves are usually provided by measuring the weight of the sample at different times. The data are normally plotted as weight gain versus square root of time. A mathematical treatment of steady-state methods and sorption methods is found in Crank (1975). In Paper III a sorption method was used to measure the sorption behaviour of wood treated with coating additives.

The water transmission properties of coatings and coating systems can be expressed in different ways, for example as the moisture-excluding effectiveness, MEE (Feist et al. 1985) as the water uptake coefficient, \( w_t \) (DIN 1987), or as water absorption value. The latter approach is used in EN 927 – 5 and is more elaborated in 6.2.1.
The moisture-excluding effectiveness, MEE is defined as:

\[ MEE = \frac{U - C}{U} \cdot 100 \]  

(13)

where  
\[ U = \text{weight of moisture absorbed by uncoated wood sample} \]
\[ C = \text{weight of moisture absorbed by finished wood sample} \]

\( U \) and \( C \) are the weight gains when the samples are subjected to a step-wise raise in relative humidity from 30% to 90%. Variations in the absorption characteristics of the wood samples do not to any large extent affect the amount of moisture absorbed by the finished wood samples. However, they seriously affect the unfinished wood samples thus causing the MEE value to be too dependent of wood characteristics rather than to be a measure of the characteristics of the finished wood.

The water uptake coefficient, \( w_t \), is defined as:

\[ w_t = \frac{\Delta W_t}{\sqrt{t}} \]  

(14)

where:
\[ w_t = \text{water uptake coefficient [kg/m}^2 \cdot \sqrt{\text{h}} \] .
\[ \Delta W_t = \text{difference in weight between start and time t, [kg/m}^2 \] .
\[ \sqrt{t} = \text{square root of measuring time [hr]} \] .

An advantage with presenting results as "water uptake coefficient", \( w_t \), is that the results are normalised with respect to absorption time.

6.2.1 EN 927 - 5

The European standard EN 927-5 specifies a test method for assessing the liquid water permeability of coating systems for exterior wood by measuring the water absorption of coated wood panels (EN 927-5:2000). A summary of the development of the EN 927 standards has been published by Miller (1998). This standard method has been used in Paper I, II and IV. Some deviations from the standard procedure have been used in order to focus on different properties of the coating systems. These deviations from standard procedures are explained in close contact to the presentations of Paper I, II and IV. A general deviation from EN 927-5 is that, except for some measurements reported in Paper I, the pre-conditioning procedure in EN 927-5 clause 6.1 was not performed prior to initial water absorption measurements. The reason for this deviation was that pre-leaching of water-soluble substances and substances influencing water absorption values would obscure the aim of some tests, which was to assess the initial water protection properties.
Water absorption measurements are specified in EN 927-5. After conditioning the test samples, the samples are exposed to deionized water for 72 hours. This exposure is achieved by floating the panels on the surface of the water in a filled container with the coating under test facing downwards. This test procedure was carried out in a controlled environment at 20°C and 65 % RH in the measurements reported in Paper I, II and IV. The weight increase of the test samples was recorded after 72 hours. After this initial water absorption measurement, the test samples were subjected to artificial weathering. The liquid water permeability was determined as the increase in weight of the test samples after 72 hours of floating on water as specified in EN 927-5. For each set of five replicates, the arithmetic mean value of the weight increase and the standard deviation were calculated. The arithmetic mean value of the weight increase after 72 hours of floating is reported as the water absorption value (WAV) and is expressed as g/m².

To test the repeatability of the EN 927-5 test procedure, uncoated spruce samples and spruce samples with coating systems applied on tangential and radial cut wood surfaces respectively were subjected to water absorption measurements according to EN 927-5. Figure 7 shows that the type of surface (tangential or radial cut) had very little effect on the water absorption value. Figure 7 and Table 2 show that the standard deviation is quite small in spite of the fact that the samples have been subjected to artificial weathering. This strengthens the opinion that the limiting factor for water absorption in these measurements is the coating itself and not the substrate.

**Fig. 7** Water absorption values for uncoated spruce (Systems 1 and 4) and spruce coated with two layers of an acrylic coating (Systems 2 and 5) and wood samples coated with an alkyd primer and an acrylic topcoat (Systems 3 and 6) applied to tangential and radial wood surfaces respectively. Columns represent water absorption values after 0, 5, 10, 15, 20, 25 weeks of artificial weathering according to weathering schedule outlined in Table 1 and in section 4.2. Bars represent standard deviation.
The water absorption value for uncoated spruce gradually increases during weathering. It seems that the water absorption value for uncoated spruce is about the same regardless of the surface (i.e. tangential or radial cut surfaces) facing the water.

Table 2. Standard deviation (%) for the water absorption values reported in Figure 8, before weathering (Init.) and after 5, 10, 15, 20 and 25 weeks of artificial weathering.

<table>
<thead>
<tr>
<th>System</th>
<th>Primer</th>
<th>Topcoat</th>
<th>Init.</th>
<th>After 5 weeks</th>
<th>After 10 weeks</th>
<th>After 15 weeks</th>
<th>After 20 weeks</th>
<th>After 25 weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Tang.</td>
<td>Untreat.</td>
<td>-</td>
<td>-</td>
<td>1.8</td>
<td>4.0</td>
<td>3.4</td>
<td>2.7</td>
<td>2.9</td>
</tr>
<tr>
<td>2 Tang.</td>
<td>-</td>
<td>2x acrylic</td>
<td>3.2</td>
<td>3.3</td>
<td>21.1</td>
<td>10.3</td>
<td>12.4</td>
<td>9.8</td>
</tr>
<tr>
<td>3 Tang.</td>
<td>-</td>
<td>SB alkyd</td>
<td>2x acrylic</td>
<td>8.3</td>
<td>6.2</td>
<td>7.7</td>
<td>3.6</td>
<td>7.8</td>
</tr>
<tr>
<td>4 Rad.</td>
<td>Untreat.</td>
<td>-</td>
<td>-</td>
<td>3.4</td>
<td>2.1</td>
<td>1.2</td>
<td>1.8</td>
<td>1.9</td>
</tr>
<tr>
<td>5 Rad.</td>
<td>-</td>
<td>2x acrylic</td>
<td>2.1</td>
<td>7.4</td>
<td>10.9</td>
<td>10.1</td>
<td>9.7</td>
<td>8.2</td>
</tr>
<tr>
<td>6 Rad.</td>
<td>-</td>
<td>SB alkyd</td>
<td>2x acrylic</td>
<td>7.4</td>
<td>4.3</td>
<td>25.5</td>
<td>4.5</td>
<td>5.2</td>
</tr>
</tbody>
</table>

*individual water absorption values: 137, 145, 151, 179 and 224 g/m², 72 hr.

*individual water absorption values: 65, 66, 69, 70 and 110 g/m², 72 hr.

The measurements that are reported in Paper I and IV show that the standard deviations is at an acceptable level regardless of the small number of samples. Absorption of 0.1 gram of water in a test sample is equivalent to 9.5 g/m² in water absorption value.

6.3 Assessment of moisture uptake in coated wood (Paper I)

6.3.1 Introduction

Within the standard, EN 927, there is a performance standard, ENV 927 - 2 proposing "Limit values for performance criteria" for coatings intended for different end uses, for example coatings for windows (stable substrate), for cladding (semi-stable substrate) or for fences (non-stable substrate). The proposed maximum accepted water absorption value for coatings or coating systems intended for "stable constructions" is 175 g/m² and for "semi-stable constructions" 250 g/m². These values refer to the water uptake through the coating after 72 hours of exposure to liquid water. Paper I reports the water permeability properties of a number of commercial decorative and industrial coatings, measured as water absorption values according to EN 927-5 with minor modifications. The objective was to search for correlation between the water absorption values for different coatings and the performance of the coatings in practice, to discuss the proposed limits for classification and to discuss and exemplify the need to standardise a method for artificial ageing.
6.3.2 Materials and methods

Test panels

Test samples of Norway spruce (Picea abies) were used. The dimensions of the test samples were 150x70x20 mm (longitudinal, tangential and radial directions respectively). All faces were planed. The test samples were manufactured in accordance with the specifications in EN 927 - 5. Prior to coating, the test samples for Systems 2 – 9 (see Table 3) were conditioned to constant weight at 23°C and 50% relative humidity. This climate is normally used in standard methods for coatings, but is not in accordance with the climate recommended in EN 927 - 5 which is 20°C and 65% relative humidity which is normally used when testing wood. The initial moisture content in panels for Systems 2 – 9 was approximately 9 %. The test samples to be used for System 1 and Systems 10 - 14 were conditioned in accordance with prEN 927 - 5 (20°C and 65% relative humidity). The initial moisture content in the panels for System 1 and Systems 10 – 14 was approximately 12 %. The discrepancy in conditioning for the different systems is discussed in Paper I but not considered to have any effect on the results of the water absorption measurements. Table 3 shows the different coatings that were tested in Paper I. Full description of the coating systems are given in Table 1 in Paper I.

Table 3. Coating systems tested in Paper I. SB = solventborne, WB = waterborne, ICP = Internal Comparison Product, specified in EN 927-3.

<table>
<thead>
<tr>
<th>System</th>
<th>Coatings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SB alkyd primer</td>
</tr>
<tr>
<td>2</td>
<td>SB alkyd primer + SB alkyd paint 1</td>
</tr>
<tr>
<td>3</td>
<td>SB alkyd primer + WB acrylic paint</td>
</tr>
<tr>
<td>4</td>
<td>2x SB alkyd paint 2</td>
</tr>
<tr>
<td>5</td>
<td>2x WB alkyd paint 3</td>
</tr>
<tr>
<td>6</td>
<td>2x WB acrylic paint</td>
</tr>
<tr>
<td>7</td>
<td>2x WB alkyd emulsion paint</td>
</tr>
<tr>
<td>8</td>
<td>3x linseed oil paint</td>
</tr>
<tr>
<td>9</td>
<td>2x SB alkyd stain</td>
</tr>
<tr>
<td>10</td>
<td>2x WB polyurethane dispersion paint</td>
</tr>
<tr>
<td>11</td>
<td>Swedish red paint</td>
</tr>
<tr>
<td>12</td>
<td>2x SB polyurethane paint</td>
</tr>
<tr>
<td>13</td>
<td>2x polyurethane/acrylic paint</td>
</tr>
<tr>
<td>14</td>
<td>2x ICP</td>
</tr>
</tbody>
</table>

The decorative coatings (System 1 – 11) that were tested represent normal coatings used in Scandinavia. The industrial coatings (Systems 12 and 13) are special coatings for windows, and they represent products for applications defined as "Stable constructions" according to the classification in EN 927 - 1. Also included is the Internal Comparison Product (ICP), a transparent wood stain. The ICP (System 14) is defined in EN 927 - 3 and is used as a reference coating in testing. The test samples for all the systems, except
Systems 12 and 13, were coated by brush on one tangential surface. Systems 12 and 13 were spray applied. The different coating systems were applied to one lateral face according to the manufacturer’s recommended spreading rate. For each system, five replicates were coated. The amount of paint applied was weighed and the dry film thickness was calculated. After drying, the end grains and the uncoated faces were coated with a solventborne alkyd primer followed by one layer of a moisture-impermeable coating.

6.3.3 Results
The results in Paper I show that the European standard method, EN 927-5, for measurement of the water absorption value for coatings gives significant differences in water absorption values for different types of coatings on wood. The proposed limits for the water absorption values, for coatings to be used in different constructions, seem to be set at acceptable levels, at least if measurement before any weathering is considered. There is good correlation between the level of water absorption and practical experience of the performance of the paints in Scandinavia. The water absorption values for the tested coatings are shown in Figure 8.

Fig. 8 Water absorption values for different types of coatings. Mean values for five replicates and the 95 % confidence intervals are shown. The water absorption value for the untreated wood was 1101 g/m². The horizontal lines show the proposed limits in ENV 927-2 for coatings used on wood for "stable construction", 175 g/m² and for "semi-stable" constructions, 250 g/m². Paper I.
The results for the traditional solventborne alkyd paints, Systems 1, 2 and 4, clearly show a good protection against liquid water. All these paint systems fall well into the proposed category for use on stable and semi-stable constructions. This agrees well with many years of practical experience with these types of paints on wooden facades in Scandinavia. The waterborne alkyd paint, System 5, also shows good protection against water and falls into the category for use on stable constructions. The new type of waterborne alkyd used in System 5 is based on another technology without any free surfactant. The more traditional waterborne alkyd paint, based on an alkyd emulsion, System 7, however shows a higher water absorption value than the other alkyd paints.

The higher water permeability that was recorded for the alkyd emulsion paint in relation to the other alkyd paints is probably due to the presence of surfactants, which are used to stabilise the emulsion droplets and can cause bad film formation. The linseed oil paint, System 8, shows a similar water absorption value as the solventborne alkyd paints. The reference coating, the ICP, System 14, shows a low water absorption value. The waterborne acrylic paint, System 6, shows a high water absorption value despite a considerable film thickness. The industrial coatings that were tested in this study are used for stable constructions such as windows. The solventborne polyurethane coating, System 12, falls well into the category of paints for "stable constructions", whereas the waterborne PU/acrylic coating, System 13, falls on the proposed limit. These two paints have shown very good outdoor performance during the last 15 years of commercial use.

The change in water absorption value during artificial weathering for some of the tested coating systems were evaluated and shown in Figure 9. The results show, however, that ageing can have a large impact on the water protection efficiency for a coating.
Fig. 9 Water absorption values for three coating systems during artificial weathering. The coated test samples have been aged between the water absorption measurements. Mean values for five replicates and the 95% confidence intervals are shown. The artificial weathering was carried out according to the schedule in Table 1 and section 4.2. LWA 1 is water absorption value before weathering and LWA 2, 3 and 4 is water absorption value after 5, 10 and 15 weeks weathering respectively. Paper I.

System 1, the solventborne alkyd primer, shows a typical change in water absorption value during exposure similar to other solventborne systems. System 10, a waterborne polyurethane dispersion coating, shows the typical decrease in water absorption value often found for waterborne coatings during the very first part of exposure. With increasing exposure time the water absorption values increases.

System 14 is the Internal Comparison Product (ICP); the solventborne reference coating used in EN 927-3, Natural weathering test. The ICP is an alkyd stain based on an ordinary alkyd resin (Synolac® 6005 W, Cray Valley). It shows a typical performance of a solventborne high performing alkyd coating. Newton (1986) has performed durability testing of the Synolac® 6005 W alkyd. Using a Payne cup technique he found “specific permeability” for Synolac® 6005 W alkyd to lie between “conventional solvent based gloss paints” and “commercial water based paints”.
6.4 Influence of coating composition on moisture dynamics (Paper II)

6.4.1 Introduction
Although moisture dynamic properties of coatings related to composition play an important role for the raw material suppliers as well as for the paint industry in developing new resins and coating formulations, little are actually reported in the literature. Most studies published use commercial products whose confidential formulation limits generalisations. However, in Paper II model coatings with known composition were assessed for liquid water permeability both as single coat systems and combined as primers and topcoats to form coating systems very similar to those normally used. During artificial weathering, the samples were subjected to measurement of water absorption value thus showing the change in water permeability as a function of weathering.

The objective of Paper II was to assess the water absorption through coatings on wood related to the chemical and physical composition of the coatings. Fourteen model coatings were used. The model coatings were one priming oil, three solventborne paints, five alkyd emulsion paints and five acrylic paints. These fourteen model coatings were assessed both as single coat systems and combined as primers and topcoats to form normally used coating systems. In total, thirty-eight different systems were assessed.

6.4.2 Materials and methods
The formulations of the model coatings are given in Paper II. The raw materials were products normally used in the coating industry. The model coatings were developed in close contact with, and approved by, coating manufacturers and raw material suppliers. Some ingredients, which normally occur in commercial paints, have been omitted in the model coating formulations, e.g. fungicides and some other additives that are regarded as not having an influence on the moisture dynamic behaviour. The model coatings were manufactured by The Swedish Institute for Wood Technology Research, Stockholm (priming oil), Engwall & Claesson AB, Stockholm (Swedish paint manufacturer) (solventborne coatings) and the Institute for Surface Chemistry, Stockholm (waterborne coatings).

Test samples of Norway spruce (Picea abies) were coated, by brushing, with the different coating systems to the same dry thickness, 80 µm for each coating layer. Three replicates were coated for each coating system. After application of the different coatings, each test sample was conditioned in an atmosphere of 20°C and 65 % RH until constant weight was achieved, thus, resulting in a starting moisture content in the test samples of approximately 12 %.

The water absorption property of the coatings was measured by a "floating" method similar to the method that now is a European standard for assessment of liquid water permeability. The reasons for some of the deviations between the procedure used in Paper II and EN 927-5 is due to the fact that the measurements reported in Paper II were performed before EN 927-5 was confirmed. The deviations are not regarded to have any
major influence on the assessment when comparing results from tests carried out according to EN 927-5. After measurement of the water absorption value the test samples were subjected to artificial weathering. The artificial weathering was performed in accordance with the test schedule outlined in Table 1 and section 4.2. Liquid water permeability was measured after 5, 10 and 15 weeks of artificial weathering.

6.4.3 Results
The study showed that excess of surfactants in the alkyd emulsions has a negative effect on the coating's ability to exclude water from the test samples. Waterborne acrylic paint, based on a dispersion of larger particle size (0.4 µm), shows a poor ability to exclude water compared to a similar paint based on smaller dispersion particles (0.1µm). The alkyd emulsion paints, as single coats, showed high water absorption values compared to solventborne paints and acrylic paints.

Fig. 10 Water absorption values for alkyd emulsion paints initially and after artificial weathering. LWA 1 represents the initial water absorption value. LWA 2, 3 and 4 represents the water absorption values after 5, 10 and 15 weeks of artificial exposure respectively. Bars represent standard deviation. Paper II.

Figure 10 shows the results of the water absorption tests for the alkyd emulsion paints, with and without priming oil treatment. The terms an-ionic, non-ionic and 2x non-ionic refer to the stabilising surfactants in the coating. PVC is the pigment volume concentrations. All coatings had a pigment volume concentration of 20% except the coating AE 4. “PO” refers to priming oil.

The single coat alkyd emulsion systems (AE 1 to AE 5) show higher water absorption
values than all the other tested systems. The water absorption values for the alkyd emulsion paints, regardless of composition, decrease during the first step of artificial weathering to a minimum after which the water absorption values increase with weathering. The same variations in the water absorption values during weathering were also observed for the acrylic paints. The decrease in water absorption values during the first stages of weathering that was observed for the waterborne coatings was not observed for the solventborne coatings.

It is clearly shown that an excess of surfactants in the coating has a negative effect on the coatings ability to prevent water ingress, which most probably is due to the hydrophilic character of the surfactant (AE 2 and AE 3). Increasing the pigment volume concentration from 20% to 30% increases the water absorption value (AE 2 and AE 4). This result differs from expected results. The effect of pigmentation on permeability is generally a decrease in water permeability with increasing pigment volume concentration. The difference between expected and obtained results may be due to non-ideal pigmentation. The type of surfactant, an-ionic or non-ionic, as emulsifier for the alkyd resin seems to have no significant influence on water permeability (AE 1 and AE 2).

Figure 11 shows the results of the water absorption tests for the acrylic paints.

![Graph showing water absorption values for acrylic paints](image)

**Fig. 11** Water absorption values for acrylic paints, initially and after artificial weathering. Columns represent water absorption values after 0, 5, 10 and 15 weeks of artificial weathering. Bars represent standard deviation. **Paper II.**

The particle size of the acrylic dispersion has a great influence on water permeability.
Waterborne acrylic paint (A 2) based on a dispersion of large particles (0.4 µm) shows a poor ability to prevent water ingress compared to the similar paint based on a dispersion of small particles (0.1 µm) (A 1). The acrylic paint based on a bimodal distribution of dispersion particles (A 4), showed similar water absorption characteristics as the acrylic paint based on a mono-modal distribution (0.1 µm) (A 1). There is reason to believe that the smaller particles in the bimodal dispersion fill out the voids between the 0.4 µm particles and thus make a paint film with almost the same sorption characteristics as a paint film formed from a 0.1 µm mono-modal dispersion. The change from polyurethane (HEUR) based rheology modifier (in A 1) to a cellulose based rheology modifier (in A3) had no significant influence on water permeability.

### 6.5 Influence of coating additives on moisture sorption (Paper III)

#### 6.5.1 Introduction

Wood is a hydrophilic material and, therefore, shows changes in moisture content depending on the surrounding climate. These changes often lead to changes in physical properties, which include susceptibility to cracking, checking, blistering and microbiological attacks by decay or blue-stain fungi. Water vapour transport in wood is governed by diffusion, i.e., the random motion of water molecules tending to level out concentration gradients. If local accumulation of hydrophilic substances occur in wood, this random motion of water will be disturbed and high concentrations of water and/or moisture can develop locally.

Coté (1983) found that materials could migrate from a coating film into a wood substrate and accumulate in different areas due to chromatographic separation depending on their hydrophilic/hydrophobic character and change the moisture sorption characteristics of the wood substrate. Ekstedt (1993) found that the presence of two different emulsifier systems, present in some alkyd emulsions, changed the moisture sorption characteristics of the wood. It was shown that wood samples, which were treated with emulsifiers, reached significantly higher moisture content under humid conditions and retained the moisture significantly longer than untreated wood samples during desorption.

The objective for Paper III was to investigate if the presence of substances normally used in coatings could change the sorption characteristics of wood.

#### 6.5.2 Materials and methods

Wood samples of Norway spruce (Picea abies) were treated with solutions of coating additives commonly used in waterborne coating systems. The test samples were 150 x 70 x 5 mm, longitudinal, tangential and radial, respectively. The density of the test samples were between 323 kg/m³ and 493 kg/m³ measured at 12 % moisture content.

The wood samples were treated by an impregnation method with water solutions of the different additives. The studied additives were one non-ionic surfactant (nonylphenol-
ethylene oxide-propylene oxide adduct, molecular weight approx. 2900, HLB-value = 15) (abbr. NPEP), one rheology modifier (hydroxyethyl ether of cellulose) (abbr. HEC) and one anti-foam agent, tributylphosphate (abbr. TBP). For each system, five replicates were treated. The concentrations of the different additives in the test samples were chosen to simulate concentrations that might be reached in the one millimetre area close to the coating/wood interface. For the surfactant three concentrations (by weight) were used 0.3%, 1.0% and 3.0 %, for the rheology modifier, two concentrations 0.3% and 0.6%, and for the anti-foam agent, one concentration 1.0%. The wood samples were then subjected to step-wise alternating humid conditions according to Figure 12. The temperature was held constant at 20 °C. The moisture absorption and desorption in the treated samples were compared to that of untreated wood samples to determine whether the presence of coating additives could influence the moisture sorption characteristics of the wood.

![Fig. 12](image)

**Fig. 12** Template for the absorption/desorption measurements showing the step-wise change in humidity during the experiment. Phase 1 is a pre-phase for conditioning. Measurements were performed during Phase 2-4. Paper III.

6.5.3 Results

It is shown in Paper III, that the presence of some substances common in waterborne coatings alter the moisture sorption characteristics of wood. The presence of a surfactant, nonylphenol ethoxyphenoxylate adduct, and the presence of a rheology modifier, hydroxyethyl cellulose, lower the rate of moisture absorption and, to a great extent, delay the release of moisture during desorption. Considering that these substances occur in waterborne coatings, and may be mobilised during and after film formation and accumulate at the coating/substrate interface, there is a great probability that these substances change the moisture sorption characteristics of the wood substrate in an unfavourable way and create unexpected moisture conditions at the coating/wood interface.
Figure 13 shows the results from absorption/desorption measurements in Phase 2. There are great similarities between the results for Phase 2 and Phase 4. This suggests that the measured effects seem to be retained even after subsequent absorption/desorption. The presence of NPEP, HEC and TBP in the wood samples lower the rate of moisture absorption relative to untreated wood samples. This effect seems to be concentration dependent for the surfactant NPEP (Figure 13 left) whereas for HEC a concentration of 0.6% is needed to get statistically significant difference from untreated wood samples (Figure 13 right). The samples treated with NPEP and HEC reached almost the same weight difference as the untreated samples. Whereas the samples treated with TBP even after a prolonged time, never reached the same weight difference as the untreated samples. The results for NPEP (Figure 13 left) do not agree with the results shown by Ekstedt (1993), where wood treated with emulsifiers showed significantly higher weight gain than untreated wood after equilibrium had been reached. The reason for this discrepancy is not known, but as the actual chemical composition of the emulsifier systems in Ekstedt (1993) was not known, direct comparison is not justified. The surfactant NPEP and the rheology modifier HEC strongly lower the rate of desorption of moisture from the wood samples during the desorption phase and the rate of moisture desorption is concentration dependent. The statistical analysis shows that the presence of 0.6% HEC in spruce gives a statistical significant difference in moisture desorption versus untreated spruce. A statistically significant difference in moisture desorption was also found for wood samples containing NPEP. Interestingly, TBP does not seem to have any retarding effect on desorption of moisture, but shows a good hydrophobic effect on absorption of moisture. Figure 13 shows that it takes three times longer to reach the level “weight difference = 0.03” for samples containing 3% NPEP than it takes for untreated samples during the desorption phase. This indicates that the presence of this additive in
the wood strongly effects the drying of the wood and thus might have an impact on the moisture-related performance of waterborne coatings on wood.

6.6 Moisture dynamics in coated wood during artificial weathering
(Paper IV)

6.6.1 Introduction
Assessment of the water absorption properties using the EN 927 - 5 standard give the water absorption through the coating after 72 hours of exposure to liquid water. Paper I shows however that ageing might drastically change the water absorption for a coating or a coating system during weathering and thus alter the water protection properties of the coating. Hence ageing of the coated test samples is needed for proper assessment of the water absorption properties, especially for assessing the long-term performance of the coating. Measurement of the water absorption value, before any ageing, has a rather limited usefulness for the prediction of long-term water absorption behaviour.

Paper IV reports measurements of the water absorption values for different coatings and coating systems before and during artificial, accelerated weathering and illustrates the possible use of reliability-based prediction of service life techniques as a tool for predicting durability based on water protection efficiency as failure mode.

6.6.2 Materials and methods
Test samples of tangentially cut Norway spruce (Picea abies) were used. They had a dimension of 150 x 70 x 20 mm (longitudinal, tangential, and radial directions, respectively). Panels were free from knots and cracks, straight-grained and with between four and seven annual rings per 10 mm. The densities of the test samples were between 450 and 500 kg/m³, measured at 12% moisture content. All faces were fine sawn. This is in fact a deviation from EN 927-5, which requires planed wooden surfaces. The reason for the deviation is that the tested coating systems are mainly intended for sawn surfaces. Prior to coating application, the test samples were conditioned to constant weight at 20°C and 65% RH, thus giving initial moisture content in the test samples of approximately 12 %. The coatings that were studied in Paper IV are outlined in Table 4.
Table 4 - Coatings

<table>
<thead>
<tr>
<th>Coating system</th>
<th>Coating and number of layers&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Binder</th>
<th>PVC&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Classification according to EN 927-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2 x alkyd topcoat 1</td>
<td>Linoleic acid based alkyd with 52% oil length</td>
<td>20</td>
<td>High build, opaque, semi gloss</td>
</tr>
<tr>
<td>2</td>
<td>2 x alkyd topcoat 2</td>
<td>Vegetable fatty acid alkyd with 60% oil length</td>
<td>21</td>
<td>High build, opaque, semi gloss</td>
</tr>
</tbody>
</table>
| 3              | 1 x alkyd primer 2 x alkyd topcoat 2   | Primer: tall oil alkyd with 70% oil length and linseed oil  
Topcoat: Vegetable fatty acid alkyd with 60% oil length | 38              | High build, opaque, semi matt        |
| 4              | 1 x alkyd primer 2 x alkyd topcoat 3   | Primer: tall oil alkyd with 70% oil length and linseed oil  
Topcoat: tall oil alkyd with 70% oil length and linseed oil | 38              | High build, opaque, semi matt        |
| 5              | 1 x alkyd primer 2 x acrylic topcoat   | Primer: tall oil alkyd with 70% oil length and linseed oil  
Topcoat: pure acrylic | 32              | High build, opaque, semi matt        |

<sup>a</sup> 1 x = one layer; 2 x = two layers  
<sup>b</sup> pigment volume concentration

After measurements of water absorption values the test samples were subjected to artificial weathering as outlined in Table 1 and section 4.2. The schedule was carried out for 35 weeks of exposure. The total artificial exposure for each test sample is 3096 hr of floating on water, 840 hr of cooling/freezing and 2520 hr of Weather-Ometer exposure.

6.6.3 Results

The water absorption values for the five coating systems reported in Paper IV are shown in Figure 14.
System 1 and 2 in *Figure 14*; initially, perform well and up to 15 weeks of exposure and they are both below the proposed limits for “semi-stable constructions” in ENV 927-2 “Performance specifications”, 250 g/m², *i.e.* for use on claddings. At further ageing, however, the alkyd system 2 shows a more rapid increase in water permeability compared to System 1. Both these paints show a good performance for at least 4 to 6 years in outdoor use in a Scandinavian climate. In System 3, the same paint as in System 2 is used together with an alkyd primer, giving a higher total dry thickness, 114 µm. It is quite clear that the alkyd primer and the thicker film have a positive influence on the water absorption properties of the coating. The large standard deviation after 35 weeks of exposure is mostly an effect of a very high water absorption value (423 g/m²) for one test sample due to cracking.

In System 4, the same primer as in System 3 is used together with a topcoat based on the same alkyd as the primer. This system has a higher total dry film thickness, 144 µm, compared to System 3 and also lower water permeability. System 4 shows a low, initial water absorption value, 53 g/m² and a slight increase in the water absorption value with increased weathering. Even after 35 weeks of weathering, the water absorption value is still very low, 105 g/m² and below the limit for stable construction. System 4 performs well in practice in Scandinavia for at least 8 to 12 years depending on the climatic conditions.

System 5, which consists of the same primer used in System 4 with two coats of a waterborne acrylic topcoat, shows a relative high water absorption value 166 g/m² before weathering. After five weeks of weathering, the water absorption value has decrease to less than half the initial value, 75 g/m². The explanation of this may be that leaching of
water-soluble material from the coating makes the coating less permeable to water transport.

**Paper IV** shows that the combination of a standard procedure for water absorption measurement and an artificial weathering procedure gives more information regarding expected durability and long-term performance than a single measurement of water absorption on fresh, unweathered coated wood. This combination of water absorption measurement and artificial weathering could become a useful tool in product development as well as in benchmarking. Together with statistical tools, such as reliability-based methodologies for predicting the service life of coating systems and increasing the numbers of replicates, a reduction in testing times may be achieved.

A behaviour similar to that recorded for the waterborne coatings in the artificial weathering reported in **Paper IV** is also shown in **Figure 15**, which shows results from measurements of moisture content during natural exposure in vertical wooden claddings on a test house in Norway. Measurements of moisture content were performed 3 mm behind the coating layer by means of electrical moisture meter equipment. One system was an all solventborne (SB) system, SB primer and SB topcoat (grey line in **Figure 15**). The other system consisted of a SB primer and a waterborne hybrid topcoat (black line in **Figure 15**). Initially the moisture content in the test panels coated with the waterborne system is higher than the moisture content for test panels coated with the solventborne system but the difference decreases with subsequent exposure. The same effect was found for waterborne systems in **Paper I** and **II** and for System 5 in **Paper IV**. **Figure 15** is used by courtesy of Jotun A/S, Sandefjord, Norway.

![Figure 15](image)

**Fig. 15** Moisture content (%) in wooden cladding on a test house in Sandefjord, Norway during natural exposure between Jan. 1998 and Jan. 1999. MC was measured by resistance measurement 3 mm behind the coating. Black line represents a waterborne hybrid coating (alkyd/acrylic) and the grey line represents a solventborne alkyd coating.
7. MOISTURE DISTRIBUTION IN COATED WOOD

7.1 Introduction

Measurement of spatial distribution of water and moisture in coated wooden constructions is of great importance for revealing the effects of bad constructions. Despite the fact that even if a wooden construction shows acceptable moisture content, based on the average moisture content of the whole object, local accumulation of water may occur due to anisotropy and non-uniform structure of the wood. Local high moisture content is likely to increase the possibility of microbiological colonization with subsequent wood degradation as a result.

The influence of the coating on the accumulation of moisture is most likely to occur at the wood/coating interface and in the layer some millimetres under the coating surface. Different techniques have been used to measure spatial distribution of moisture in small volumes of wood. Measurements of electrical resistance between two conducting screws mounted in the substrate have been used for example by Hjort (1996) and Derbyshire and Miller (1997a, 1997b). However, this conductivity technique does not record the moisture content of an exactly defined volume of wood since the exact route of the electrical current is unknown. Derbyshire and Miller (1997a) conclude the possibility that leached water-soluble material from waterborne coatings could penetrate the wood. That this will, in turn, affect the relationship between wood moisture and conductivity can not be excluded.

Hattori and Kanagawa (1985), Lindgren (1985, 1991) and Lindberg et al. (1990) have shown how computerized tomography can be used to measure the moisture content in small volume elements of wood. The method is based on measurements of the X-ray absorption in each volume element. The X-ray attenuation in a material is a function of the density of the material, its chemical composition and the photon energy. There is a linear relationship between the X-ray attenuation and the density of wood (Lindgren 1985). For wood, there is also a linear relationship between the density and the moisture content. The X-ray absorption value can thus be transformed into moisture content with the help of mathematical models.

7.2 Computerized tomography

The basic principle for computerized tomography involves an X-ray emitting source that rotates around sections of materials and transmits photons through the object. The transmitted X-rays are attenuated and detected by an array of detectors opposite the source (Figure 16). After a 360° rotation, X-ray absorption coefficients in small volume elements (voxels) in a slice of the object can be calculated using mathematical algorithms. By measuring the attenuated intensity in a number of directions, described in Figure 16 a set of intensities is created that form the basis for calculation of the Hounsfield number or CT number in each picture element (pixel). All these pixels constitute the “slice” of the material.
The objective of Paper V is to briefly describe the CT technique and to show how it can be used to study the spatial distribution of moisture in coated wooden components during artificial weathering. The basic elements in a CT measurement are Data acquisition, Image reconstruction and Image display and handling, which are described in more detail in Paper V. The measured CT image can be regarded as a matrix of CT numbers, each number representing the CT number in the corresponding picture element (pixel). The image reconstruction is the mathematical procedure that must be performed in order to produce a two-dimensional distribution of X-ray attenuation values. By subtracting the CT image taken at the beginning of the exposure (reference image) from the CT image taken at a certain moment in the exposure cycle, the actual moisture content in that pixel can be determined. The difference in CT number in each pixel is then due to the presence of water. The reference image is the test panels were conditioned to known and evenly distributed moisture content, in these experiments to 12 % moisture content. A complication in this subtraction process arises due to the change in geometrical shape (swelling) upon moistening the wood. This creates a spatial mismatch between the reference CT image and the actual CT image. This change in shape must be corrected for by geometrical transformation before the subtraction. Image analysis is used to perform these corrections.

7.3 Spatial distribution of moisture in coated wood (Paper V)

7.3.1 Materials and methods
The wood material for the experiments was Scots pine (*Pinus silvestris*). The test panels were made from the dried boards and had a dimension of 450 x 100 x 20 mm (longitudinal, tangential, and radial directions respectively). The dry densities of the test
samples were between 447 and 620 kg/m³. All faces were fine sawn. Prior to coating, the test samples were conditioned to constant weight at 20°C and 65% relative humidity, thus giving an initial moisture content in the test samples of approximately 12%.

Four laboratory-made coatings were used in the experiments; an alkyd primer, an alkyd paint, an acrylic paint and a hybrid paint (alkyd/acrylic). Composition of the coatings and their physical properties are given in Paper V, Table 1. Complete recipes for the different coatings can be found in Ekstedt (1995).

The X-ray absorption images (CT scans) were obtained using a General Electric model 9800 Quick® CT scanner at Skellefteå Hospital, Dept. of Radiotherapy. The X-ray tube operated at 120 keV (peak) and 70 mA beam current producing a beam with an average energy of 73 keV. Slice thickness was 1.5 mm. The spatial resolution was approximately 1 mm. Within a 3x3 mm area the accuracy in moisture content measurements is ± 1.4% when below fibre saturation point (FSP) and ±4% when above FSP (Lindgren 1992). The image analysis was carried out using an image processing system (TERAGON 4000®) and PC. Data processing and image analysis using the latter was carried out using NIH IMAGE software. This software was developed at the National Institute of Health (NIH), Maryland, USA.

The artificial weathering of the test panels was performed in the Weathering Simulator at Trätek, Skellefteå. The Weathering Simulator consists of three chambers for rain and wind load, freezing, light and heat load, respectively. The Weathering Simulator is described in Swedish Standard SS 81 81 36. The test panels were mounted with its longitudinal direction vertically on walls that were movable between the different chambers. The test panels were fastened to the wall by mechanical interlocking in a similar way as cover boarding with rib flanges. Neither screws nor nails were used on the test panels. Behind the test panels were an air gap, 20 mm wide. This air gap simulates the air gap that is common behind claddings in ventilated wooden facades in Scandinavia. No liquid water (i.e. water-spray) was able to enter the air gap. Only air circulating in the test chambers was ventilated through the air gap.

**Acquisition of CT images**

After certain time intervals during the artificial ageing the test samples were subjected to measurements in the tomograph, producing CT images at positions shown in Figure 17. The samples were tomographed after the wet period in the 2nd, 6th and 7th exposure cycle and after the dry period in the 6th exposure cycle.
Fig. 17  The position of the CT scans in the test samples.

Using the technique described above and in Paper V, the moisture distribution maps in cross sections of four of the test panels were constructed. These moisture distribution maps are shown in Figures 18-20.

7.3.2 Results

Moisture measurements

In Paper V it is shown that there is good correlation between moisture content measured by weighing the panels and moisture content determined by CT scanning. A correlation coefficient of 0.98 was obtained. The results indicated that the maximum deviation in moisture content was ±3% in the interval between 10% and 20%.

Moisture gradients in test panels

The results in Paper V show that even when the acrylic coating was intact high moisture contents (between 13.4% and 26.7%) were recorded in the 0-4 mm layer beneath the coating after wetting periods. For the alkyd coating moisture contents were between 13.2% and 15.4% in the 0-4 mm layer for intact films. It was observed that quite often the 16 – 20 mm layers show higher moisture contents compared to the 0–4 mm layers. This may be due to absorption of moisture from the ventilated air gap behind the test panels.

Moisture distribution images:

Moisture distribution in test panels with cracks.

Obtaining a visual image of the distribution of water and moisture in cross-sections of coated wood panels is of great interest. An image of the water distribution can highlight local moisture concentrations in the wood, which may be correlated to physical inhomogeneities, for example cracks, blisters or microbiological activities. Figure 18 shows a CT image of a cross-section of a test panel coated with the waterborne hybrid
alkyd/acrylic coating. The CT image was obtained after a rain and wind period in the artificial weathering schedule. The coated surface had four cracks in the longitudinal direction passing through the coating and extending to about one third of the panel thickness. The corresponding moisture distribution image show a high accumulation of moisture and water around the cracks (Figure 19). A large portion of the cross-section had moisture content of more than 40%. Moving radially from the cracks, the moisture content shows a considerable decrease in a short distance, from > 40% to < 15% within 5 mm. This large gradient in moisture content may cause high mechanical stress in the wood due to alternating wetting and drying. It is reasonable to believe that this mechanical stress may cause crack initiation and propagation.

Fig. 18  CT image of a cross-section of a moistened coated board. Paper V.

Fig. 19  Grey-scale image of a cross-section of a coated board showing spatial distribution of moisture. Paper V.

Moisture accumulation due to blue-stain colonization

Figure 20 shows a moisture distribution map of a cross-section of a test panel that was coated with the waterborne acrylic paint. The coated surface had no defect, but on the uncoated reverse side of the panel there were bands of blue-stain fungi (Figure 12 in Paper V). The reverse side was facing an air gap in the test set-up where no water spray could enter, only water vapour. The moisture distribution map shows that there is a large accumulation of moisture and water on the reverse side of the panel in the area where the blue-stain had developed. The blue-stain fungi had accumulated water from the moist air gap and had a moisture content well above the fibre saturation point.
Fig. 20  Grey-scale image of a cross-section of a coated board showing large accumulation of moisture around a blue-stain colonization. The coating was applied on the upper horizontal face and on the vertical faces. The lower horizontal face (i.e. reverse side) was uncoated. Pseudo-coloured image is shown in Paper V.

Computerized tomography has been found to be a valuable, non-destructive tool for visualising the spatial moisture distribution of water and moisture in coated wood panels. The method is suitable for recurrent testing of a specimen exposed to a series of processes of wetting followed by drying. The study, presented in Paper V, showed that:

- high moisture contents occur locally at and around cracks. In these areas there is an increased risk of internal tension and stress, resulting in crack initiation and propagation.
- high moisture contents can occur in the first few millimetres under waterborne coatings despite intact coating films.
- even with good barrier properties of the coating, moisture may accumulate by water-vapour absorption in air gaps behind the cladding thus causing favourable conditions for microbiological colonization.

7.4 Magnetic Resonance Imaging

7.4.1 Introduction

Magnetic resonance imaging (MRI) is a technique which can be used for measuring moisture and moisture distributions. MRI is based on the principles of nuclear magnetic resonance (NMR). It produces an image of the NMR signal in a thin slice through an object. NMR relaxometry and magnetic resonance imaging have been used to study moisture in wood (Araujo 1992; Baranowska et al. 2000; Dawson-Andoh et al. 2001; MacMillan et al. 2002; Rosenkilde and Glover 2002). A high resolution MRI technique has been developed at University of Surrey, UK (Glover et al. 1999). If a linear magnetic field gradient is applied to an object containing water in different regions in the object the different regions will experience different magnetic fields. This principle forms the basis behind magnetic resonance imaging. The spatial resolution is proportional to the magnetic field gradient. The MRI technique has been used to monitor the moisture distribution in and close to a coating layer (Ekstedt et al. 2002). The results are obtained as part of an EU funded project MARWINGCA (2000) (MAgnetic Resonance Imaging of
Wood at the Interface with Glues, Coatings and Air), the aim of which is to study the drying process of wood, moisture related processes at the wood/coatings interface and glue interaction with wood.

7.4.2 Methods

The MRI measurements were performed at University of Surrey, School of Physics, Guildford, U. K. The instrument is described in detail by Glover et al. (1999). The magnetic field strength on the sample was 0.7 T with a magnetic gradient strength of 17 Tm⁻¹. The instrument operated at 26.7 MHz and with a 90° pulse length of 9 μs. The spatial resolution for the measurements reported in section 7.4.3 is in the order of 15-20 μm.

7.4.3 Results

Figure 21 shows the coating to the left (coating thickness approx. 300 μm) applied to spruce. The coating was a waterborne acrylic paint where the binder was stabilised with surfactants. The water proton density profile (white graph) has been superimposed on an ESEM image of the area where the MRI measurements were carried out. The water proton density is proportional to the moisture content. It is clearly shown that an accumulation of moisture occurs at the interface between coating and wood, at “distance 700“.

Fig. 21 Environmental Scanning Electron Microscopy (ESEM) image of coated wood. White graph shows the water proton density profile. Ekstedt et al. (2002).
8. DISCOLORATION OF COATINGS

8.1 Introduction

Many houses in the Nordic countries are constructed with wooden panel facades, painted with various coating systems. The outdoor exposure of the coatings leads to colour changes and surface roughening, the former being an aesthetic problem, caused by simultaneous action of weathering and wood/coating interactions. The problems with discoloration of coatings on wood have been regarded as a serious problem in the U. S. (Donegan et al. 1992) though the problem was addressed earlier (e.g. Feist 1977) and solutions were placed on the market (Rohm and Haas Co. 1985).

Discoloration on spruce and pine is most frequently associated with knots. The barrier properties of coatings play an important role in minimising discoloration. Measurement of discoloration in a repeatable and reproducible way is undoubtedly a difficult task due to the variability of wooden test material. A standard procedure for measuring discoloration on coated wood due to resin exudation from knots has been developed at Trätek and reported by Ekstedt (2000). A recent paper by Suttie and Ekstedt (2002) reports the evaluation of a proposed EN 927-7 standard procedure for assessing knot and tannin staining resistance where different means for developing discoloration is evaluated.

Water-soluble substances and other wood extractives may migrate into coatings and cause discoloration (Black and Mraz 1974; Hse and Kuo 1988). Kiln and air drying, as well as drying by different kiln drying schedules, redistribute and accumulate the low-molecular weight (LMW) sugars and nitrogenous compounds at the lumber surface in different ways (Boutelje 1990; Terziev 1995). Although the soluble sugars and nitrogen are minor wood compounds, not exceeding a few percent of the dry weight of the wood, they are of importance for the colour of wood (Millett 1952). Redistribution of the soluble sugars and nitrogen during drying, especially affect the wood surface, it may also influence adhesion properties and finishing characteristics of the coatings.

The aim of Paper VI was to determine the susceptibility to discoloration of some white coatings, commonly used in Sweden, applied on kiln- and air-dried lumber surfaces having different content of LMW sugars and nitrogen. Since planing of wood may remove the zone richest in soluble substances (Terziev et al. 1996), its effect on the susceptibility to discoloration of the coatings was also studied. This discoloration was compared for the coatings applied on the original and the planed surfaces of Scots pine lumber, dried with different drying treatments.
8.2 Discoloration of coatings and kiln- and air-dried Scots pine lumber
(Paper VI)

8.2.1 Materials and methods
Four white paints (primers and topcoats) and one priming oil were used in different
combinations described in Paper VI, Table 1. The coatings were applied by brushing on
test panels (50 x 50 x 20 mm) of Scots pine (Pinus silvestris). The primers were dried for
48 hrs at room temperature, the topcoats were then applied on lateral surface and dried for
the same time and at the same temperature and, finally, the end-grain surfaces and edges
of the samples were sealed.

Weathering of the samples was performed in an Atlas Weather-Ometer. The weathering
cycle consisted of 102 minutes of radiation followed by 18 minutes of radiation combined
with water spray, which was repeated until the total difference in $\Delta E_{ab}$ for one of the
coating systems exceeded 2 units. The samples were exposed for 144 hrs. After
weathering, the samples were conditioned at room temperature.

The evaluation of colour change (i.e. discoloration) was done with a Topcon RD-100
Color difference meter (Topcon, Tokyo, Japan) with a pulse xenon lamp in accordance
with the CIE 1976 (L*a*b*) colour space. This colour space contains the colour co-
ordinates L* (lightness), a* (green-red axis) and b* (blue-yellow axis). The CIE standard
illuminant D 65 was used (ISO 7724/1-1984). The Topcon difference meter had a circular
measuring area of 8 mm in diameter. The colour co-ordinates (L*a*b*) of the coatings
were measured at five points on each sample before and after exposure in the Atlas
Weather-Ometer according to ISO 7724/2-1984. The difference in colour co-ordinates
$\Delta L^*$, $\Delta a^*$ and $\Delta b^*$ before and after exposure was calculated. These colour differences
were used to calculate the colour difference $\Delta E_{ab}^*$ using Equation 15 (ISO 7724/3-1984).

$$\Delta E_{ab}^* = \left[ (\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2 \right]^{\frac{1}{2}}$$ (15)

The total difference $\Delta E_{ab}^*$ for the coatings before and after weathering was used to
characterize their discoloration.

8.2.2 Results
The different coatings showed a significant difference with regard to discoloration. Two
microscopy investigations (before and after painting) verified that the discoloration was
not caused by fungal growth. The chemical nature of the coatings can explain the
significant differences between them with regard to discoloration. The waterborne alkyd
emulsion primer showed the highest discoloration, $\Delta E_{ab}^* = 2.14$ (SD = 0.60). The same
primer applied as a topcoat on priming oil (based on modified fish oil) was less
discoloured, $\Delta E_{ab}^* = 1.88$ (SD = 0.46). The two best performing systems (i.e. less
discoloration) were a waterborne primer with solventborne topcoat, $\Delta E_{ab}^* = 0.74$ (SD = 0.12) and a solventborne primer with waterborne topcoat, $\Delta E_{ab}^* = 0.85$ (SD = 0.10) whereas the all waterborne system, with the waterborne primer and the waterborne topcoat, showed a $\Delta E_{ab}^*$ value of 1.22 (SD = 0.13). The presence of a solventborne coating seems to enhance tannin blocking.
9. CONCLUSIONS
The European standard method for assessment of the water absorption value for coatings, EN 927 – 5 gives significant differences in water absorption values for different types of coatings on wood. The proposed performance specifications in EN 927 - 2 for the water absorption values for coatings to be used in different constructions seem to be set at acceptable levels. There is good correlation between the level of water absorption and practical experience of the performance of the paints in Scandinavia. However, it has been shown that the combination of a standard procedure for water absorption measurement and an artificial weathering procedure gives more information regarding expected durability and long-term performance than a single measurement of water absorption on fresh, unweathered coated wood. A combination of water absorption measurement and artificial weathering could become a useful tool in product development as well as in benchmarking. Together with statistical tools, such as reliability-based service life prediction methodologies for predicting the service life of coating systems, a reduction in testing times may be achieved.

Surface-active substances in coatings have a negative effect on the coatings ability to prevent water ingress, which is most probably due to the hydrophilic character of these substances. The presence of these substances, which are common in waterborne coatings, alters the moisture sorption characteristics of wood. Considering that these substances occur in waterborne coatings, may be mobilised during and after film formation and accumulate at the coating/substrate interface, there is a great probability that these substances change the moisture sorption characteristics of the wood substrate in an unfavourable way and create unexpected dynamic moisture conditions at the coating/wood interface.

Computerized tomography and Magnetic Resonance Imaging have been found to be a valuable, non-destructive tool for visualising the spatial moisture distribution of water and moisture in coated wood panels. The method is suitable for recurrent testing of a specimen exposed to a series of processes of wetting, drying etc.

10. FUTURE WORK
The work that has been carried out regarding assessment of the water protection efficiency shows promising results regarding the possibility to use reliability-based service life prediction methodology for the assessment. Many of the coating systems that have been assessed during artificial weathering and reported in the present thesis have also been exposed outdoors at test fields in Sweden. Some systems have been naturally exposed for more than 15 years at test fields. Future plans involve assessment of these natural exposed coating systems and to try to find correlation with the assessments reported in Paper I, II and IV. The aim of future work will be to establish more reliable techniques and protocols for assessing service life expectancy and durability, especially for waterborne coatings with special focus on tendencies to early failure and robustness of the coating systems.
Studies of the interaction of water and moisture at the interface between wood and coating and the impact on performance and durability as well as on adhesion and moisture dynamics will increase with the recently acquired Magnetic Resonance Imaging instrument at Trätek. New possibilities for studies of spatial distribution of moisture have been added to the institute and will be utilized in the future.
11. REFERENCES


Formation from Cellulose Acetate Latexes, Experimental Study of Phase Separation Phenomena Due to Sodium Dodecyl Sulfate. I. Journal of Applied Polymer Science, Vol. 34, 2631-2647.


