CHARACTERISATION OF THE SYDNEY REGION IN RELATION TO CORROSION, TIMBER DECAY RISK FACTORS AND THE CORROSION OF NAILS IN TIMBER IN COVERED CONDITIONS

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STATEMENT OF AUTHENTICATION

The work presented in this thesis is, to the best of my knowledge and belief, original except as acknowledged in the text. I hereby declare that I have not submitted this material, either in whole or in part, for a degree at this or any other institution.

.................................................................

(Signature)
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<th>DEFINITION</th>
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<tr>
<td>$\Delta_{\text{climate}}$</td>
<td>Factor relating to building spaces used when predicting the moisture content of timber in those spaces.</td>
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<tr>
<td>$\Delta_{\text{sea}}$</td>
<td>Factor of +2 for sites within 1 km of the coast used in predicting the timber moisture content in a building space.</td>
</tr>
<tr>
<td>$\Delta_{\text{radiation}}$</td>
<td>Factors of −2.5 and −1 for sites having high and low radiation levels, used in predicting the timber moisture content in building spaces.</td>
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<tr>
<td>$\Gamma$</td>
<td>Conductivity of timber (μs).</td>
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<tr>
<td>$\alpha_{\text{coast}}$</td>
<td>Zone factors relating to the geographic location of the coast, used in estimating atmospheric salt content attributable to coastal aerosols.</td>
</tr>
<tr>
<td>$\alpha_{\text{ocean}}$</td>
<td>Zone factors relating to the geographic location of the coast, used in estimating atmospheric salt content attributable to ocean aerosols.</td>
</tr>
<tr>
<td>$\beta_{\text{coast}}$</td>
<td>Exposure factor relating to the degree of shelter afforded by a coastline, used when calculating airborne salt content attributable to coastal aerosols.</td>
</tr>
<tr>
<td>$\beta_{\text{ocean}}$</td>
<td>Exposure factor relating to the degree of shelter afforded by a coastline, used when calculating airborne salt content attributable to ocean aerosols.</td>
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<td>$C_{\text{bright,nail,max}}$</td>
<td>Maximum corrosion rate of bright nails (g/m²/year).</td>
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$C_{\text{nail}}$  Corrosion rate of nails ($g/m^2\cdot\text{year}$).

$C_{\text{nail.bright}}$  Corrosion rate of bright nails in a nominated timber ($g/m^2/\text{year}$).

$C_{\text{nail.gal}}$  Corrosion rate of galvanised nails in a nominated timber ($g/m^2/\text{year}$)

$C_{\text{nail.\% max}}$  The percentage of maximum nail corrosion resulting from timber moisture contents below the moisture content causing the maximum corrosion.

$C_{\text{nail.time}}$  Estimated nail corrosion rate adjusted for the reduction likely to take place over time.

$C_r$  Corrosivity. Corrosion rate of metal ($\mu m/\text{year}$ or $g/m^2\cdot\text{year}$ as appropriate)

$C_{r.zinc}$  Corrosion rate of zinc ($g/m^2\cdot\text{year}$).

$D_{\text{rain.x}}$  The mean number of days in a month with 0.1 inches (2.54mm) or more of precipitation, used in calculating Scheffers Index (SI).

$D$  Damping factor related to building location used in predicting seasonal average moisture content of timber in a building space.

$\text{DRH}$  Deliquescence relative humidity (%). The relative humidity at which a particle will wet (absorb significant moisture). The relative humidity at which wetting occurs varies from material to material.
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<td>Salinity factor for a site, based on whether the coast is a very sheltered bay, partially closed bay, sheltered surf/very open bay or open surf (5, 15, 45 or 130).</td>
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<td>EMC</td>
<td>Equilibrium moisture content of timber (%)</td>
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<td>EMC_{outdoors}</td>
<td>Equilibrium moisture content of timber in outside covered conditions (%)</td>
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<td>Mean equilibrium moisture content of combined timber species at a specific site (%)</td>
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<td>EMC_{9am}</td>
<td>Equilibrium moisture content of timber at a site at 9am (%)</td>
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<td>F</td>
<td>F-ratio for regression equations</td>
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<td>GIS</td>
<td>Geographic information system</td>
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<td>IP</td>
<td>The moisture content value of timber where the shrinkage/moisture content curve on a graph intercepts the moisture content axis (%)</td>
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<td>Ln</td>
<td>Natural logarithm</td>
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<td>L_{coast}</td>
<td>Distance of a fastener’s location from the coast (km)</td>
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<td>MC_{bsa}</td>
<td>Seasonal average moisture content of a specified timber in a building space (%)</td>
</tr>
<tr>
<td>MC_{mnsdf}</td>
<td>Mean near surface moisture content of Douglas Fir (%)</td>
</tr>
<tr>
<td>MC_{mmnsm}</td>
<td>Mean near surface moisture content of Mountain Ash (%)</td>
</tr>
<tr>
<td>MC_{mnsrp}</td>
<td>Mean near surface moisture content of Radiata Pine (%)</td>
</tr>
<tr>
<td>MC_{mnsug}</td>
<td>Mean near surface moisture content of Spotted Gum (%)</td>
</tr>
</tbody>
</table>
$\text{MC}_{\text{mnstp}}$ Mean near surface moisture content of CCA Treated Pine (%).

$\text{MC}_{\text{near-surface}}$ Near surface moisture content of timber (%).

$\text{MC}_{\text{outdoors.aa}}$ Annual average moisture content of a specified timber in outdoor sheltered conditions (%).

$\text{MC}_{\text{outdoors.sa}}$ Seasonal average moisture content of a specified timber in outdoor sheltered conditions (%).

$\text{MC}_{\text{s.monthly.x}}$ Standard deviation of monthly average moisture content of timber.

$\text{MC}_{\text{surface}}$ Surface moisture content of timber (%).

$M_{\text{loss.steel}}$ Mass loss of steel through corrosion ($\mu$m/year).

$M_{\text{loss.zinc}}$ Mass loss of zinc through corrosion ($\mu$m/year).

$N$ Factor used in estimating the reduced level of nail corrosion over a period of time, relating to the proximity of the site to the ocean (0.5 for non marine sites and 0.7 for marine sites).

$O_{\text{air.dry}}$ Air dry density of timber.

$P$ Pollutant level. For example chloride deposition ($\text{mg/m}^2\cdot\text{day}$).

$p$ $p$ value for regression equations.

$P_{\text{Hrain.water}}$ The pH of rainwater.

$R^2$ Coefficient of determination for regression equations (% of the dependent variable explained by the linear relationship to the independent variables under consideration).
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R² (adj)</td>
<td>Coefficient of determination adjusted for degrees of freedom.</td>
</tr>
<tr>
<td>R_f</td>
<td>Annual rainfall (mm).</td>
</tr>
<tr>
<td>RH</td>
<td>Relative Humidity (%).</td>
</tr>
<tr>
<td>RH_{9am}</td>
<td>Yearly average 9am relative humidity (%).</td>
</tr>
<tr>
<td>RH_{3pm}</td>
<td>Yearly average 3pm relative humidity (%).</td>
</tr>
<tr>
<td>RH_{12pm}</td>
<td>Relative humidity at 12pm (%).</td>
</tr>
<tr>
<td>RH_{wall cavity}</td>
<td>Relative humidity in the wall cavity of a building (%).</td>
</tr>
<tr>
<td>RH_{external}</td>
<td>Relative humidity in external covered conditions (%).</td>
</tr>
<tr>
<td>RH_{external,lag7}</td>
<td>Relative humidity in external covered conditions with a lag of seven hours (%).</td>
</tr>
<tr>
<td>S</td>
<td>Exposure factor used in calculating salt deposition levels attributable to coastal aerosols (1, 2, 3 or 4 depending on whether the nearest coastal location is a very sheltered bay, partially closed bay, sheltered surf / very open bay or open surf respectively).</td>
</tr>
<tr>
<td>S_{air}</td>
<td>Atmospheric salt level (mg/m²/day)</td>
</tr>
<tr>
<td>S_{air, ocean}</td>
<td>Atmospheric salt level from ocean aerosols (mg/m²/day).</td>
</tr>
<tr>
<td>S_{air, coast}</td>
<td>Atmospheric salt level from coastal aerosols (mg/m²/day).</td>
</tr>
<tr>
<td>SE</td>
<td>Standard error of the estimate from regression equations (standard deviation around the regression line).</td>
</tr>
<tr>
<td>SI</td>
<td>Scheffers climatic index for predicting timber decay.</td>
</tr>
<tr>
<td>S_{SR}</td>
<td>Short range atmospheric salt distribution (mg/m².day).</td>
</tr>
<tr>
<td>S_{LR}</td>
<td>Long range atmospheric salt distribution (mg/m².day).</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>---------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>( t )</td>
<td>Time (years).</td>
</tr>
<tr>
<td>( T )</td>
<td>Temperature (°C).</td>
</tr>
<tr>
<td>( T_{\text{external}} )</td>
<td>External temperature in covered conditions (°C).</td>
</tr>
<tr>
<td>( T_{\text{external,lag}} )</td>
<td>External temperature in covered conditions with a 5 hour lag (°C).</td>
</tr>
<tr>
<td>( T_{\text{max}} )</td>
<td>Maximum temperature (°C).</td>
</tr>
<tr>
<td>( T_{\text{mean,monthly}} )</td>
<td>Mean monthly temperature (°C).</td>
</tr>
<tr>
<td>( T_{12\text{pm}} )</td>
<td>Yearly mean of 12pm temperature (°C).</td>
</tr>
<tr>
<td>( T_{\text{wall,cavity}} )</td>
<td>Temperature in a wall cavity (°C).</td>
</tr>
<tr>
<td>( \text{TOW} )</td>
<td>ISO time of wetness (time relative humidity is greater than 80%).</td>
</tr>
</tbody>
</table>
ABSTRACT

The aim of the study was to characterise the environment in the Sydney region in respect of atmospheric corrosivity, timber decay risk factors and the corrosion of nails in timber in covered conditions. A number of durability related risk factors were measured with a view to assisting designers and conservators when taking design decisions and analysing durability related defects associated with timber and nails in timber.

The study involved, reviewing contemporary research of others working in this field, particularly in Australia; developing an understanding of the durability failure mechanisms for timber and nails in timber; collecting data in the field and laboratory on climatic aspects, pollutants, corrosion and timber decay risk factors and statistically analysing this data to determine the relative level of the risk factors across the region.

Regression analysis was also carried out to determine whether it was possible to develop equations for predicting nail corrosion rates in the timbers used in the project based on measuring techniques that could be used with relative ease by conservation practitioners.

In general the conclusions of the study were that the levels of risk in terms of timber degradation, corrosion and nail corrosion were greatest adjacent to the coast and then relatively uniform across the remainder of the region. Subtle differences between non marine sites were evident. However it was also found that the effects of variability in
the materials used, particularly in some of the timbers, could mask the effects of differences in geographical location.

Relatively robust regression equations were developed for predicting the rate of corrosion of galvanised and bright steel nails in Radiata Pine, CCA Treated Radiata Pine and Douglas Fir based on near surface moisture content.

Maps and tables were prepared indicating the levels of the environmental aspects measured across the region during the study. Maps were also prepared indicating the relative risk of timber decay, corrosion and nail corrosion. Potential building defects related to these risks were also summarised along with recommended mitigation and prevention measures.

A conclusion of the study was that testing of the regression models based on larger sample sizes and other timbers would be a worthwhile area for further research. Another area of potential research recommended was the characterisation of the degradation of other materials in the Sydney region.
CHAPTER 1

INTRODUCTION

1.1 Objectives of the Study

Buildings and infrastructure account for approximately 50% of real capital in the developed countries of the world. There is increasing concern about the decline in the state of this built environment.

This concern has two main focuses. Firstly there is a growing awareness that much of our cultural heritage is being lost through failure to adequately conserve our historic buildings and secondly it is apparent that if we are to reduce our consumption of energy and materials to a sustainable level, measures aimed at reducing degradation of our building stock must be given far greater emphasis (Haagenrad 1996).

If appropriate steps are to be taken to conserve our buildings and maximise their useful lives it is essential that there be a thorough understanding of the factors that contribute to their degradation and methodologies need to be developed to characterise environments so that their relative effects on the service life of components and materials can be assessed (Haagenrad 1996).

To this end the aim of this project was to characterise the environment in the Sydney region in respect of atmospheric corrosivity, timber decay risk factors and the corrosion of nails in timber in covered conditions. Covered conditions for the purposes of this study are defined as those providing shelter from rain, wind and direct sunlight but allowing high levels of air circulation. The relative level of degradation factors was
measured to assist building industry professionals and conservators in making design
decisions and analysing the causes of durability related defects associated with timber
and nailed members.

The general approach taken in the study was to:

- explore the concepts and research techniques associated with durability
  characterisation of geographical areas;

- review the contemporary research of others working in this field, particularly in
  Australia;

- gain an understanding of the durability failure mechanisms for timber and nails in
  timber;

- monitor relevant climatic and pollutant aspects at sites representative of the sub
  climates in the study area;

- measure the extent of timber degradation risk factors and the rates of corrosion of
  metal and nails at these sites;

- statistically analyse the climatic, pollutant, corrosion and timber degradation data
  gathered to determine the relative environmental risks in the sub climates;

- where possible develop prediction models that can be conveniently used to estimate
  nail corrosion rates in the Sydney Region; and

- carry out condition surveys of timber buildings at selected sites to ascertain whether
  defects present were consistent with degradation risk factors studied or whether
  there were other influences giving rise to failures.
2.1 Outline of the Thesis

This report on the study first discusses the corrosion of metals; the factors contributing to the atmospheric degradation of timber; the degradation of timber connectors; the effects of connector corrosion on timber; the implications of the building envelope for the service life of timber building elements; the effects of the building envelope on the service life of connectors; approaches used to characterise atmospheres in Australia; areas identified as requiring further research and the nature of and influences on the Sydney climate.

The methodology used in the study for the collection and analysis of data is then set out.

This is followed by the results, discussion of the results and finally the conclusions drawn from the study are presented.
CHAPTER 2

REVIEW OF THE RELATED LITERATURE

2.1 Corrosion of Metals.

2.1.1 Atmospheric Corrosion

Corrosion is the deterioration of a material through its interaction with the environment within which it is located. The term is most frequently used with reference to metals but it can relate to any material (Fontana 1986).

The rate of corrosion can vary greatly depending on the material concerned and the nature of its environment. For example, sensitised stainless steel can be seriously affected by environments containing polythionic acid within hours. Railroad tracks on the other hand in most natural environments usually have service lives of many years (Fontana 1986).

This study was primarily concerned with atmospheric corrosion of metals and the corrosive effects of timber on nails.

Fontana (1986) has reported that the atmosphere is responsible for more corrosion, in terms of tonnage and cost, than any other environment.

Atmospheric corrosion is principally caused by moisture and oxygen. However it is increased by pollutants such as sodium chloride and sulphur compounds (Fontana 1986).
Pollutant deposition causing corrosion can be categorised as wet or dry. The former is deposition taking place through fog and rain. Dry deposition covers most other situations.

Cole has highlighted the differences within these groups by the use of the following subdivisions:

**Dry Deposition**
- Deposition by aerosols.
- Gaseous deposition into moisture films.
- Gaseous deposition into a surface which is truly dry.

**Wet Deposition**
- Deposition through fog.
- Deposition through fine rain drops.
- Deposition through coarse rain drops (Cole 2000).

Of the above, all except gaseous deposition on to dry surfaces involve gaseous / aqueous phase interactions and gaseous phase reactions (Cole 2000).

The range of sizes of atmospheric particles is from 0.01 to 100 μm. Three subdivisions have been identified; (a) < 0.1 μm (nuclei range), (b) 0.1 to 2.5 μm (accumulation range) and (c) > 2.5 μm (coarse range). The most important ranges, when considering atmospheric corrosion are the coarse and accumulation ranges (Cole 2000).

The concentration of pollutants will vary considerably depending on whether the deposition of the particles is on to a dry or wet surface (Cole 2000).
A large number of small concentrated droplets will reside on a dry surface. They will either evaporate or continue to wet according to the deliquescence relative humidity (DRH). The deliquescence relative humidity for a material is the relative humidity at which a particle will wet (absorb significant moisture). For example the DRH for ammonia sulfate is 80%, for ammonia bisulfate it is 52% whereas H₂SO₄ absorbs significant amounts of moisture at less than 20% relative humidity because it does not have a deliquescence point. This type of deposition may result in a large number of active corrosion sites. They will generally be small though and may not last long because of evaporation (Cole 2000).

On the other hand deposition involving a moisture film will generally be less concentrated than the aerosol and less aggressive to the metal in question.

2.1.2 The Effects of Industrial Atmospheres and Climate on Corrosion

The fact that industrial atmospheres cause increased corrosion of metal is well known. This has been attributed to the acidification of moisture films on the metal through their absorption of sulphur dioxide (Cole 2000).

Nitric oxide and ozone have also been identified as being of importance to corrosion (Cole 2000).

Investigations have found that there is a synergistic effect in relation to the corrosion of some metals when nitric oxide and sulphur dioxide are present together. Similarly it has been found that synergy exists when ozone and sulphur dioxide are present (Cole 2000).
A five nation study involving Australia, Indonesia, the Philippines, Thailand and Vietnam was recently carried out to investigate the relationship between climatic and pollution factors and the corrosion of mild steel and zinc (Cole 2000). Following exposure of corrosion specimens, regression analysis was undertaken. The models developed from this analysis and the factors of greatest consequence are shown below (Cole 2000).

\[ M_{\text{loss,steel}} = 1.3 \times TOW^{0.27(1.3-pH_{\text{avg.}})} + (0.9 \times SO_2 + 0.3 \times S_{\text{air}})^{0.81} \]  
\( R^2 = 0.86 \quad \text{Mean Average Error} = 1.3 \)  

\[ M_{\text{loss,zinc}} = 0.9 + 0.065 \times TOW^{1.4(5.5-pH_{\text{avg.}})} + 0.014 \times (0.5 \times SO_2 + 3.3 \times S_{\text{air}}) \]  
\( R^2 = 0.78 \quad \text{Mean Average Error} = 1.6 \)

Mass loss of steel and zinc \((M_{\text{loss,steel}} \text{ and } M_{\text{loss,zinc}})\) are expressed in \(\mu\text{m/year}\), time of wetness \((TOW)\) as the % of the time the relative humidity exceeded 80%, rainwater acidity as \(\text{pH}\), airborne salinity as \(\text{mg/m}^2\cdot\text{day}\) and \(\text{SO}_2\) in \(\mu\text{g/m}^3\).

When testing the above equations it was found that there was a strong correlation between steel corrosion and the levels of \(\text{SO}_2\) and the \(\text{pH}\) of the rainwater. However when testing the fit for zinc, although it was reasonable (Mean Average Error of 1.6), most of it related to the variations caused by the salinity. Dependence of zinc mass loss on \(\text{SO}_2\) levels or rainwater \(\text{pH}\) could not be demonstrated through regression analysis as \(R^2\) values did not exceed 0.4. This contrasted with the results of research in Europe and North America where there was a strong correlation between zinc mass loss and the levels of \(\text{SO}_2\) and the rainwater \(\text{pH}\) (Cole 2000).
Follow up work was carried out to identify the factors influencing the chemistry of dry and wet deposition of sulfates on surfaces. In essence it was concluded that the HSO$_3$ and HSO$_4$ content of moisture films and acidity are significantly affected by the NH$_3$ / SO$_2$ ratio and the concentration of oxidizing agents for S(IV) present. The highest levels of corrosion were found to result from a high SO$_2$ level and high oxidant level. The lowest levels were found to occur when the SO$_2$ level was low and the ratio of NH$_3$/SO$_2$ was high.

The study also highlighted that coarse raindrops, such as those experienced in monsoonal rains, are less likely to be acidic than the fine rain drops and fogs experienced in North America and Europe (Cole 2000).

2.1.3 The Effects of Atmospheric Salt Levels on Corrosion

There is a strong relationship between the rate of corrosion and the level of salt deposition from the atmosphere (Paterson 2001).

Salt aerosol can be generated from the open ocean, the near coastal margin, in enclosed waterways such as rivers, from dust or through industrial processes. The open ocean generates most airborne salt and this can be transported for large distances. The coastal margin is also of significance but the impact is largely confined to adjacent locations. Other sources of aerosols are of little relative importance, except on a very localised basis (Paterson 2001).
The processes that generate salt from the open ocean are:

- strong winds ripping spray from the leading edges of waves, creating large aerosol droplets;
- bubbles breaking, producing jet drops which are intermediate sized aerosols; and
- film drops generated at the edges of bubbles forming fine aerosols (Paterson 2001).

The large particles carry the greatest volume of salt and have an average dry radius of approximately 4.4 microns (Paterson 2001).

As the average seasonal wind speed is greatest at higher latitudes in each of the earth’s hemispheres so is wave whitecap coverage. Salt concentrations at near coastal locations at latitudes of 50 degrees and above are more than twice as high as at the equator (Paterson 2001).

Breaking waves near the coast create large aerosols having a dry salt radius of approximately 6 microns. However due to their size and the fact that they are confined to low levels of the atmosphere, their impact on salt levels beyond the immediate coastal area is not significant (Paterson 2001).

The amount of salt produced by waves in the surf is determined by the rate at which wave energy is moved towards the shoreline i.e., energy / m² of surface x the wave group velocity. The first factor is in turn determined by the square of the significant wave height and the latter factor is proportional to the wave period (Paterson 2001). Waves that are generated locally do not produce significant amounts of salt aerosol
because the wave period is dependent on it moving over large distances of ocean (Paterson 2001).

Salt aerosols deposit readily on trees and man made structures. They are deposited by the air streams that move around these elements (Paterson 2001).

According to Paterson the parameter that most strongly influences salt concentration is wind speed. This aspect not only creates the whitecaps that generate the aerosols but it also transports them by creating turbulent diffusion which takes them high into the atmosphere and then moves them over large distances (Paterson 2001).

Movement of aerosols generated in the surf is significantly affected by the roughness of the adjacent ground. Vegetation and man made structures reduce the amount of salt aerosols moving inland (Paterson 2001).

The relative humidity at ground level has two effects on ocean generated aerosols. Firstly higher levels of relative humidity increase the size of salt droplets causing them to settle more quickly. Secondly increased levels lower the cloud base, which reduces the amount of salt entering the upper troposphere; hence reducing the amount transported inland (Paterson 2001).

The amount of rainfall also influences salt aerosol levels. Increased rainfall results in greater amounts of salt being brought down from the atmosphere in raindrops, hence less is moved further inland.
Cole et. al. (2002) have completed a study aimed at estimating marine aerosol deposition and the factors affecting it.

Three transects were established across Australia along which airborne salinity was measured. The transects ran from approximately 10m to 300km from the beach line. They were located so that variations in the aspects that affect salt production and transport were included.

One of the transects was in South Australia where there is high wave windcap activity off the coast, a flat terrain and winds conducive to salt transport. A transect was established in Queensland where the seas and winds are mostly calm and seasonal and relative humidity and rainfall are high. The third transect was located in southern New South Wales.

Key findings of the study were:

- the relationship of salt concentration with distance from the coast involves two decay functions;
- one function has a high initial value and decays rapidly as the distance from the beach line increases;
- the other has a relatively low initial value but decays gradually;
- the beach line surf generated salt aerosol deposition rate was within the range of 350 – 400 mg/m$^2$.day; and
- ocean produced salt aerosol deposition at the beach line was approximately 20, 30 and 50 mg/m$^2$.day in Queensland, New South Wales and South Australia respectively.
Models for predicting the salinity in relation to distance from the coast were developed as set out below:

\[ A(d) = (Ai) \times \left[ (0.9 \times e^{-d/0.1}) + (0.1 \times e^{-d}) \right] \]  
(2.3)

where;

\( A(d) \) = salt concentration at a distance from the beach line (mg/m².day);

\( Ai \) = surf produced salt concentration at the beach line (mg/m².day) and

\( d \) = distance inland from the coast (km).

\[ OA(d) = [OA_i] \exp^{-d/x} \]  
(2.4)

where;

\( OA(d) \) = concentration of ocean produced salt aerosol at a distance \( d \) (km) from the beach line (mg/m².day);

\( OA_i \) = concentration of ocean produced salt aerosol at the beach line (mg/m².day); and

\( x \) = a decay function having a value of 50.

It was assumed that salt deposition was proportional to concentration.

This study has been extended (Cole et. al. 2002) to examine the effect of natural and man made landforms on the deposition of marine salts in Australia and South East Asia. In essence this research involved contrasting measured salt deposition levels at sites having various sheltering features with predicted salt deposition levels (using equations 2.3 and 2.4) to quantify the effects of the sheltering. The study also examined the extent to which bays contributed to salt deposition.
The key conclusions were that:

- there is a large degree of scatter when measured salt deposition is related to the distance from the coast;
- this scatter can be explained in terms of differing effects of oceans and surf in creating and transporting salt aerosol and the effects of landforms and buildings in reducing airborne salinity; and
- narrow bays are unlikely to contribute significant levels of salt aerosol and wide and shallow bays are only likely to affect salt aerosol levels very close to bays.

In relation to the effects of shielding the results indicated that the salt level in the vicinity of houses adjacent to surf beaches was approximately 70% of a site on a beach front without houses. The reduction was attributed to the sheltering created when winds blow at an angle from the beach to the houses and the houses provide protection. At sites further from the beach salt deposition in sheltered locations was found to be approximately 33% of that in unsheltered locations and salinity on facades was approximately 75% of that in the general vicinity of a house.

2.1.4 Classification of Atmospheric Corrosivity of Atmospheres

AS/NZ 2312 (Guide to the protection of Iron and Steel against exterior Atmospheric Corrosion) establishes six atmospheric classifications in relation to corrosion:

- Mild – This covers corrosion rates for mild steel of up to 10 µm per year. Areas having this classification will be remote from the coast and have an absence of industrial activity. They include outback Australia and rural areas not on the coast.
- Moderate – Typically first year corrosion rates are in the vicinity of 10 to 25 µm per year. Areas of this classification generally have light marine and industrial
influences. In Australia this would include inland cities and non coastal suburbs of cities on sheltered bays such as Melbourne and Adelaide.

- Tropical – This classification covers areas such as coastal north Queensland, the Northern Territory and northwest Western Australia which are not directly affected by sea spray. They tend to have low steel corrosion rates but are particularly aggressive to organic coatings.

- Industrial – These areas typically have first year corrosion rates greater than 25 \( \mu m \) per year but can exceed 50\( \mu m \) per year. There are few of these areas in Australia. Newcastle and Port Pirie fall under this classification.

- Marine – First year mild steel corrosion rates of 25 to 50 \( \mu m \) per year are typical. These areas are subjected to moderate amounts of coastal salt. Most ocean fronts in south east Australia fall into this classification. Generally the classification covers the zone commencing approximately 1km from the coast and extending to around 10km inland. Large parts of Perth, the Gold Coast and Sydney are covered by the classification.

- Severe Marine – These areas have mild steel corrosion rates in excess of 50 \( \mu m \) per year. Locations are on the coast or off-shore. Local topography, prevailing winds and the extent of wave action determine how far the classification extends inland. Usually it extends from the beachfront to approximately 1 km inland. However adjacent to sheltered bays it extends to approximately 100m inland (Standards Australia 1994).

International Standard ISO 9223 (referred to in AS/NZ2312) sets out five categories of corrosivity (for mild steel):

- C1 – very low, <1.3\( \mu m \) per year, arid / inland;
• C2 – low 1.3 to 25 μm per year, arid / urban;
• C3 – medium, 25 to 50 μm per year, coastal;
• C4 – high, 50 to 80 μm per year, sea-shore (calm); and
• C5 – very high, 80 to 190 μm per year, seashore (surf) (Standards Australia 1994).

AS/NZ 2312 stresses that areas underground, underwater, in splash zones and industrial complexes such as chemical plants are of special significance and require particular consideration and protection given their aggressive environments.

2.2 Principal Factors Contributing to the Atmospheric Degradation of Timber

The principal factors affecting the building and engineering properties of timber are:

• temperature;
• moisture content;
• chemicals;
• weathering;
• decay due to fungi and bacteria;
• insects; and
• time (Malhotra c.198-).

Of these, temperature, moisture content and weathering have obvious connections with the atmosphere, which was the principal area of focus for this study. Chemical, fungal and bacterial degradation can be related to the atmosphere. Insect attack is not influenced directly by atmospheric conditions. The extent of degradation can be regarded as a function of time and one or more of the other factors.
If the temperature is increased for a short period only, the strength of timber is not reduced on a permanent basis. However if the moisture content is also increased allowable stress levels will require adjustment. Very low temperatures (to -185°C) can increase the strength of timber beyond the values that would be expected at normal temperatures (Malhotra c.198-).

Moisture content has a considerable effect on the strength of small timber samples. It is apparent however that larger timber members are not always adversely affected to the same extent (Malhotra c.198-).

Timber is a rheological material that can behave differently if subjected to wetting and drying cycles. In laboratory load tests creep failure has been found to occur at approximately 27% of the maximum load that would have sustainable had the same timber been kept at a constant moisture content level (Malhotra c.198-).

Wood generally performs relatively well in relation to degradation by chemicals (Wangaard 1966). However the effects of chemicals on the strength performance of wood varies considerably from species to species. Hardwoods are generally more prone to degradation from chemicals than softwoods. Alkaline chemicals tend to cause greater degradation than acids as the former dissolves hemicelluloses and attacks the lignins. Acids reduce the strength of timber and make it more brittle. Salts vary in their effects, some causing loss of strength and others enhancing strength (Malhotra c.198-).

The surface layers of wood absorb water from rain and other forms of precipitation and expand. Heat from the sun and dryer, less humid conditions then force the water out of the surface. This cycling puts the surface under stress and for species which have a high shrinkage rate causes cracks and checks. These defects gradually increase in depth furthering the weathering process (Bootle c.1983).
Weathering and erosion are advanced by oxidation brought about by ultra violet radiation. Soft rot fungi also enter the weathering surface of timber causing softening (Bootle c.1983).

The rate of weathering is generally slow and varies from species to species (approximately 0.1mm / year). It is not regarded as a major problem unless rot is introduced (Bootle c.1983).

Rot and decay are brought about by fungi, which is present in the atmosphere as spores. These spores can enter wood before tree felling or fungi can invade milled timber when conditions are damp and warm enough, feeding off the starch and sugars in it. Sapwood has more of these nutrients than heartwood and is particularly susceptible. Heartwood often contains fungitoxic extractives and is less susceptible to attack by fungi. However the extent and toxicity of these extractives varies significantly from species to species (Bootle c.1983). Decay may commence in either sapwood or heartwood depending on the timber and environmental conditions.

There are three main types of wood destroying fungi; brown rot, white rot and soft rot (Foxton & Moss c.198-).

Brown rot uses cellulose from wood as the principal source of nutrients. The timber becomes dark brown and is badly cracked. It looks like it has been burnt in a fire. It generally attacks softwoods rather than hardwoods. The residual wood is light, dry, burns readily and has diminished strength (Foxton & Moss c.198-).

White rot involves the break down of both the cellulose and lignin in the wood, which becomes lighter, weakened and lighter in colour. The timber breaks down in the longitudinal direction. Pockets of decay are separated by wood that appears unaffected (Foxton & Moss c.198-).
Soft rot fungi look like corrosion on iron. Degradation starts in the surface layers of the cells and gradually causes the wood to crumble away with decay moving inwards (Foxton & Moss c.198-).

Mould type fungi affect the surface of wood but the hyphae (fine strands) can penetrate deeper in to the wood (Foxton & Moss c.198-).

The level of moisture present generally controls wood decay in Australia (Walters 1973). If the equilibrium moisture content (EMC) of untreated timber exceeds 30 %, decay is very likely to take place (Thornton 1991). According to Bootle, the EMC of timber must be kept below 20% to ensure fungi associated with biodeterioration will not germinate. However fungi once established will continue to grow at moisture levels below 20%. The level below which it will stop growing is debatable. Thornton in a communication to Cole has suggested that it will stop growing below approximately 18% (Cole 1993b). According to Dix the lower limit is approximately 15%. (Dix 1983).

For wood decay fungi to germinate and grow the EMC thresholds must be exceeded for relatively significant durations. Cole has suggested that the respective limits must be exceeded for at least 10% of the time (Cole 1993b).

Decay normally starts on sapwood when the moisture content reaches the level that the fungi present prefers. A loss of strength in the wood occurs in the early stage of decay when the fungi can not be seen by the eye. This is called incipient decay. As the fungi develops hyphae progress through the wood. If the fungi feeds on lignin then they are whitish in colour. When the primary food source is cellulose they are brown. On the surface of the wood the fungi can manifest themselves as moulds, toadstools or brackets (Foxton & Moss c.198-).
The common terms of wet and dry rot are not particularly useful as moisture must be present for fungal attack to take place. The term dry rot relates to the fungi called Serpula lacrymans or Merulius lacrymans, which in Australia is generally confined to Victoria. This fungi transfers moisture from nearby areas on to the dry wood (Foxton & Moss 198-).

There are three types of voids in wood:
- lumina of cells (radius of 5 to 200 micrometres);
- pit apertures and pit membrane pores (1 x 10^{-2} to 5 micrometres); and
- transient intra mural voids (very small and only appear when water is present; 10^{-2} micrometres or less) (Griffin 1977).

The distribution of pore sizes in the substrate must facilitate the holding of water if fungi are to grow. This allows the diffusion of enzymes, other metabolic catalysts from the fungi and the partial degradation products that they feed on (Griffin 1977).

2.3 The Degradation of Nailed Timber Joints

2.3.1 The Corrosion of Timber Connectors

The extent of corrosion of nails in is dependent on a number of factors including the moisture content of the timber, decay and insect attack, the wood species involved, preservative treatment and atmospheric and other pollutants that may be present (Davis 1994)

The basic mechanism for the corrosion of nails in timber as described by Davis is shown in Figure 2.1 below.
According to Baker (1980), the exposed end of a nail in damp wood forms hydroxyl ions (OH\(^-\)) and becomes a cathode. The shank becomes an anode and galvanic corrosion commences. The reaction at the cathode is:

\[
O_2 + 2H_2O + 4e^- \rightarrow 4OH^-
\]  

(2.5)

The reaction at the anode is:

\[
Fe \rightarrow Fe^{++} + 2e^-
\]

(2.6)

Ferrous ions (Fe\(^{++}\)) formed at the anode are oxidised, become feric ions (Fe\(^{+++}\)) and react to form black iron tannate dyes or rust. The iron ions are catalysed and promote reactions causing a loss of strength in cellulose.

Chloride ions (Cl\(^-\)) and hydroxyl ions (OH\(^-\)) are formed as the reactions at the cathode and anode take place. These move in to the crevice between the nail and the wood (Baker 1980).
Iron ions at the anode react with the hydroxyl ions in the crevice and present in the bulk solution and insoluble iron hydroxides are formed. The process in the crevice causes the solution to be acidic because the concentration of hydroxyl ions decreases at a rate greater than that of the hydrogen ions (H⁻) i.e., the material in the crevice is acidic because of the high concentration of (H⁺) (Baker 1980).

Crevice corrosion normally occurs after an incubation period. Having started it proceeds at an accelerated rate (Baker 1980).

The rate of corrosion depends on the moisture content of the wood. As the moisture content reaches 20% the electrical conductivity of the wood approaches the point where corrosion can take place (Baker 1980).

Excessive moisture content can, as discussed earlier, also cause decay. The decayed area in the wood can retain moisture longer than usual further promoting corrosion. Similarly termite attack can also increase the moisture content and the risk of corrosion. The wood has higher porosity, lower density and absorbs moisture (Davis 1994).

The acidity of timber has a bearing on the extent of corrosion. Acetic acid is formed through the hydrolysis of acetylated polysaccharides in wood. The extent of acetic acid required to promote corrosion is relatively small (< 0.5 ppm). There is usually more acetic acid in hardwood than softwood (Davis 1994).

Wood is not very homogenous, hence the amount of acetic acid present can vary significantly. The plant class, genus, species and variety determine the composition and structure of the wood. Further environmental factors and the part of the tree from which it is taken can result in variations in the amount of acetic acid in a particular piece of timber (Davis 1994).
The variation in the timber can create a corrosion cell i.e., through differences in moisture content, pH and salts present (Davis 1994).

Some species of timber are more permeable than others. Permeable wood allows more oxygen and electrolyte to penetrate increasing corrosion (Davis 1994).

2.3.2 Treated Timber and Connector Corrosion

Corrosion of steel nails can be exacerbated by copper ions in waterborne preservatives containing copper salts. The copper ions are deposited on the nails, as they are more electronegative. A galvanic couple is created comprising the nail, moist wood and the copper on the nail (Baker 1980).

The copper salts used as preservatives are generally chromated copper arsenates (CCA). These products can be made from different constituents:

- potassium dichromate, copper sulphate and arsenic acid: or
- chromium trioxide, copper carbonate and arsenic acid.

The first mixture will produce a by-product of potassium sulphate which increases electrical conductivity. The second mixture produces carbon dioxide which dissipates without changing conductivity (Baker 1980).

The corrosive behaviour of metal fasteners in preservative treated timber has been investigated by the Queensland Forest Service. Eight types of metal fasteners were inserted in 125 x 50 x 4800 mm Slash Pine timber boards, treated with CCA preservative. The fasteners were placed in the timber shortly after treatment and during the drying period. Test boards were also prepared for monitoring moisture content. Weight loss measurements were carried out after six months and twelve months to determine the mass loss through corrosion (Davis & Allen 1993).
The fasteners used were:

- stainless steel screws (40 x 3 mm);
- monel boat nails (45 x 2.5 mm);
- brass CSK wood screws (32 x 3 mm);
- copper square boat nails (32 x 3 mm);
- silicon bronze boat nails (45 x 2.5 mm);
- nickel plated steel round head wood screws (45 x 2.5 mm);
- hot dipped galvanised steel clouts (40 x 2.8 mm); and
- mild steel bullet head nails (40 x 2.5 mm) (Davis & Allen 1993).

Following exposure the boards were split and the corrosion products removed in accordance with ASTM Standards. The mass loss for each type of fastener was then determined and least squares regression analysis carried out to describe the mass loss of the metals in relation to the initial moisture content. This was not possible with the stainless steel fasteners as no significant relationship could be found (Davis & Allen 1993).

Corrosion was found to be negligible for moisture contents of less than 20%. When the moisture content was above 20% the ranking of fasteners according to the extent of corrosion was:

1. mild steel;
2. hot dipped galvanised steel;
3. nickel plated steel;
4. silicon bronze; copper
5. brass;
6. monel; and
7. stainless steel (Davis & Allen 1993).
The metals were subsequently divided into three groups in relation to the corrosion level:

1. mild steel, hot dipped galvanised steel, nickel plated steel;
2. silicon bronze, copper, brass and monel; and
3. stainless steel.

It was concluded that where CCA treated timber is to be used with a high moisture content for extended periods the material group 3 should be used. It was also concluded that corrosion could be minimised if the timber is left to reach its equilibrium moisture content before fasteners are placed in it (Davis & Allen 1993).

It has been argued by the timber preservation industry that if contact occurs between fasteners and CCA preserved timber before the copper ions become fixed copper may be deposited on the fasteners leading to galvanic corrosion but if they are not inserted until after setting (90 days approximately) the problem does not eventuate. However research by the Scientific Branch of the Greater London Council contradicts this view (Greater London Council 1981).

Samples of treated European redwood were obtained, some of which were placed in polythene to slow down fixation. Others were allowed to dry to equilibrium moisture content. Samples of untreated timber were obtained for comparative purposes. Fasteners were placed in the samples and they were maintained at 100% relative humidity and 25°C for thirty months. Subsequently the corrosion was measured by recording the weight loss and reduction of diameter (Greater London Council 1981).

The fasteners were screws made from austenitic stainless steel (type 302), aluminium alloy (type 2014A), mild steel and zinc plated mild steel (Greater London Council 1981).
The conclusions of the study were:

- CCA treated timber increases the corrosion of fasteners made from mild steel, zinc plated mild steel, and aluminium fasteners (at 100% relative humidity);
- there was severe grain boundary attack associated with aluminium alloy fasteners used with CCA treated timber causing splitting of the samples;
- stainless steel fasteners were not affected by the treated timber;
- fixing of the preserved timber had no impact on corrosion; and
- the extent of loading in the preserved timber did not correlate with the corrosion parameters.

Copper napthenate, when used as a preservative can cause a similar problem as it forms soluble copper. However zinc napthenate does not present a problem (National Physical Laboratory, U.K. 1979).

Oxide preservatives have not proven to be excessively corrosive. Zinc plated nails for example form a thick preservative layer of zinc oxide and zinc carbonate that is eroded slower than would be the case with CCA treated timber (Davis 1994).

There have been no apparent problems with boron or borax treated timber (fire retardant treatment) (Davis 1994).

Oil based preservatives such as creosote or tar oil are similarly not seen as a problem as they coat the surface of the connectors (Davis 1994).

Chloride ions have a considerable influence on the corrosion of nails. Timber naturally contains chloride. This is generally in the range of 10ppm to 2000ppm depending on the species and the part of the tree from which the timber is taken (National Physical Laboratory, U.K. 1979).
Proximity to marine sources also influences the amount of chloride present in wood. There have been reports of corrosion of metal in wood that was subsequently found to have up to 0.8% salt by weight. Salt can find its way into wood through marine aerosol deposition and subsequent diffusion, through the floating of logs in sea water or from salt seasoning (National Physical Laboratory, U.K. 1979).

Organic solvents such as lauryl pentachlorphenate and pentachlorphenol used as water repellants are not usually a problem in relation to corrosion except when alkalis are created by other corrosion which decomposes these solvents producing soluble chlorides (National Physical Laboratory 1979, U.K.).

2.4 The Effects of Connector Corrosion on Timber

In timber construction not only do fasteners corrode but also the corrosion products in turn have a detrimental effect on the surrounding wood. This phenomenon is commonly known as ‘nail sickness’ (Pinion 1970).

The alkali created at the cathodic surface attacks the wood and makes it spongy; hence the fastening effect is weakened. Alkaline solution in the surrounding wood can be detected using phenolphthalein solution or test papers (Pinion 1970).

Dense woods tend to perform better when caustic alkalis are created because there is a greater amount of wood present. However hardwoods have more hemicellulose than softwoods and this material is dissolved readily by alkalis. Shrinkage and distortion result (Pinion 1970).

In the case of steel nails iron compounds found at the anodic area cause degradation. The blue-black staining in this area on woods containing tannin is caused by the iron salts diffusing along the grain and interacting with the tannin (Pinion 1970).
If the soluble corrosion products meet when diffusing through the wood, precipitation of the metallic corrosion product is caused by the alkali creating rust deposits. The colour of the stain depends on the amount of oxygen present (Pinion 1970).

2.5 The Effects of the Building Envelope on the Service Life of Timber Building Elements
Cole has illustrated the importance of the building microclimate to the degradation of timber elements in a study conducted in Melbourne, Sydney and Brisbane aimed at determining the effects of the building envelope on the durability of wood. The temperature and relative humidity in the wall cavities of houses in these cities were recorded and used to calculate the moisture content in these spaces. The EMC of studs in the wettest of the cavities was determined. These moisture contents were then compared to data on the EMC levels required for degradation to occur through fungal decay (Cole 1993a).

It was found that although the formation of fungi was not certain in any of the houses the possibility could not be ruled out in the Melbourne and Darwin houses. The 20% moisture content required for fungi to establish themselves was exceeded in Darwin in the summer in exposed walls, and in Melbourne in an exposed wall in winter. If fungi were to form, conditions existed in all locations for it to continue to grow (Cole 1993a).

This work has been extended by Cole et al. Eighteen houses in cold, temperate, tropical and subtropical climates across Australia were studied with a view to calculating surface equilibrium moisture content from air temperature and relative humidity. Part of the study also involved electronic readings of EMC and mass change measurements (Cole,
Ganter & Norberg 1996). The data gathered was supplemented by data from a study of 64 houses by Duncan and Vautier in New Zealand (Cole, Ganther & Norberg 1996).

The surface EMC's calculated assumed that the timber surface and air were in equilibrium. The air EMC was calculated using the following equation developed by Bramhall (Cole, Ganther & Norberg 1996):

\[ MC_{\text{surface}} = \ln \left( \frac{\ln(RH) + K_3}{K_2} \right) \cdot 0.92 \cdot \ln K_1 \]  

(2.7)

where;

\[ \text{RH} = \text{relative humidity (\%)}; \]
\[ T = \text{temperature (\degree C)}; \]
\[ K_1 = 1.0327 - 0.000674T; \]
\[ K_2 = 17.884 - 0.1432T + 0.0002362T^2; \text{ and} \]
\[ K_3 = 0.0251. \]

The estimates made using this formula were generally in accordance with those obtained by on site measurements (Cole, Ganther & Norberg 1996).

One of the key findings of the study was that surface equilibrium moisture content (SEMC) values in excess of 18% may occur in house sub floors in areas where the rainfall is high, there is cold conditions or the ventilation is poor.

Further, SEMC values above 18% (the level required for fungi to continue to grow once established) were found in wall cavities of all of the houses except those at inland locations (Cole, Ganther & Norberg 1996).

In sub tropical and tropical climates the temperature cycle in wall cavities lags behind the temperature cycle outside. In some seasons the temperature in the cavities in the
morning can be lower than the outside temperature and this could result in condensation or high humidity in the cavities. If warm moist air enters a cavity when the temperature is lower than outside a cooling effect would take place reducing the air's capacity to hold water. Under these circumstances the surface EMC of the timber would rise. This phenomenon was evident in several of the houses monitored in the study. When these moist conditions exist they could continue for some time, overriding the daily cycle (Cole, Ganther & Norberg 1996).

Leicester (1995) has proposed the use of the following equations in respect of the relationships between external and wall cavity temperature and humidity:

\[ RH_{\text{wall,cavity}} = 0.6RH_{\text{external}} + 0.3RH_{\text{external,lag7}} \]  

where;

\( RH_{\text{wall,cavity}} \) = wall cavity relative humidity (%);

\( RH_{\text{external}} \) = external relative humidity (%); and

\( RH_{\text{external,lag7}} \) = external relative humidity with 7 hour lag (%).

\[ T_{\text{wall,cavity}} = 0.5T_{\text{external}} + 0.6T_{\text{external,lag5}} \]  

where;

\( T_{\text{wall,cavity}} \) = the wall cavity temperature (°C);

\( T_{\text{external}} \) = the external temperature (°C); and

\( T_{\text{external,lag5}} \) = the external temperature with 5 hour lag (°C).

2.6 The Effects of the Building Envelope on the Service Life of Timber Connectors

As discussed earlier the extent of corrosion of metal building components is dependent on the levels of pollutants present and the TOW.

Cole and Ganther have shown that significant TOW’s occur in Australian brick veneer houses (Melbourne 25%), (Brisbane 23%) and (Darwin 20%) (Cole & Ganther 1996).
Guttman and Sereda have proposed the following model for predicting the extent of corrosion:

\[ C_r = a(TOW)^b \times (P + c) \]  \hspace{1cm} (2.10)

where;

- \( C_r \) = corrosion rate (g/m\(^2\).year);
- \( a, b \) and \( c \) are constants derived from experimental data by regression analysis (the magnitude being dependent on the pollutants and metals concerned);
- \( TOW \) = time of wetness (days); and
- \( P \) = the pollution level (for example chloride deposition in mg/m\(^2\).day) (Cole & Ganther 1996).

Sea salt is the most common pollutant in Australia in relation to metal components. Cole and Ganther have carried out a project to determine the levels of airborne salinity in a sample of Australian houses. The houses used were at coastal locations but at different distances from the sea (0.1 km to 1.3km) (Cole & Ganther 1996).

Salt levels were measured over a twelve month period using salt candles in accordance with ISO 9225. They were placed in the following locations:

- in the garden (3m from the houses);
- on exposed walls;
- on a sheltered wall;
- in the wall cavity of exposed walls;
- in the roof space; and
- within the house (Cole & Ganther 1996).

The most important factors in determining the extent of salt deposition are:

- the distance from the nearest marine body (the salt deposition rate decreases rapidly over the first 2km and then becomes somewhat constant);
• seasonal weather patterns, particularly in respect of wind (significant variability can occur within relatively small areas);
• the shielding effect of the house; and
• sheltering by the outer skin of the wall or the roofing (Cole & Ganther 1996).

Cole and Ganther found that the extent of salt lodging on the walls was approximately half of that deposited in the open garden areas. This was probably due to the eaves over the walls or the air flow patterns around the house. The deposition in the cavities was approximately, 70% of that outside on the walls. Sisalation reduced deposition to around 30%. The ratio of the deposition in the cavities to that in the roof space was on average 0.9 (Cole & Ganther 1996).

The researchers were unable to define the constants called for in the equation developed by Guttman and Sereda (Equation 2.10) with adequate accuracy. However in another study completed by King and O’Brien it was found that the corrosion rate for zinc in relation to salt deposition was almost linear and the following relationship existed:

\[ C_{r,zinc} = 2.5 \times S_{air} \]  

(2.11)

where,
\[ C_{r,zinc} \] = corrosion rate of zinc (g/m².year); and
\[ S_{air} \] = airborne salt deposition (mg/m².day) (Cole & Ganther 1996).

The salt deposition rate adjacent to the marine source was approximately 3mg/m².day and at the sites furthest away it was 1.5mg/m².day. Using the above formula for the study area and assuming a design life of 50 years, it was calculated that components in typical wall cavities in the houses closest to the marine source were likely to lose 375g/m² and those furthest away 190g/m². Therefore 600g/m² and 300g/m² of
galvanising would be required to achieve the design life of the building (Cole & Ganther 1996).

The same researchers have carried out a study into the extent of nail corrosion in building envelopes in Queensland and the contributing factors. Timber samples containing nails were placed in wall cavities, roof spaces and externally to houses in Brisbane, on the Sunshine Coast and in the Cairns area, being representative of different climates found in Queensland. The nail types were bright steel, hot dipped galvanised steel, ring shanked, zinc plated steel and zinc wire (Cole, Ganther, Bradbury & O’Brien 1996).

The samples were exposed for durations of 15 - 20 months. The nails were removed from the boards and the extent of corrosion on each nail rated. The corrosion was then removed using acid and the weight loss measured (Cole, Ganther, Bradbury & O’Brien 1996).

Analysis of the weight loss resulted in the test sites being classified as mild and severe in respect of exposure. The study found that the corrosion rate in the building envelope was five to ten times less than outside. However to ensure a life of 50 years for nails in framing in wall cavities and roofs a zinc coating of 350g/m² would be required in roof spaces and 200g/m² in wall cavities. Weight losses were expected to be in the order of 7 g/m² in roofs and 4g/m² in walls (Cole, Ganther, Bradbury & O’Brien 1996).

2.7 Approaches used to Characterise Atmospheres

There are two principal ways of classifying or characterising environments:

- degradation rate measurement of stand alone samples; and
- according to the degradation causing aspects (such as pollutant levels).
The former approach predominated until recent years. However it is now believed that the results gained this way are only valid at the time the data is collected, non explanatory and non predictive (Haagenrud 1996).

More recently with increased availability of data the latter approach is tending to be used i.e., mapping and classification of exposure environments. The end objective is to predict the service life of components (Haagenrud 1996).

One attempt to utilise this approach has involved the development of climatic indexes such as Scheffers Index for predicting wood decay. The index is calculated as follows:

$$SI = \sum_{Jan}^{Dec} \left( T_{\text{mean monthly}} - 35 \right) \left( D_{\text{rain},x} - 3 \right) / 30$$  \hspace{1cm} (2.12)

where;

$T_{\text{mean monthly}} =$ mean monthly temperature ($^\circ$F);

$D_{\text{rain},x} =$ the mean number of days in the month with 0.1 inches (2.54 mm) or more of precipitation; and

$\sum_{Jan}^{Dec} =$ summation of the products for the months January to December.

Areas with indexes $< 35$ are least likely result in decay. Areas with an index in the range of 30-65 are regarded as intermediate and areas with an index of $> 60$ are most likely to have decay (Degroot 1982).

The index has been used to prepare hazard maps in respect of timber decay for the USA.

Degroot (1982) has carried out work to compare this model of potential for wood decay with the actual incidence of decay in houses. It was found that it only correlated well with the incidence of decay in older houses.
Another example of this approach is the work carried out by Tomittta. In this project meteorological data has been used to estimate the severity of solar ultra violet radiation, time of wetness, wet-dry cycling, thermal based degradation and temperature difference. Probable deterioration of buildings in a particular location is forecast through examination of the maps prepared for these factors. Synergistic effects such as temperature modified time of wetness have also been mapped (Haagenrud 1996).

Point measurements of air quality in relation to buildings is relatively expensive. Hence air dispersion models have been developed to assist with the analysis of the effects of the environment on buildings. These models utilise Geographic Information System (GIS) computer software for the production of maps (Haagenrud 1996).

This approach has been used to model corrosion in Oslo. Dose response functions, dispersion models and air quality data have been used to prepare maps of the corrosivity of the environment. The dose response functions and maps take into consideration data on sulphur dioxide and nitrogen dioxide emission levels, ozone levels, time of wetness, rain, $H^+$ concentrations and synergistic effects obtained from various sources. Maps have also been prepared indicating where acceptable corrosion levels have been exceeded and the costs of degradation of building materials. The latter have been based on building registers and material distribution factors (Haagenrud 1996).

Pollution can move over large distances in the atmosphere and in Europe efforts have been directed to monitoring its movement across national borders. Initiatives of this type include a monitoring system operated by the World Health Organisation involving 270 monitoring stations at 86 cities across 45 countries (Haagenrud 1996). In the U.K. dose response equations and GIS software have been used to study the effects of acid deposition on buildings (Haagenrud 1996).
2.8 Characterisation of Atmospheres in Australia

In Australia the characterisation of atmospheres by mapping techniques in relation to timber degradation and corrosion has primarily involved equilibrium moisture content surveys in the former case and measuring corrosion rates of metal samples across grid patterns in the latter.

Timber degradation studies have included:

- an investigation into moisture content predictions for seasoned timbers under sheltered conditions in Australia and New Guinea;
- an equilibrium moisture content survey of timber in Queensland;
- a study in to EMC variations of timbers used in Western Australia; and
- a study of the EMC of timber in Sydney.

The most significant corrosion mapping studies have been carried out in Melbourne and Newcastle by the CSIRO.

The CSIRO has also undertaken a series of projects aimed at the development of a GIS system for predicting the equilibrium moisture content of timber building elements and the corrosion rate of nails in timber framed buildings at any location in Australia.

2.8.1 Timber Degradation Related Studies

A brief summary of each of the major timber related studies is set out below.

Moisture Content Predictions for Timbers Under Sheltered Conditions in Australia and New Guinea

In 1956 at the Forest Products Research Conference in Melbourne it was agreed that a wood moisture content survey for major timber using areas should be carried out. The intention was to be able to use the data for predicting the moisture content of timber at other localities given the weather conditions (Finighan 1966).
Specimens consisting of eight species were exposed for eight years. The sites were chosen to be representative of the climatic zones in Australia (Finighan 1966).

The specimens were exposed in shelters of uniform construction at Adelaide, Alice Springs, Brisbane, Broken Hill, Cairns, Canberra, Hobart Melbourne, Sydney and Lae in New Guinea. They were 1/4, 3/4 and 1 3/4 inches in thickness, air dried and conditioned for several months (Finighan 1966).

The specimens were weighed twice weekly at 9.00am to 0.5 grams accuracy. The moisture content was then calculated using the estimated oven dry weight. The width and depth were measured to an accuracy of 0.01 inches and the wet and dry bulb temperatures were recorded (Finighan 1966).

The study concluded that the percentage moisture content of the specimens could be calculated using wet and dry bulb temperatures and relative humidity in empirical equations (Finighan 1966).

An equation was developed for each thickness of each species of timber by utilising the combined moisture content and climatic data from all sites where specimens of a particular thickness were exposed. Moisture conditions were then predicted using theses equations and the study period weather data for the given site. The predictions were compared with the observed moisture contents for the same period. Excluding data from Alice Springs and Broken Hill, 95% of the predictions were within 1% of the observed values (Finighan 1966).

Measurements of indoor moisture contents were made at 12 sites using 3/4 inch specimens. In Melbourne in houses that did not have central heating, the moisture content was 2-4 % less than outside, depending on the time of year and species. A similar situation existed in Sydney and in Perth it was 1 - 4 %. It was concluded that the
relationship between indoor (unheated) and outdoor conditions was primarily influenced by the location, and micro climate (Finighan 1966).

**Equilibrium Moisture Content Survey of Timber in Queensland**

Bragg (1986) has conducted an EMC survey at 16 sites in Queensland over a two year period. The measured EMC was related to meteorological data by way of multiple regression analysis and prediction equations were derived.

The State was divided into three EMC zones by the use of these equations and long term meteorological data from 148 sites.

Three replicates of four species were used at each of the sixteen sites. Three replicates of a further seventeen species were monitored at the Brisbane site. The specimens were sealed at the ends with enamel paint and suspended by cup hooks in sheltered positions with unrestricted air flow.

The moisture content was monitored by first oven drying the samples whole for up to two weeks and then weighing them on a fortnightly basis at 9.00 am on Fridays to an accuracy of 0.1 grams. Mean monthly moisture contents were determined by taking the mean of the weekly moisture contents within each month.

The survey found the average moisture content to be 14.2%. There were considerable differences in the reactivity of the timber to changes in the environment and variation in the EMC. This was measured by way of the standard deviation of the weekly and monthly measurements.

EMC was found to be related to the intersection point (IP) which is the moisture content value where the shrinkage/moisture content curve on a graph intercepts the moisture content axis. This approximates fibre saturation. Intersection points were determined
from published data and used with air dry densities \( O_{\text{air,dry}} \) to formulate equations to predict EMC at Brisbane and standard deviations of monthly average moisture contents \( (MC_{s,\text{monthly},x}) \) of the specimens resulting from changes in ambient conditions.

The equations developed were:

\[
EMC = 9.11 + 0.138IP + 0.00191O_{\text{air,dry}} \quad (R^2 = 0.64) \quad (2.13)
\]

where;

IP = the intersection point (as defined above, expressed as %); and

\( O_{\text{air,dry}} = \) air dry density of timber (kg/m\(^3\)).

\[
MC_{s,\text{monthly},x} = 0.352 + 0.0266IP - 0.000511O_{\text{air,dry}} \quad (R^2 = 0.65) \quad (2.14)
\]

where;

\( MC_{s,\text{monthly},x} = \) standard deviations of monthly average moisture content (%);

IP = the intersection point (as defined above, expressed as %); and

\( O_{\text{air,dry}} = \) air dry density of timber (kg/m\(^3\)).

It was apparent from the coefficients of determination that other factors effect EMC. It was believed however that the equations could be used to determine the ranking of species with respect to EMC and standard deviation of monthly average moisture content in Brisbane.

Multiple regression analysis of the meteorological and EMC data indicated that:

- rainfall in mm;
- the natural log of rainfall in mm;
- the relative humidity at 9.00 am, yearly average; and
- the relative humidity at 3.00 pm, yearly average,

correlated well with the EMC average.
There were however strong interrelationships between the variables. When plotted against the EMC each variable except rainfall had a linear relationship with EMC. When rainfall was transformed to the log of rain there was linearity.

Forward stepwise regression of the data produced the following equations:

\[ EMC = -1.38 + 1.27 \ln Rf + 0.120 RH_{3pm} \]  \( R^2 = 0.94 \)  \( (2.15) \)

where;
\ln Rf = natural log of the rainfall measured in mm/year; and
\RH_{3pm} = relative humidity 3pm, yearly average (%).

The 95% confidence interval was approximately plus or minus 1.4% MC at each of the extremes of the predicted MC range.

\[ EMC = -11.7 + 2.55 \ln Rf + 0.114 RH_{9am} \]  \( R^2 = 0.88 \)  \( (2.16) \)

where;
\ln Rf = natural log of the rainfall measured in mm/year; and
\RH_{9am} = relative humidity 9am, yearly average (%).

It was concluded that the equations could be used to predict the EMC of 19mm samples in sheltered locations in Queensland.

On the basis of earlier work carried out by Finighan inside EMC was calculated to be:

\EMC_{\text{inside}} = 83\% \EMC_{\text{outdoors}}

**Equilibrium Moisture Content Variations of Timber Used in Western Australia**

Brennen and Pilcher (1995) carried out an EMC survey in Western Australia over a two year period involving the placement of timber samples at indoor and outdoor locations throughout the State. From the study it was determined that:
EMC curves for the sampled species were similar to those prepared for the ambient conditions which illustrated the responsiveness of timber to the ambient conditions;

- generally EMC’s measured indoors were less than those measured outdoors for the same species at the same location;
- evaporation, rainfall, relative humidity, and temperature are related to EMC with relative humidity being a strong predictor of EMC;
- changes in dimensions are closely related to changes in moisture content;
- an EMC map could be prepared for timber exposed to outdoor conditions;

The following relationships were observed through the application of regression analysis:

**Predicting EMC from Meteorological Data**

\[ EMC = 0.26RH_{12\text{pm}} - 4.393 \]  \hspace{1cm} (R^2 = 0.80) \hspace{1cm} (2.17)

where:

- \( RH_{12\text{pm}} \) = relative humidity at 12pm (%).

\[ EMC = 0.19RH_{12\text{pm}} + 0.003Rf - 2.559 \]  \hspace{1cm} (R^2 = 0.87) \hspace{1cm} (2.18)

where;

- \( RH_{12\text{pm}} \) = relative humidity at 12pm (%); and
- \( Rf \) = rainfall (mm/year).

\[ EMC = 0.248RH_{12\text{pm}} - 0.038T_{12\text{pm}} \]  \hspace{1cm} (R^2 = 0.80) \hspace{1cm} (2.19)

where:

- \( RH_{12\text{pm}} \) = relative humidity at 12pm (%); and
- \( T_{12\text{pm}} \) = temperature at 12pm, annual average (°C).
Outdoor EMC Compared with Indoor EMC

Indoor EMC’s for specific locations can be computed from outdoor EMC’s (non heated or air conditioned buildings):

\[ EMC_{\text{indoor}} = 0.83 \times EMC_{\text{outdoors}} + 0.49 \quad (R^2 = 0.70) \quad (2.20) \]

where;

- \( EMC_{\text{indoor}} \) = equilibrium moisture content of timber indoors (%); and
- \( EMC_{\text{outdoors}} \) = equilibrium moisture content of timber outdoors (%).

EMC Mapping

\[ EMC_x = 1.137 \times EMC_{9\text{am}} - 3.41 \quad (R^2 = 0.70) \quad (2.21) \]

where;

- \( EMC_x \) = mean equilibrium moisture content of combined timber species at a specific site; and
- \( EMC_{9\text{am}} \) = equilibrium moisture content of timber at a site at 9am.

The mean EMC’s were calculated using the formula above and the combined data for all the species for each of the meteorological stations using mean long term 9.00am relative humidity and temperature. The values were then plotted on a map and lines of best fit were drawn to separate the State into zones (Z1 = > 12%, Z2 = 1% to 12% and Z3 < 10%).

The Equilibrium Moisture Content of Timber in Sydney

Over the years 1958 to 1961 the CSIRO Division of Forest Products investigated the relationship between the moisture content and dimensional stability of timber and the psychrometric conditions in Sydney (Marshall 1965).

Part of the study included the placement of specimens in a sheltered outdoor position. The specimens were three replicates of eight species of three thicknesses. The location
was Putney. The shelter provided protection from rain and the sun but was open to the atmosphere. The timber was measured and weighed twice a week. The weight expressed in relation to the oven dry weight was used as a measure of the change in moisture content. Dimensions were measured at a pencil line drawn around the centre of the specimens to ensure consistency (Marshall 1965).

Weather data was gathered from a weather station set up adjacent to the test site and included wet and dry bulb temperature, continuous readings of temperature and humidity from a thermohydrograph, rainfall and wind velocity and direction (Marshall 1965).

The period March 1958 to August 1959 was used to present the results of the study as this period had climatic data that was reasonably similar to the average conditions in respect of rainfall (Marshall 1965).

The study indicated that the main factor affecting moisture content was relative humidity. The results also indicated that the thinner samples had a greater change in moisture content. In timbers with lower density the dimensional stability varied in direct relationship to the moisture content. The thinner samples with the lowest density had the greatest movement and the fastest response to changes in moisture content (Marshall 1965).

It was concluded that the results gave a general indication of the variations in moisture content that could be expected in Sydney because there is little variability in temperature and humidity across the city. It was considered that differences might occur in locations on the coast or in the western suburbs. The recommended moisture content range of 10% to 15% for Sydney was confirmed, as the conditions causing very high and low moisture contents only occurred once during the three year study period (Marshall 1965).
2.8.2 Corrosion Related Studies

A brief summary of each of the major corrosion related studies is set out below.

A Detailed Corrosivity Survey of Melbourne

King, Martin and Moresby (1982) have conducted a study to determine the rate of corrosion across the Melbourne Metropolitan area.

Steel coupons prepared to British Iron and Steel Research Association (BISRA) specifications were placed in a 2km x 2km grid pattern and exposed for one and two years. Coupons were also placed at sites where the Environment Protection Authority of Victoria monitored air quality and along two highways that have high traffic volumes.

After exposure the coupons were scraped and cleaned with Clarks Solution to remove the corroded material (in accordance with BISRA guidelines), some of which was retained from each coupon for analysis of the factors causing the corrosion. The extent of corrosion was determined through the measurement of weight loss.

The corrosion rates were plotted as contours on a map of the area. In doing this exposure sites were first manually plotted on a 1:75,000 scale map of Melbourne. A contour interval of 2 micrometres was chosen. The accepted criterion for selecting contour intervals was that they could be up to twice the accuracy of the parameter being measured.

The corrosion rates were later added to a map by using a digitiser to obtain the xy Cartesian Coordinates for the exposure sites and a computer program called CONTOUR to plot the contours.
It was found that the boundary conditions were difficult to plot accurately with the computer program (near Port Phillip Bay). In these cases values were altered to force the program to produce contours that approximated the manual plot. This only affected the contours to the first or second grid point from the coast.

As discussed earlier the most important factors influencing corrosion are the concentrations of sulphur dioxide, the level of salt spray present and the climate i.e., the time of wetness and to a lesser extent temperature during the periods of wetness.

Data on SO$_2$ pollution was obtained from the Environmental Protection Agency of Victoria but did not correlate well with the corrosion rates. In general terms corrosion rates were greatest near marine sources. The influence of climatic factors could not be determined because of a lack of available data.

The researchers believed that the map could be used as a benchmark for measuring the success of controls if a follow up study was completed. They also felt that it could be used as a basis for the selection of suitable building materials or corrosion protection measures. It was proposed that further work be carried out by analysing the pollutant ions in the corrosion product to determine the extent of influence of these factors.

King, Spicer and Kao have carried out this follow up work using electron microscopy to measure the effects of sulphur dioxide and chlorides. Samples from the corrosivity study outlined above were examined in a scanning electron microscope to determine the level of the pollutants in the rust taken from the coupons (King, Spicer & Kao 1996).
It was found that only a semi quantitative measurement was possible because of the rough surfaces on the samples. Four spectra were taken from each sample at the same position on each specimen. The mean, standard deviation and coefficient of variation for the peak to background ratios for the specimens were calculated (King, Spicer & Kao 1996).

The variations in the sulphur and chlorine contents of the rust were expressed in the form of a contour map for the study area. Multiple regression analysis was then used to relate the corrosivity of the sites to the sulphur and chlorine peak / background ratios. For some sites the time of wetness was also included in the analysis. The correlation coefficients were 0.76 when both SO₂ and chlorine were included in the model and 0.75 when only chlorine was considered (King, Spicer & Kao 1996).

A difficulty existed with this method of analysis however in that it only used X Rays generated from the top two micrometers of the rust layer which could in fact be much thicker. This could create unrepresentative results. This problem has been overcome by a new methodology, again involving the use of electron microscopy (King, Spicer & Kao 1996).

The rust is removed from the steel coupons, making it uniform. It is then examined with the scanning electron microscope using X-Ray beam excitation (King, Spicer & Kao 1996).

The new methodology was tested on coupons used in a corrosivity study in the Newcastle region of NSW. This study showed that corrosivity varied significantly across the region. Areas of hazard included the marine environment and several industrial areas (King, Spicer & Kao 1996).
The new procedure was compared with the original scanning electron microscope method by examining six specimens and one standard for sulphur and one for chlorine. The peak/background ratios for samples were determined using each of the methods and the ratio of the results was calculated to assess the relative sensitivity of each. The new technique was approximately 20 times more sensitive in relation to sulphur and 50 times for chlorine (King, Spicer & Kao 1996).

The new method indicated that the maximum sulphur content was 0.35% and the maximum chlorine content was 0.54%. Sulphur and chlorine contour maps produced for the study area had aspects that paralleled those on the corrosivity map produced earlier.

**Atmospheric Corrosivity of the Greater Newcastle Region**

The methodology used for this study was similar to that used in the initial corrosivity survey of Melbourne outlined above (King & Carberry 1992). This study showed that corrosivity varied significantly across the region. Areas of hazard included the marine environment and several industrial areas.

An important outcome of the study was the development of a hyperbolic model for predicting corrosivity at sites close to the ocean (King & Carberry 1992). The model was:

\[
\log_e C_r = A + \left( \frac{B}{1 + C \times L} \right)_{coast}
\]  

(2.22)

where;

- \(C_r\) = corrosivity, measured using low alloy copper/steel coupons (\(\mu\)m/year);
- \(A\), \(B\) and \(C\) were coefficients determined through regression analysis of corrosion rates at sites in the region that were up to 5km from the ocean; and
- \(L_{coast}\) = distance from the coast to the site (km).

The analysis yielded the estimates for the coefficients set out in Table 2.1
Table 2.1 Coefficients for Hyperbolic Model of Corrosivity

<table>
<thead>
<tr>
<th>COEFFICIENT</th>
<th>ESTIMATE</th>
<th>STANDARD ERROR</th>
<th>ESTIMATE / STANDARD ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.9757</td>
<td>0.1014</td>
<td>29.36</td>
</tr>
<tr>
<td>B</td>
<td>2.3202</td>
<td>0.1996</td>
<td>11.62</td>
</tr>
<tr>
<td>C</td>
<td>4.3648</td>
<td>1.6065</td>
<td>2.72</td>
</tr>
</tbody>
</table>

The residual standard deviation was 0.259 and $R^2$ was 0.851.

Corrosivity Survey of South Australia

A corrosivity survey of South Australia was conducted by the CSIRO over the period 1991 to 1993. The model developed in this study for predicting the corrosion rate in South Australia was subsequently tested to determine whether it was suitable for predicting corrosion on an Australia wide basis (Cole, King, Trinidad, Chan & Patterson 1999).

The initial study in South Australia involved the exposure of low-alloy copper bearing steel coupons on brackets fixed to low voltage electric power supply poles. The brackets were fixed at a height of 3.7m above ground. The orientation was towards the north. There were 475 sites over an area of 420,000 km².

Corrosion rates were determined after one and two years by measurement of the weight loss of the coupons. Statistical analysis of the two-year corrosion data was carried out to develop a model of South Australian corrosion.

The model was developed using regression analysis of corrosion rates and climatic and pollutant parameters. The data set for climatic parameters was derived by the use of a triangular irregular network (TIN) model and data from meteorological stations. A data set for solar radiation was constructed using the same approach.
The regression analysis covered the following parameters:

- solar radiation;
- average relative humidity at 3pm;
- average relative humidity at 9am;
- average daily maximum temperature;
- average daily minimum temperature;
- mean temperature;
- rainfall (mm);
- raindays; and
- airborne salinity.

The airborne salinity value for each location was estimated with the use of the model below:

\[ S_{air} = \left[ S_{LR} + (S_{SR} \times s) \right] / (s + 1) \]  \hspace{1cm} (2.23)

where;

\( S_{air} \) = atmospheric salt level (mg/m\(^2\).day);

\( S_{LR} \) = long range salt distribution term (mg/m\(^2\).day);

\( S_{SR} \) = short range salt distribution term (mg/m\(^2\).day); and

\( s \) = value for the definition of the coast line type.

The value of \( s \) was 1,2,3 or 4 depending on whether the nearest coastal location was a very sheltered bay, partially closed bay, sheltered surf / very open bay or open surf respectively.

The values of \( S_{LR} \) and \( S_{SR} \) were calculated using the following equations:

\[ S_{LR} = E \times \exp \left[ -L_{coast} \times (s + 1.5) / 275 \right] \]  \hspace{1cm} (2.24)

where;
E = salinity factor for a site, based on whether the coast is a very sheltered bay, partially closed bay, sheltered surf/very open bay or open surf (5,15,45 or 130mg/m².day);

$L_{coast}$ = the minimum distance from the site to a point on the coast from which the wind is known to originate for at least 5% of the year (km); and

$s$ = integer based on the coast type (1,2,3 or 4 depending on whether the nearest coastal location is a very sheltered bay, partially closed bay, sheltered surf / very open bay or open surf respectively).

\[ S_{SR} = E \times \exp\left(-\frac{L_{coast}}{\sqrt{s}}\right) \] (2.25)

The values of $s$ and $E$ were based on measurements of salinity and studies of salt production and wave mechanics.

The regression analysis provided the following equations for estimating the corrosion rate at sites in South Australia:

\[ \ln(C_r) = A \times \ln RH_{9am} + B \times \ln T_{max} + C \times \ln S_{air} \] (2.26)

where:

\[ \ln(C_r) = \text{natural logarithm of corrosion (\mu m/year);} \]

A, B and C are constants;

RH$_{9am}$ = relative humidity at 9am, annual average (%);

T$_{max}$ = maximum temperature ($^\circ$C); and

S$_{air}$ = atmospheric salt deposition (mg/m².day).

The accuracy of the model was such that 80% of the predictions were within 20% of the measured corrosion rates.

Variables were added to the equation to test the effects of terrain factors. They included the site elevation, the highest elevation between the site and the coast and the ratio of these two variables. The effects on the fit of the model were not significant.
The model was tested using a corrosion data set compiled from a variety of sources to determine whether it might be used Australia wide. There were 75 measurements taken across all climatic zones of the country.

The fit of the model for an Australian data set was very poor. More than 41% of the predictions were greater than the measured values by a factor of 2. The misfit was very high for the north west coast in particular.

The unreliability of the model for the whole of the continent was attributed to airborne salinity in South Australia being relatively constant. The state of the ocean does not vary greatly in this region. This was not considered to be the case for other centres, where details of wind direction may be required because of the differing effects on the transport of airborne salt.

A model has subsequently been developed for Australia that includes parameters for salinity sources and the effects of wind on the distribution of airborne salt.

Testing of the new model using the Australia wide data set indicated significant improvement over the South Australian model. However the model still had a high level of misfit because it did not yet include parameters for industrial pollutants. Further work was proposed for the inclusion of such parameters.

One of the principal conclusions of the project was that salinity distribution terms that take into account short, medium and long range factors are appropriate for inclusion in models estimating corrosion rates.

Subsequent to the reporting of the corrosivity study of South Australia Leicester et. al. (2000) have proposed the following model for the estimation of salinity in Australia in relation to fasteners:
\[ S_{\text{air}} = S_{\text{air, coast}} + S_{\text{air, ocean}} \]  

where;

\[ S_{\text{air, coast}} = \text{salt from coastal aerosols (mg/m}^2\text{.day)} \text{ and} \]

\[ S_{\text{air, ocean}} = \text{salt from ocean aerosols (mg/m}^2\text{.day)} \text{.} \]

The calculation of \( S_{\text{air, coast}} \) and \( S_{\text{air, ocean}} \) takes into account the location on the coast concerned, the coast type and the distance from the coast to the location of the connector (\( L_{\text{coast}} \)) as indicated in the following equations:

\[ S_{\text{air, coast}} = \alpha_{\text{coast}} \cdot \beta_{\text{coast}} \exp\left(-L_{\text{coast}} / \sqrt{s}\right) \]  \hspace{1cm} (2.28)

\[ S_{\text{air, ocean}} = \alpha_{\text{ocean}} \cdot \beta_{\text{ocean}} \exp\left(-L_{\text{coast}} / 200\right) \]  \hspace{1cm} (2.29)

\( \alpha_{\text{coast}} \) and \( \alpha_{\text{ocean}} \) are factors that are related to the geographic zoning of the coast affecting the site. Leicester (2000) has divided the Australian coastline into three zone classifications C1 (northern Australia), C2 (parts of eastern and western Australia) and C3 (southern Australia). The factors \( \alpha_{\text{coast}} \) and \( \alpha_{\text{ocean}} \) relating to these zones are 0.1, 0.3 and 1.0 respectively. Sydney falls within the C2 zone on the east coast which stretches from a point in New South Wales adjacent to Bega to a point adjacent to Bundaberg in Queensland. Hence \( \alpha_{\text{coast}} \) and \( \alpha_{\text{ocean}} \) for Sydney are 0.3. The coastal exposure factors \( \beta_{\text{coast}}, \beta_{\text{ocean}} \) and \( s \) can be determined according to Table 2.2 below.
Table 2.2 Coastal Exposure Factors for Estimating Air Salt Content

<table>
<thead>
<tr>
<th>COAST TYPE</th>
<th>EXPOSURE FACTORS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\beta_{\text{coast}}$</td>
</tr>
<tr>
<td>VERY SHELTERED BAY.</td>
<td>3</td>
</tr>
<tr>
<td>PARTIALLY CLOSED BAY.</td>
<td>10</td>
</tr>
<tr>
<td>SHELTERED SURF OR VERY OPEN BAY.</td>
<td>35</td>
</tr>
<tr>
<td>OPEN SURF.</td>
<td>110</td>
</tr>
</tbody>
</table>


2.8.3 Timber Connector Corrosion Studies

A brief summary of each of the major timber connector corrosion related studies is set out below.

Nailed Joint Performance in Australian Houses

Cole, Bradbury and O’Brien (1999) have reported on a study of nailed joint performance in Australian Houses as part of the development of a reliability based durability design method for the Forest Wood Products Research and Development Corporation.

Nailed joints were placed in the sub floor, wall cavity, roof space and on the facade of houses in Innisfail, Brisbane, Sydney, Narrabeen, Mt Buller and Melbourne. The houses were a mixture of timber lined, brick veneer, concrete block and solid brick dwellings. The nails used were blue processed, bright steel, hot dipped galvanised, zinc plated, copper and polymer coated. They were placed in Douglas Fir, Brush Box, Spotted Gum, Mountain Ash, LOSP Treated Pine and H3 and H5 Treated Pine boards. Not all nails were used at each site.
The test joints were constructed of timber samples 35mm x 20mm x 200mm. The ends were sealed with epoxy resin. The nails were inserted in offset lines and were at least 15mm apart.

The nail boards were placed 0.4 to 0.8 metres below the eaves on the facades (sheltered from rain and direct sunlight), hung on wires from floor joists in the sub floor space and in the wall cavity at least 0.5m from the bottom. The period of exposure was two years.

Following exposure the nails were extracted in the laboratory, the extent of corrosion rated and the weight loss from corrosion established by removing the corrosion products and weighing the nails. The data was placed in a database for analysis.

A GIS Based Approach to the Prediction of the Impact of the Environment on Timber Components in Australia

In parallel work to the above project Cole, Ganther and Trinidad (1999) developed an information technology system for the prediction of the moisture content of timber and the corrosion rate of nails.

The system utilises a geographical information system and meteorological data to estimate the surface moisture content of the timber and predict the extent of corrosion of nails in wood in covered conditions in Australia.

The following tasks are carried out by the models used in the system:

- generalised meteorological data is used to estimate the nominal moisture content of ideal timber in sheltered external conditions at sites selected by the user;
- the moisture content of specific timbers in the same external conditions is calculated based on rules determined previously in chamber tests;
- the moisture content of timber elements in particular locations in the building is then
estimated based on further rules established through a house monitoring program completed by the CSIRO; and

- the corrosion rate of connectors in building cavities is estimated based on experimental results establishing the relationship between connector corrosion, moisture content and timber properties.

The nominal surface moisture content is estimated using the approximation method developed by Bramhall discussed earlier (Bramhall 1979). A database obtained from the Bureau of Meteorology for relative humidity and temperature was utilised in these calculations. A triangular irregular network (TIN) model was used in the system to determine values at locations between meteorological stations.

The following model is used to estimate the moisture content for nominated species in outside sheltered conditions:

\[ MC_{outdoors} = A_i + B_i \times MC_{surface} \]  

(2.30)

where;

\( MC_{outdoors} \) = Moisture content of nominated species of timber in sheltered external conditions (%);

\( A_i \) and \( B_i \) = constants for particular species determined through regression analysis; and

\( MC_{surface} \) = the moisture content for ideal timber calculated using Bramhall's approximation formula (equation 2.7, discussed earlier) (%).

The average seasonal moisture content in building locations is obtained by adjusting the annual average moisture content for the species in sheltered external conditions by factors which take into account the damping of the building envelope (0.5 to 1), proximity to the coast, climatic factors relating to the geographic zone of the site and solar radiation (for external elements).
The following equation is used:

\[ MC_{bas} = MC_{outdoors,sa} + d \times (MC_{outdoors,sa} - MC_{outdoors,as}) + \Delta_{sea} + \Delta_{climate} + \Delta_{radiation} \quad (2.31) \]

where:

- \( MC_{bas} \) = average seasonal moisture content in a building (%);
- \( MC_{outdoors,sa} \) = annual average moisture content for a particular species in external sheltered conditions (%);
- \( MC_{outdoors,sa} \) = seasonal average moisture content for a particular species in external sheltered conditions (%);
- \( d \) = damping factor (approximately 1 for facades and 0.5 for sub floors, wall cavities and roof spaces);
- \( \Delta_{sea} \) = +2 for all external locations within 1km of the coast;
- \( \Delta_{climate} \) = factors for facades, subfloors wall cavities and roof spaces depending on the climatic zone of the site; and
- \( \Delta_{radiation} \) = -2.5 and -1 for sites with high and low solar radiation respectively.

The values of \( \Delta_{climate} \) are shown in Table 2.3 below.

**Table 2.3 Values of \( \Delta_{climate} \) for Building Spaces in Different Climate Zones**

<table>
<thead>
<tr>
<th>ZONE</th>
<th>FAÇADE</th>
<th>SUBFLOOR</th>
<th>WALL CAVITY</th>
<th>ROOF SPACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TROPICAL</td>
<td>1</td>
<td>1.2</td>
<td>0</td>
<td>-3</td>
</tr>
<tr>
<td>SUBTROPICAL</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>-3</td>
</tr>
<tr>
<td>TEMPERATE</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>-3</td>
</tr>
<tr>
<td>INLAND</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>-3</td>
</tr>
<tr>
<td>ALPINE</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>-3</td>
</tr>
</tbody>
</table>

The $\Delta_{sea}$ factor of +2 takes into account the high levels of relative humidity found close to the coast and the hygroscopic effects of salt deposits on the timber.

The model used by the system adopts the following rules in relation to equilibrium moisture content when estimating the corrosion rate of nails:

- the maximum corrosion rate takes place at an equilibrium moisture content threshold for a particular species;
- there is a minimum threshold for each species below which corrosion will not occur; and
- between the minimum and maximum thresholds the corrosion rate changes as equilibrium moisture content changes.

Timbers covered by the system are divided into three classes depending on the moisture content at which corrosion was found to plateau in the chamber experiments conducted. For example in the case of bright nails in Class 1 timbers nail corrosion plateaued at 16-18%, in Class 2 timbers at 20-24% and in Class 3 it did not plateau.

The timbers included in each classification are:

- Class 1 – brush box, meranti, spotted gum huon pine, karri, red iron bark and LOSP treated pine;
- Class 2 – douglas fir, mountain ash, radiata pine; and
- Class 3 – CCA treated timber.

Moisture content data gathered during the chamber tests and data on the pH, conductivity and acid content of the water in equilibrium with the timber for each species were analysed using regression analysis to construct models for the system to predict maximum nail corrosion rates at the plateau threshold (Cole, Ganther, Furman & Page 1999 and Cole, Ganther & O’Brien 1999).
An example of the equations for maximum corrosion is shown below (bright nails in Class 2 timbers):

$$C_{\text{nail, max}} = 0.8 + 3.0 \times \exp \left[ -0.526 - 0.238 \times \left( \frac{CH_3COOH}{300} \right)^{1.3} + 0.531 \right] \times \ln(\Gamma) + 0.251 \times \left( \frac{O_{\text{air, dry}}}{500} \right)^{1.2}$$

(2.32)

where;

$C_{\text{nail, max}} = $ maximum corrosion (g/m$^2$.year);

$O_{\text{air, dry}} = $ the dry density of the timber (kg/m$^3$);

$pH = $ the pH of the timber;

$\Gamma = $ the conductivity of the timber (µs); and

$CH_3COOH = $ the acid concentration (meq/100 of wood) assuming the acid is $CH_3COOH$ of water in equilibrium with the timber.

Models were also developed for the system to estimate the rate at which corrosion takes place at moisture contents below that at which maximum corrosion takes place (Cole, Ganther, Furman & Page 1999). The model for bright nails in Class 2 timbers is shown below:

$$C_{\text{nail, % max}} = \begin{cases} 100 \times [0.02 + 0.071 \times (EMC - 4)] & \text{when} 10 \leq EMC \leq 16.5 \\ 0 & \text{when} EMC < 10 \end{cases}$$

(2.33)

where;

$C_{\text{nail, % max}} = $ the rate of nail corrosion resulting from moisture contents which are below the level at which the maximum corrosion rate occurs (% of maximum); and

$EMC = $ the equilibrium moisture content for the timber (%).
Recognising that the corrosion rate will decrease with time the system developers have made provision for adjusting the estimates of nail corrosion according to the following model:

\[ C_{\text{nail, time}} = C_{\text{nail}} \times t^n \]  \hspace{1cm} (2.34)

where;

- \( C_{\text{nail, time}} \) = estimated nail corrosion rate adjusted for the reduction in the rate likely to take place over time (g/m²-year);
- \( C_{\text{nail}} \) = the corrosion rate estimated using the regression equations discussed above (g/m²-year);
- \( t \) = time (years); and
- \( n \) = a constant (0.5 for non marine sites and 0.7 for marine sites).

Testing of the system has indicated that it is reasonably accurate. There are however differences between climatic conditions at sites and those predicted by the use of data from the nearest meteorological stations and this causes some error. The developers have foreshadowed investigation of means of combining local terrain data and meteorological data for use in the models utilised.

Several aspects of the work involved in developing this system are of particular relevance to further research characterising environments in relation to nail corrosion in timber.

Laboratory tests involving the exposure of nail boards in chambers having various humidity levels confirmed that the moisture content of timber had a strong influence on the corrosion rate of nails. Further tests also revealed that the conductivity, acid content and pH of absorbed water within the timber also strongly affected the corrosion rate. However these tests did not provide details on the influences that other environmental aspects might have. The environmental aspects identified as having the potential to
affect the chemistry of the water absorbed by timber were airborne salinity and washing by rain. Potential was seen for airborne salt to be transported into the timber and for rain to leach it from the timber (Cole & Ganther 1999).

Field exposure of nail boards in a variety of atmospheres and subsequent analysis indicated that moisture content was the major aspect influencing shank corrosion at non marine sites. However at severe marine sites it was found that salinity also influences shank corrosion rates. Three possible reasons for the different effects on corrosion rates were put forward:

- deposition at marine sites may be onto a wet surface or the aerosols may be wetter than at non marine sites;
- oxides might form at non marine sites that form protection against chloride deposition; and/or
- chloride content at the non marine sites may be of less consequence than the solutes extracted from the timber (Cole & Ganther 1999).

In relation to head corrosion it was found that airborne salinity was an important influence at marine sites but not so much so at non marine sites. The species of timber was found to have as strong an influence at non marine sites as airborne salinity (Cole & Ganther 1999).

The researchers also found that geographic location tended to have a stronger relationship with nail corrosion rates where softwoods and treated pines were involved rather than hardwoods (Cole & Ganther 1999).
2.9 The Sydney Climate and Topography

2.9.1 Broadscale Climatic Influences

Broadscale, regional and local geographical aspects combine in a complex way to determine the weather and climate in the Sydney region (Bureau of Meteorology 1991). The broadscale aspects are the latitude (34°S) and the influence of the large land and water masses the region lies between.

As is the case with eastern Australia generally, Sydney is affected by two major circulations of the atmosphere. One originates in the tropics and results in a series of high pressure centres. These high pressure centres are referred to as anticyclones and their mean position is called the subtropical ridge (Bureau of Meteorology 1991).

Air from the anticyclones moves downwards towards their centre and then outwards producing an easterly airflow to their north and a westerly airflow to their south. The subtropical ridge moves to the north of Sydney in the winter and to the south in the summer months. During periods when the subtropical ridge is over Sydney the winds are generally lighter and the rainfall less.

The other atmospheric circulation is called the Walker Circulation. The major influence on this circulation is the surface temperature of the Pacific Ocean. Air in the circulation usually ascends over Indonesia and descends over the eastern equatorial region of the ocean (Bureau of Meteorology 1991).

The sea surface temperature is usually 8-10°C higher in the western equatorial Pacific than in the eastern equatorial Pacific, promoting atmospheric rising in the western area.
and increasing rainfall in this region. It also has the effect of decreasing these aspects in
the eastern equatorial Pacific (Bureau of Meteorology 1991).

Periodically the central eastern area of the Pacific warms abnormally. This phenomenon
is called the El Nino. When this occurs the sea surface temperature in the equatorial
Pacific falls and the zone of enhanced rising motion and rainfall, normally over
Indonesia, moves to the central Pacific. The effect on Indonesia, northern Australia and
eastern Australia, including Sydney, is that the rising motion is suppressed and rainfall
decreases (Bureau of Meteorology 1991).

The topography of the Sydney area, the sea surface temperature and the orientation of
the coastline are the most significant regional influences on the weather and climate
(Bureau of Meteorology 1991).

The Great Dividing Range to the west of Sydney has a major influence on rainfall in the
region. Unstable air streams moving in from the southwest usually shed their moisture
on the western and southern slopes. In a similar way airflows coming from the south
and east encounter the coast and this mountain range (Bureau of Meteorology 1991).

The coastal waters tend to increase atmospheric moisture and because of their thermal
inertia create moderate temperatures in the region (Bureau of Meteorology 1991).

Topography is the most significant local influence on rainfall and temperature. Higher
rainfall is experienced on higher ground in the path of moist air streams. Differences in
temperature and humidity are mainly attributable to differences in elevation and the 
distance from the ocean (Bureau of Meteorology 1991).

Droughts and floods are natural variations in the climate in Australia generally and 
Sydney is no exception. These phenomena should be seen as longer-term fluctuations 
and not necessarily as a change in climate. Having said this there is evidence that 
increased amounts of carbon dioxide and other gasses in the atmosphere are causing a 
greenhouse effect and climatic change. The extent and rate of this change is largely 
undetermined at this stage (Bureau of Meteorology 1991).

Development within the region has resulted in a large scale reduction of vegetation and 
widespread increases in domestic, industrial and agricultural activity, all of which have 
affected the local climatic pattern. Changes in wind flow patterns, fog, frost and higher 
temperatures in highly developed areas are outcomes of this development (Bureau of 

2.9.2 Winds in the Region

The broadscale winds in the region are:

Northwest winds – surface air dried out over the continent comes over the Great Divide, 
generally resulting in fine weather with average to high temperatures and moderate to 
high wind speeds. Although these winds generally occur more frequently in winter they 
can bring about heat wave conditions if they occur in summer (Bureau of Meteorology 
Southwest winds – this air stream generally passes over the Southern Ocean gathering moisture. However this moisture is normally discharged over the southern coast, the Victorian ranges and NSW ranges. When southwest winds do come over the NSW ranges the temperature normally increases and the weather is dry and warm and the skies over Sydney are clear. This air flow usually occurs after periods of northwest winds (Bureau of Meteorology 1991).

Northeast winds – these winds are affected by the surface temperature of the water over which they have passed. The air stream is generally stable, cool and is associated with high relative humidity. Rarely do these winds bring persistent cloud cover or rain. However if there is a low pressure system over inland NSW heavy rain can result (Bureau of Meteorology 1991).

Southeast winds – these affect Sydney when there is an anticyclone over the south Tasman Sea. The effects on the Sydney region vary greatly, depending on the depth, strength and convergence of the airflow and the sea surface temperature. The outcome is usually cool, cloudy but dry conditions. However long periods of heavy rain can also result (Bureau of Meteorology 1991).

Local winds can mask broadscale air flows at the surface. The most influential are sea breezes caused by differences in air temperature above the sea and the coastal strip resulting in a pressure gradient and flow of cool moist air near the surface and a return flow above (Bureau of Meteorology 1991).
The reverse can also occur. The land can cool rapidly and if it becomes cooler than the sea a land breeze takes place. When this effect extends to sloping terrain the cool air drains into low lying areas such as the Nepean – Hawkesbury plain. It can ultimately merge with westerly land breezes on the coast (Bureau of Meteorology 1991).

The other significant local wind is a strong cold front which moves up the coast referred to as Southerly Burster or Southerly Buster. This phenomena brings gusts of wind up to approximately 130km / hour. They generally develop in advance of cold fronts moving across the Southern Ocean. The temperature gradient between the land and the sea on the south coast and the mountainous topography in this southeastern region are important factors in the development of Southerly Bursters (Bureau of Meteorology 1991).

Southerly bursters occur approximately ten times a year between September and March. They can result in temperature falls of up to 10 – 15 °C within minutes. They may or may not involve the onset of clouds (Bureau of Meteorology 1991).

The winds that have their origins over the ocean and are hence likely to have more influence on salt deposition come from the north east, east, south east and south.

In summer the air flows are predominantly from the easterly direction. In winter air flows are predominantly from the westerly direction. On the coast the sea breezes during the afternoon in spring, summer and autumn reinforce the east to northeast flows. During the winter months the land breeze creates a flow with a westerly component (Bureau of Meteorology 1991).
2.9.3 Rainfall

Spatial distribution of rainfall across the region is influenced mainly by topography. Highest rainfall levels are experienced on the coast and on the windward slopes of the mountains where the air stream rises and convergence occurs through the friction resulting from the rough land surface (Bureau of Meteorology 1991).

The wettest part of the region is around Cataract Reservoir and just to its east, adjacent to the coast. The median annual rainfall at this location is approximately 1600mm. Other areas of high rainfall include Katoomba and Mount Wilson in the Blue Mountains to the west and Kulnurra in the northeast of the region (Bureau of Meteorology 1991).

The driest parts of the region are in the central plain and in the Burradorong Valley, which are sheltered from moisture carrying air streams. The median annual rainfall is approximately 700-800mm (Bureau of Meteorology 1991).

2.9.4 Temperature

The temperature in Sydney is relatively even because of its proximity to the ocean. The main influences within the region are proximity to the coast, height above sea level, the aspect of the location, it’s slope and the slope of the surrounding area (Bureau of Meteorology 1991).

The central part of the region experiences the hottest temperatures and the lowest are encountered in the Blue Mountains around Mount Victoria. Average maximum temperatures vary by up to 7°C (Bureau of Meteorology 1991).
Cold air drainage, discussed earlier, is a significant influence on minimum temperatures, which are not always experienced at the highest altitudes. Places such as Richmond below the Blue Mountains experience low temperatures in winter for this reason (Bureau of Meteorology 1991).

Very little long term variability of temperature has been observed in the region. There has been a slight and steady increase in measured temperature, probably a result of development (Bureau of Meteorology 1991).

The mean minimum annual temperature near the coast is in the range of 13–14°C. In the centre of the region on the plains it is in the range of 9-10 °C and in the Blue Mountains it is between 5 and 8 °C (Bureau of Meteorology 1991).

The mean maximum annual temperature on the coast is around 20-21 °C. In the centre of the region it is 22-23 °C and in the Blue Mountains it is between 17 band 20 °C (Bureau of Meteorology 1991).

2.9.5 Humidity

Vapour pressure, a measure of water vapour in the air, is relatively uniform in the lower areas of the region. Major influences are the air and sea surface temperature and the direction of the wind. Vapour pressures are lower in the elevated locations in the region (Bureau of Meteorology 1991).
Average annual 3pm vapour pressure on the coast is approximately 17hPa. It is then relatively even to the foot of the Blue Mountains (12.8 to 14.5 hPa) and at sites such as Katoomba in the mountains it drops to 10.5 hPa (Bureau of Meteorology 1991).

The average monthly 9am relative humidity across the region is fairly even and is within the range of approximately 68 – 77 %. There is more variability in the 3pm average monthly relative humidity (47 – 70 %) the highest being experienced on the coast (Bureau of Meteorology 1991).

2.9.6 Topography and Development

The Sydney Region is bowl shaped in appearance. The centre of the bowl is formed by the flood plain of the Nepean – Hawkesbury Rivers that is approximately 30km from the coast. The plain is walled on three sides by the Hawkesbury sandstone plateau. These sandstone areas contain many deep and rugged gorges (Bureau of Meteorology 1991).

On the central eastern side of the flood plain there is a gap formed by the Parramatta River and the Georges River valleys connecting the plain to the coast and Pacific Ocean.

At the western boundary of the region the ground level rises to approximately 1000m in the Blue Mountains. On the northern boundary near Wyong the sandstone ridges are approximately 450m above sea level. The southern boundary south of Port Hacking and west of Wollongong has an elevation of approximately 600m (Bureau of Meteorology 1991).
The most densely populated and developed part of the region is the Sydney metropolitan area, which is concentrated to the east around the Parramatta River. However development is rapidly spreading inland. The metropolitan area is also relatively highly industrialised (Bureau of Meteorology 1991).

2.9.7 Likely Influences of the Sydney Climate and Topography on Timber Decay, Corrosion and Nail Corrosion

It appears reasonable having reviewed the literature related to this topic and the data available on the Sydney climate to make the following tentative broad conclusions about the aspects that are most likely to result in differing rates of timber decay, corrosion and nail corrosion across the region.

Variations in relative humidity result in different timber moisture contents and hence rates of decay. As discussed above long term data on the levels of relative humidity indicates that it is generally fairly even across the region with the exception of locations very close to the coast line where it tends to be elevated. Consequently all other things being equal the risk of timber decay is likely to be slightly greater near the coast. However the effects of human development need to be taken into account when considering long term data as this development may have had an insidious influence, particularly in areas such as the CBD where the modification of the environment has been extreme.

Differing levels of relative humidity also result in variations in the rate of corrosion because they influence the time of wetness, particularly where covered conditions are involved. As relative humidity is greatest near the coast and fairly even elsewhere the effects on corrosion are likely to be greatest in coastal locations and similar in other places.
The direction and velocity of the wind influences the amount of salt aerosols in the atmosphere and the level of deposition. Winds in the area are variable both in terms of velocity and direction. Some have their origins over the ocean and others have traversed large distances of land before reaching the region. There are daily and seasonal variations. The level of salt in the air is therefore also likely to be variable. Nevertheless the zone close to the coast is likely to have significantly higher levels of airborne salt and consequent corrosion than the remainder of the region because it is both affected by aerosols originating over the ocean and from the surf. Inland areas on the other hand are not likely to be greatly affected by aerosols generated in the surf or coastal margin.

Moving inland, salt deposition is likely to diminish slightly as the distance from the coast increases. Variability in wind direction and velocity combined with local differences in topography and shielding by natural features and man made structures is likely to result in subtle differences in salt deposition and corrosion rates. The exact causes of these differences may not be immediately obvious and the extent of the variation attributable to each phenomenon could be difficult to quantify.

Air movement is also important in determining the extent of man made pollutants in the atmosphere and the direction in which they travel. The daily and seasonal variability in air flows is likely to make the deposition rates at various locations variable. However as human development and industrial activity is greatest in the metropolitan area it appears reasonable to expect deposition rates to be greatest in this area and diminish towards the less developed extremities of the region.

As discussed earlier the level of relative humidity influences the rate of nail corrosion. As this aspect is highest near the coast it seems reasonable to expect the extent of nail corrosion caused by it to be greatest at coastal locations. It also seems reasonable to expect that the rate of nail corrosion attributable to this aspect to be relatively constant across the remainder of the region where there is not a great deal of variation in its level.
As the rate of deposition of salt and man made pollutants also influences the rate of nail corrosion (albeit to a relatively minor extent) it appears likely that nail corrosion caused by them will be greatest near the coast and CBD respectively. The rates of nail corrosion that are caused by these aspects elsewhere are likely to be less than near the coast and CBD and subject to the subtle influences of local differences in topography, shielding and development.

Due to the large and small scale natural fluctuations in climatic conditions and the changes brought about by continuing development within the region (and on a global scale) care must be taken not to draw absolute conclusions from data gathered in relation to these aspects. The data should be treated as ephemeral and predictions about their effects on the rates of degradation of building elements based on short periods of measurement should be seen as generalised and treated with care.

2.10 Areas Identified by Others as Requiring further Research

The following areas have been internationally identified as requiring further research in relation to the characterisation of environments:

- identification of degradation factors;
- service life research based on damage functions;
- automated monitoring of degradation factors in buildings and micro climates;
- measurement and modelling of degradation in micro environments; and
- development of limit states for damage or service life functions (Haagenrud 1996).

In Sydney, efforts to characterise the atmospheric environment have been concentrated on the metropolitan area. With the development that has taken place in the greater Sydney area it is apparent that characterisation research needs to be expanded to include coastal and western extremities.
In addition many of the cities heritage buildings incorporate timber framing and nailed connections. There is limited data available to those charged with the care of these buildings on how the nailed connections are likely to be degraded by local environmental factors, giving further emphasis to the need for local research in this field.

This study was carried out with these needs in mind
CHAPTER 3
METHODOLOGY

3.1 Overall Approach

The overall approach to the field work and analysis of the results was to:

- monitor relevant climatic and pollutant aspects at sites representative of the sub climates in the study area;
- measure the extent of timber degradation risk factors and the rates of corrosion of metal and nails at these sites;
- statistically analyse the climatic, pollutant, corrosion and timber degradation data gathered to determine the relative environmental risks in the sub climates;
- where possible develop prediction models that could be conveniently used to estimate nail corrosion rates in the Sydney Region; and
- carry out condition surveys of timber buildings at selected sites to determine whether defects present were consistent with the environmental risk aspects observed or whether there were other influences giving rise to failures or partial failures.

In addition nail corrosion rates were measured in humidity chambers in a laboratory to contrast corrosion caused by moisture content changes only with corrosion rates measured in the field.
3.2 Selection of Test Sites

Test sites were chosen to give both a range of sub climates (based on topography) and pollutant levels. The test sites and their geographical characteristics are set out in Table 3.1. The topographical and pollutant classifications of the sites are shown in Table 3.2.

### Table 3.1 Test Sites and Geographical Characteristics

<table>
<thead>
<tr>
<th>SITE AND SITE REFERENCE NUMBER</th>
<th>NATIONAL GRID REFERENCE</th>
<th>APPROX. ALTITUDE (m)</th>
<th>DISTANCE FROM COAST (Approx. km)</th>
<th>MEDIAN ANNUAL RAINFALL (mm)</th>
<th>MEAN MAX. TEMP. (°C)</th>
<th>MEAN MIN. TEMP. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. WENTWORTH FALLS</td>
<td>6261000N 257000E</td>
<td>772</td>
<td>85</td>
<td>1,300</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>2. RICHMOND</td>
<td>6277900N 291000E</td>
<td>20</td>
<td>55</td>
<td>800</td>
<td>23</td>
<td>10</td>
</tr>
<tr>
<td>3. ILLAWONG</td>
<td>6235900N 317820E</td>
<td>80</td>
<td>18</td>
<td>1,000</td>
<td>21</td>
<td>12</td>
</tr>
<tr>
<td>4. SYDNEY CBD</td>
<td>6250700N 345300E</td>
<td>25</td>
<td>6</td>
<td>1,200</td>
<td>21</td>
<td>13</td>
</tr>
<tr>
<td>5. LITTLE BAY</td>
<td>6238600N 338200E</td>
<td>25</td>
<td>0.2</td>
<td>1,200</td>
<td>21</td>
<td>12</td>
</tr>
<tr>
<td>6. COLEDALE</td>
<td>6203800N 310600E</td>
<td>40</td>
<td>0.05</td>
<td>1,300</td>
<td>21</td>
<td>12</td>
</tr>
</tbody>
</table>


### Table 3.2. Site Topography and Pollutant Zoning

<table>
<thead>
<tr>
<th>SITE</th>
<th>TOPOGRAPHY</th>
<th>NOMINAL POLLUTANT ZONING</th>
</tr>
</thead>
<tbody>
<tr>
<td>WENTWORTH FALLS</td>
<td>VERY HILLY</td>
<td>INLAND RURAL - ISO C2 (LOW) *</td>
</tr>
<tr>
<td>RICHMOND</td>
<td>FLAT PLAIN</td>
<td>INLAND URBAN / SEMI RURAL - ISO C2</td>
</tr>
<tr>
<td>ILLAWONG</td>
<td>HILLY</td>
<td>NEAR COASTAL SUBURBAN - ISO C2</td>
</tr>
<tr>
<td>SYDNEY CBD</td>
<td>FLAT</td>
<td>NEAR COASTAL URBAN - ISO C2</td>
</tr>
<tr>
<td>LITTLE BAY</td>
<td>RISING</td>
<td>MARINE - ISO C3</td>
</tr>
<tr>
<td>COLEDALE</td>
<td>STEEPPLY RISING</td>
<td>MARINE - ISO C3</td>
</tr>
</tbody>
</table>


A 1:250,000 map of the Sydney region is included in this report (inside back cover).

This map indicates the location of the test sites used according to the site reference.
numbers in Table 3.2. The topography and significant features around each site and across the region are indicated on the map.

3.3 General Description of the Sites

3.3.1 Wentworth Falls

This site was located at the Queen Victoria Hospital in a bushland setting several kilometers from the township of Wentworth Falls. Monitoring equipment and exposure samples were located in and on a test enclosure adjacent to a disused and somewhat dilapidated domestic scale timber building formerly used as a residence that was constructed in 1903. Monitoring equipment and specimens were also placed in various spaces within the building itself (details provided later). A photograph of this site is shown as Figure 3.1. Figure 3.2 illustrates the test enclosure utilised and the placement of the material specimens and monitoring equipment. A sketch showing the location of experimental items in the building is shown as Figure 3.3. Figure 3.4 shows a section through the building.

The test enclosure was afforded some sheltering by the adjacent building, which was to its west, and by trees to the west and north. Otherwise the enclosure was relatively exposed.
Figure 3.2 Details of Test Enclosure
NOTE:
Timber moisture content measured in roof space, wall cavities, sub floor space, window (south end) and door (north end). Temperature and relative humidity measured in roof space, wall cavities (north, east and south), and sub floor space. Salt deposition measured in roof space, eastern wall cavity and sub floor space. SO$_2$, NO$_2$ and HNO$_3$ measured in test room adjacent to opening to ceiling.

Figure 3.3 Sketch Indicating Location of Experimental Items at Wentworth Falls
Figure 3.4 Section Through Building at Wentworth Falls
3.3.2 Richmond

An existing climate station compound on the University of Western Sydney campus at Richmond was utilised to locate a test enclosure holding monitoring equipment and exposure samples.

The site was very exposed with little sheltering from built or natural features. A photograph of the site is shown as Figure 3.5.

![Figure 3.5 Test Enclosure at Richmond](image)

3.3.3 Illawong

Experimental equipment and materials were located in and on a test enclosure on the southern side of a two storey house.
Illawong is a bushland suburb on the southern outskirts of Sydney. The house is located on the northern side of a valley. The enclosure was sheltered by the house but otherwise generally exposed. A photograph of the site is shown as Figure 3.6.

![Test Enclosure at Illawong](image)

**Figure 3.6** Test Enclosure at Illawong

3.3.4 Sydney Central Business District (CBD)

The test enclosure was located on the roof of an outbuilding at the Hyde Park Barracks on Macquarie Street. This is a heritage site and the barracks are currently used as a museum.

The site was sheltered by surrounding buildings to the north, east and south. However there was a significant amount of air turbulence at the site. A photograph of the site is shown as Figure 3.7.
Figure 3.7 Test Enclosure in the CBD

3.3.5 Little Bay

The test site was located in the grounds of the Prince Henry Hospital adjacent to a domestic scale building known as the Sewing Room.

The Sewing Room was to the west of the enclosure and provided moderate sheltering from this direction. It was otherwise exposed with the Pacific Ocean being to its east.

A photograph of the site is shown as Figure 3.8.
3.3.6 Coledale

This site was in the grounds of the Coledale Hospital and the test enclosure was located adjacent to the gardeners shed.

The hospital was located close to the ocean on its east. The ground level rises steeply to the west of the site. The test enclosure was relatively sheltered to its north, south and west but was exposed to the influences of the ocean on the eastern side. A photograph of the site is shown as Figure 3.9.
3.4 Climatic Aspects

3.4.1 Rainfall
Measurement of rainfall was undertaken using Yates plastic rain gauges. They were wrapped with duct tape to minimise evaporation. Readings were taken on each site visit, which were carried out at approximately monthly intervals. Samples of water were obtained and stored in plastic bottles on each visit for rainwater chemistry analysis. The rain gauges were mounted on posts on each of the test enclosures at approximately 1500mm above ground level (base of the enclosure)

3.4.2 Temperature
The temperature in the test enclosure at each site was recorded on an hourly basis. At Wentworth Falls it was measured using combined temperature and humidity sensors
(Vaisala Humitter 50Y) and recorded on a data logger (Determ Datataker 500). At other sites it was measured and recorded using Testo data loggers with built in temperature and humidity sensors.

The data was downloaded using software provided by the respective data logger manufacturers and a KTX notebook computer. The data was placed in spreadsheets for processing.

3.4.3 Relative Humidity

Hourly readings were recorded at each site in the same places as the temperature readings using the same sensors, data loggers, software and computer hardware.

3.4.4 Time of Wetness

The time of wetness was determined by counting the proportion of the hourly relative humidity readings that were in excess of 80% for each site.

3.5 Rainwater Chemistry and Pollutants

3.5.1 Rainwater pH

Water samples were taken from the rain gauges at each site during monthly site visits. They were tested for pH levels using a combined pH / conductivity / salinity meter (TPS, HP81 with a pH electrode, Part No. 121207). This equipment was calibrated each time of use with pH 4.00 and 6.00 buffers.
3.5.2 Rainwater Conductivity

Rainwater conductivity was measured in a similar way to pH using the same meter and a TPS HK1 conductivity electrode. The equipment was calibrated using a 2.76 mS/cm (1452ppm) conductivity standard solution.

3.5.3 Rainwater Salt Content

Rainwater salt content was measured using the same meter and probe used to measure conductivity. Again water samples were taken on monthly field trips. The meter was calibrated each time of use using 10ppk salt standard solution (NaCl).

3.5.4 SO$_2$, NO$_2$ and HNO$_3$ Levels in the Air

These pollutants were measured using passive samplers supplied and processed by the CSIRO. They were suspended in the test enclosure at each of the sites using cable ties. They were removed at the end of each season and transported for processing in sealed containers.

3.5.5 Air Salt Content

Air salt content at each site was measured using salt candles according to ISO 9225. In essence the salt candles comprised a gauze bandage wrapped around a test tube which was mounted on a jar. The bandage extended into the jar as wick. The jar contained 200ml of water and glycerol solution. The glycerol reduced the evaporation rate. A photograph shown at Figure 3.10 displays one of the salt candles used.

The salt candles were mounted on a sheltered platform above each test enclosure.
On monthly site visits the gauze was washed into the contents of the jar using distilled water. The contents of the jar were stored in plastic bottles for testing. A sample of the distilled water used was also taken and tested.

Laboratory processing involved titration of the samples to determine the salt content. The deposition rate was expressed in terms of surface area (the surface area of the salt candle being known).

![Salt Candle](image)

**Figure 3.10. Salt Candle Arrangement**
3.6 Corrosivity

3.6.1 Measurement of Corrosion using Zincorr Units

Zincorr units were used to measure and compare corrosivity at the sites. The units utilise a system whereby zinc wire is wrapped around nylon, copper and iron bolts.

The purpose of the units is to obtain a reliable measure of the aggressiveness of the environment towards metals. The two metal cores provide a bimetallic couple which accelerates corrosion and permits significant measurement within three months. A second effect is that the iron core / zinc wire couple is reputed to be more sensitive to marine environments and the copper core / zinc wire couple is said to be more sensitive to industrial environments (Ganther, Cole & King 1999).

The units were mounted on brackets above the test enclosure at each of the sites.

Following exposure (for each season of the study) the wire was cleaned of the corrosive products using chromic – phosphoric acid solution according to ASTM standard practice and the extent of corrosion measured by weight loss of the wire. The results were expressed as an index number, normalised to an exposure period of three months.

3.6.2 Measurement of Corrosion using Copper / Steel Coupons

Corrosivity at each site was also measured using copper (5%) steel alloy coupons prepared to British Iron and Steel Research Association (BISRA) specifications. Two coupons were mounted adjacent to the zincorr units above the test enclosures at each site (see Figure 3.11).
The coupons were exposed for a season. Laboratory processing involved scraping and cleaning in accordance with ASTM G1 - 90 Standard Practice for Preparing, Cleaning and Evaluating Corrosion Test Specimens (1996). The extent of corrosion was measured by weight loss.

![Copper / Steel Coupon Arrangement and Suspended Painted Radiata Pine Boards](image)

**Figure 3.11** Copper / Steel Coupon Arrangement and Suspended Painted Radiata Pine Boards

### 3.6.3 Measurement of Corrosion using Zinc Plates

In a similar way to the copper / steel coupons zinc plates (100 x 150 x 1mm, 99.9% zinc) were mounted on brackets on the test enclosures at each of the sites and exposed for each season of the study.
Following exposure the plates were cleaned with in accordance with ASTM G1 (1996) guidelines and the extent of corrosion measured through weight loss.

3.7 Timber Moisture Content

3.7.1 Timber Near Surface Moisture Content in Sheltered External Conditions

The near surface moisture content of six species of timber was measured at each site at approximately monthly intervals. The six species were Radiata Pine, CCA Treated Radiata Pine, Douglas Fir, Mountain Ash, Brush Box and Spotted Gum.

Moisture boards with approximate dimensions of 35mm wide x 20mm thick x 200mm long were prepared by sealing the ends with epoxy and installing identification labels and cup hooks at the ends. The preparation work was carried out generally according to the methods established by the Queensland Department of Forestry for it’s Equilibrium Moisture Content Survey of Queensland (Bragg 1986).

Three replicates of each species were suspended in each test enclosure at the sites by the cup hooks on the end of the boards. The boards were placed in position in random order and in a way that protected them from rain, wind and direct sunlight but allowed the air to circulate freely.

The near surface moisture content was measured on each field trip using a moisture meter (Protimeter Timberrmaster). Each moisture board was marked at mid length with a pencil line so that the readings were taken in the same approximate location each time. The readings were taken with the meter set for automatic temperature correction.
3.7.2 Total Timber Moisture Content in Sheltered External Conditions

This aspect was measured by weighing the moisture boards discussed in the previous section on each field trip with a balance to one decimal place. On completion of the fieldwork the dry weight of each board was determined after oven drying and then used to calculate the total moisture content of the boards at each weighing point.

3.7.3 Painted Timber Moisture Content in Unsheltered External Conditions

The moisture content of painted Radiata Pine boards suspended on the test enclosure at each site was measured on each field trip.

The boards were 70 wide x 20mm thick x 400mm long. Two of the boards at each site were painted using one coat of oil based primer and two coats of (premium quality) brown acrylic paint. A further two boards at each site were painted using two coats only of the brown acrylic paint.

The boards were suspended on an arm above the test enclosure using cup hooks and chord. They were fully exposed to the elements of rain, sun and wind (refer to Figure 3.11.

The moisture content of each board was measured prior to exposure using a moisture meter (Protimeter Timberrmaster). Readings on each board were taken and averaged and the weight of the boards at this moisture content was recorded. The weight of each board was subsequently recorded on each field trip to 1 decimal place and compared to the pre exposure weight to determine the change in moisture content.
3.7.4 Timber Surface Moisture Content in Sheltered External Conditions

This was estimated using Bramhall’s formula and the data collected for relative humidity discussed earlier (Cole & Ganther 1996).

3.8 The Effects of a Timber Building on Measured Aspects

Data was gathered from a building adjacent to the test test enclosure at Wentworth Falls to observe the effects of such a building on a number of the aspects discussed above.

3.8.1 Temperature and Relative Humidity

Hourly readings of temperature and relative humidity were measured in the wall cavity on the eastern side, the roof space and the sub floor space using the same equipment used to record these aspects in the test enclosure outside the building (refer to section 3.4 above). Temperature and relative humidity were also measured in the north and south walls for several months (using Tiny Tag data loggers and Vaisala Humitter 50Y sensors).

3.8.2 Air Salt Content

Air salt content was measured in the roof space, wall cavity and sub floor space using the salt candle method described earlier. Measurement periods were monthly.

3.8.3 \( \text{SO}_2, \text{NO}_2 \) and \( \text{HNO}_3 \) Levels

These aspects were measured using passive samplers placed in a room at approximately nine feet above the floor level. Measurements were made for each season.
3.8.4 Timber Moisture Content

The approximate moisture content of the floor, wall and roof members was recorded hourly by measuring the variations in electrical resistance between two screw points in the timber approximately 10mm apart.

The moisture content was also measured in the roof space, wall cavity and sub floor space using moisture boards. The species used were Radiata Pine, CCA Treated Radiata Pine, Douglas Fir, Mountain Ash, Brush Box and Spotted Gum. Near surface moisture content in the moisture boards was measured monthly using a moisture meter, corrected for temperature. Total moisture content was also measured monthly by weighing the moisture boards (which were subsequently dried in an oven and weighed to ascertain their dry weight).

Surface moisture content was estimated for the roof space, wall cavity and sub floor area using Bramhall’s formula (Cole & Ganther 1996).

3.9 Nail Corrosion

3.9.1 Laboratory Measurement of Nail Corrosion at Different Levels of Moisture Content

Corrosion rates for 40mm x 2mm bright steel, 40mm x 2mm hot dipped galvanised, 30mm x 1.6mm zinc coated and 30mm x 2mm copper nails in joined Radiata Pine, CCA Treated Radiata Pine, Douglas Fir, Mountain Ash and Spotted Gum boards were determined in a laboratory for varying degrees of relative humidity. The boards were approximately 20mm thick x 35mm wide x 200mm long except for the CCA Treated
Radiata Pine boards which were 45mm wide x 25mm thick x 200mm long. The nails were placed so as to be a minimum of 10mm apart.

Three nails of each type were placed in timber specimens of each species. The boards were suspended in plastic tanks above solutions of K₂SO₄, BaCl₂ and NaNO₃ in accordance with a protocol developed by the CSIRO (Cole, Ganther, Furman & Page 1999). The tanks were in turn placed in a controlled temperature room at 20°C to control relative humidity levels and maintain the timber surface moisture content at 16%, 20% and 25% respectively. Electrically driven fans were placed in the top of each tank to ensure the air in the tanks was adequately circulated.

Moisture boards were also suspended in the tanks and weighed regularly to ensure the desired humidity levels and moisture contents were maintained.

One set of boards for each species was exposed in the tanks for five months and another for eleven months. The nails were extracted from the boards, cleaned in accordance with ASTM G1 and weighed to determine the weight loss through corrosion. The nails were weighed to three decimal points before insertion in the timber and after extraction.

The extent of corrosion on the heads and shanks of the nails was also rated. Corrosion of uncoated nails was rated on a scale of 0 to 5 (0 = no corrosion, 1 = 1 to 5% of surface corroded, 2 = 5% to 25%, 3 = 25% to 60%, 4 = 60% to 90% and 5 = 100%). Nails coated with zinc products were rated on an extended scale of 0 to 8 (0 = no corrosion, 1 = 1% to 5% of surface with white rust, 2 = 5% to 25% white rust, 3 = 25% to 60% white rust, 4 = 1% to 5% of surface with red rust, 5 = 5% to 25% red rust, 6 = 25% to 60% red rust, 7 = 60% to 90% red rust and 8 = 100% red rust).
The data gathered in this manner was used to establish nail corrosion where species and moisture content were the only variables and the effects of atmospheric pollutants were for practical purposes not present.

3.9.2 Field Measurement of Nail Corrosion under External Sheltered Conditions

Three 40mm x 2mm bright, 40mm x 2mm galvanised, 30mm x 1.6mm zinc coated and 30mm x 2mm copper nails were driven into three replicates of six species of timber. The nails were individually weighed to three decimal places. The species were Radiata Pine, CCA Treated Radiata Pine, Douglas Fir, Spotted Gum, Mountain Ash and Brush Box. Templates were used to ensure the nails were placed in a consistent manner and at least 1cm apart.

The boards were approximately 35mm wide x 20 mm thick x 200mm long in all cases except the CCA Treated Radiata Pine, which was 45mm wide x 25mm thick x 200mm long. They were sealed at the ends with epoxy and had cup hooks placed in the ends. Three pieces of timber were used for each nail board except for the CCA Treated Radiata Pine where two pieces were used (refer to Figure 3.12).
The nail boards were hung inside the test enclosure at each site by the cup hooks in their ends and left in place for two years.

The test enclosures provided shelter to the nail boards from rain, wind and direct sunlight but allowed the air to circulate freely. A sketch showing the dimensions and details of the test enclosures is shown earlier in this chapter (Figure 3.2).
Following exposure the nails were extracted from the timber using a claw hammer and hole saw in a manner that avoided damage to the nails.

Each of the nails was rated for corrosion of the head and shank according to the scale described in the previous section. They were then cleaned in accordance with ASTM G1 prior to being weighed to determine the weight loss through corrosion.

3.10 Building Condition Surveys

Building condition surveys were carried out in buildings at three of the sites to ascertain whether defects present were consistent with the degradation risk factors observed during the study and / or whether there were other influences giving rise failures or partial failures.

The three sites involved were Wentworth Falls, Ilawong and Little Bay. It was considered that these sites differed sufficiently to be discriminating in respect of risk factors.

The condition surveys covered all major building elements and spaces that were accessible. They involved visual inspections commencing with the external elevations and roof, proceeding to the sub floor areas, internal rooms and roof space.

3.11 Statistical Analysis of Results

Statistical analysis of each aspect measured in the study was undertaken using Microsoft Excel and Minitab software packages. Descriptive statistics were prepared for each
aspect. Differences and similarities between sites were identified by comparing measures of central tendency.

Correlation and stepwise regression analysis were carried out to determine, where possible, convenient predictors that might be used to estimate the level of nail corrosion that could be expected for popular nail / timber combinations used in the region in timber building elements. The nails subjected to this analysis were bright and galvanised.

Regression analysis was also used to compare the extent to which nail corrosion could be attributed to the environmental aspects measured as opposed to the natural properties of the timber, variability in the materials used and other factors.
CHAPTER 4

RESULTS

4.1 Climatic Aspects at Test Sites

The results of the field measurement of climatic aspects at each of the sites are summarised below.

4.1.1. Rainfall

The total rainfall at each site over study period is shown in Figure 4.1.

![Rainfall Chart](image)

*Figure 4.1 Total Rainfall - December 1997 to December 1999*

The sites at Wentworth Falls, coastal and near coastal sites had relatively high rainfalls, whilst the site at Richmond had approximately two thirds the rainfall of these locations.

4.1.2. Temperature

There were a number of data logger battery failures at the various sites between field visits. This was despite the data logger software indicating a high remaining battery capacity. Although these failures will have introduced a level of error into the results the number and spread of recorded data points over the two years of the field work and the consistency of the results with long term Bureau of Meteorology data suggest that the
validity of the results overall has not been compromised significantly. The number of successful readings at each site is shown in Table 4.1.

Table 4.1 Number of Successful Temperature and Humidity Readings Taken with Data Loggers at Each Site

<table>
<thead>
<tr>
<th>SITE</th>
<th>NUMBER OF READINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>WENT. FALLS</td>
<td>14648</td>
</tr>
<tr>
<td>RICHMOND</td>
<td>14565</td>
</tr>
<tr>
<td>ILLAWONG</td>
<td>15448</td>
</tr>
<tr>
<td>CBD</td>
<td>16276</td>
</tr>
<tr>
<td>LITTLE BAY</td>
<td>16775</td>
</tr>
<tr>
<td>COLEDALE</td>
<td>15298</td>
</tr>
</tbody>
</table>

The maximum possible number of hourly readings for a site for two years was 17520. The mean temperature recorded at each site over the study period is shown in Figure 4.2.

![Figure 4.2 Mean Temperature - December 1997 to December 1999](image)

The minimum and maximum temperatures recorded at the sites in the test housings are shown in Figure 4.3. The maximum temperatures at all the sites were very similar, with the highest temperature being recorded at Richmond. The lowest temperatures were recorded at Richmond and Wentworth Falls. Minimum temperatures were highest at the coastal and near coastal sites.
4.1.3 Relative Humidity

The difficulties with the data loggers discussed above also impacted the relative humidity readings. The number of relative humidity readings for each site was the same as that for temperature (refer to Table 4.1). Again, although this would have introduced a level of error it is not believed to have compromised the results significantly.

The mean relative humidity recorded at each of the sites is shown in Figure 4.4.

It can be seen that the highest level was recorded at Little Bay and the lowest in the CBD. All other sites had very similar means.
4.1.4 Time of Wetness

The ISO time of wetness (% of the time that relative humidity was over 80%) at each of the sites is shown in Table 4.2.

<table>
<thead>
<tr>
<th>SITE</th>
<th>% TIME OF WETNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>WENTWORTH FALLS</td>
<td>50</td>
</tr>
<tr>
<td>RICHMOND</td>
<td>58</td>
</tr>
<tr>
<td>ILLAWONG</td>
<td>56</td>
</tr>
<tr>
<td>CBD</td>
<td>21</td>
</tr>
<tr>
<td>LITTLE BAY</td>
<td>78</td>
</tr>
<tr>
<td>COLEDALE</td>
<td>61</td>
</tr>
</tbody>
</table>

4.2 Rainwater Chemistry and Pollutants

4.2.1 Rainwater pH

The minimum, maximum and mean rainwater pH readings for each site are shown in Figure 4.5.

![Figure 4.5 Minimum, Maximum and Mean Rainwater pH - December 1997 to December 1999](image-url)

**Figure 4.5** Minimum, Maximum and Mean Rainwater pH - December 1997 to December 1999
The lowest rainwater pH reading was taken at Richmond (pH 3.5). The highest pH was recorded for Wentworth Falls (pH 7.2). The lowest mean pH was at Richmond (pH 5.0). The highest mean results was recorded at Coledale (pH 5.9).

4.2.2 Rainwater Conductivity

The minimum, maximum and mean rainwater conductivity readings for each site are shown in Figure 4.6. There were two abnormally high readings for Richmond in October 1998 (0.15mS) and January 1999 (0.49mS) which have been deleted to produce this graph. They can not be explained readily and hence need to be considered with caution.

Figure 4.7 shows the mean monthly rainwater conductivity readings for each site in relation to the distance from the coast. It can be seen from this graph that conductivity is highest near the coast, diminishes rapidly within a relatively short distance of the coast and then reduces slowly inland.
4.2.3 Rainwater Salt Content

The minimum, maximum and mean rainwater salt content readings for each site are shown in Figure 4.8. The meter used did not differentiate between salts, therefore the readings are for the total of all salts. However the meter was calibrated using a 10 ppK sodium chloride solution i.e., all salts were treated as if they were common salt.

Unusually high readings were experienced at Wentworth Falls in October 1998 (0.16 ppk) and at Richmond in October 1998 (0.09 ppk) and January 1999 (0.31 ppk). As these readings cannot be explained they have been removed from the data in Figure 4.8.
Figure 4.9 shows the mean monthly rainwater salt content readings for each site in relation to the distance from the coast. It can be seen from this graph that in general, as is the case with conductivity, salt content is greatest near the coast, diminishes rapidly within a relatively short distance of the coast and then reduces slowly inland.

**Figure 4.9 Mean Monthly Rainwater Salt Content in Relation to Distance from the Coast**

### 4.2.4 Salt Deposition

Figure 4.10 shows the mean daily airborne salt deposition rates for the period December 1997 to September 1999.

**Figure 4.10 Mean Daily Salt Deposition - December 1997 to September 1999**

The relationship between mean daily salt deposition at the sites and their approximate distance from the coast is shown in Figure 4.11. It can be seen from this graph that the
salt deposition rate is very high near the coast and diminishes rapidly as the distance inland increases. It remains fairly constant for all but coastal sites.

![Graph](image)

**Figure 4.11** Mean Daily Salt Deposition in Relation to Distance of Sites from Coast

### 4.2.5 Sulphur Dioxide Levels

Figure 4.12 shows the mean sulphur dioxide readings recorded during the study period. It can be seen from the graph that the highest levels were experienced in the CBD and the lowest at the rural site of Wentworth Falls. The levels at Little Bay and Coledale were slightly elevated.

![Bar Chart](image)

**Figure 4.12** Mean Sulphur Dioxide Levels - December 1997 to December 1999
4.2.6 Nitrogen Dioxide Levels

The mean nitrogen dioxide level experienced at each of the sites is shown in Figure 4.13.

![Figure 4.13 Mean NO₂ Levels - December 1997 to December 1999](image)

The highest mean reading was in the CBD and lowest was at Wentworth Falls.

4.2.7 HNO₃ Levels

The mean levels of the airborne acid HNO₃ measured at the sites are shown in Figure 4.14. The highest levels were experienced at the urban site of Illawong and the CBD. The lowest levels were measured at Wentworth Falls.

![Figure 4.14 HNO₃ Levels - December 1997 to December 1999](image)
4.3 Corrosion Levels

4.3.1 Corrosion Measured Using Zincorr Units

The corrosivity of the sites measured over the period December 1997 to 1999 using zinc wire on nylon, iron and copper cores is shown in rank order in Tables 4.3, 4.4 and 4.5.

Table 4.3 Corrosivity of Sites Measured using Zincorr Units – Zinc Wire on Nylon

<table>
<thead>
<tr>
<th>RANK AND SITE</th>
<th>INDEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.LITTLE BAY</td>
<td>2.7</td>
</tr>
<tr>
<td>2.COLEDALE</td>
<td>1.3</td>
</tr>
<tr>
<td>3.WENTWORTH FALLS</td>
<td>0.3</td>
</tr>
<tr>
<td>4.RICHMOND</td>
<td>0.3</td>
</tr>
<tr>
<td>5.ILLAWONG</td>
<td>0.3</td>
</tr>
<tr>
<td>6.CBD</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 4.4 Corrosivity of Sites Measured using Zincorr Units – Zinc Wire on Iron Core

<table>
<thead>
<tr>
<th>RANK AND SITE</th>
<th>INDEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.COLEDALE</td>
<td>9.4</td>
</tr>
<tr>
<td>2.LITTLE BAY</td>
<td>8.2</td>
</tr>
<tr>
<td>3.CBD</td>
<td>4.3</td>
</tr>
<tr>
<td>4.WENTWORTH FALLS</td>
<td>4.1</td>
</tr>
<tr>
<td>5.ILLAWONG</td>
<td>4.1</td>
</tr>
<tr>
<td>6.RICHMOND</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Table 4.5 Corrosivity of Sites Measured using Zincorr Units – Zinc Wire on Copper Core

<table>
<thead>
<tr>
<th>RANK AND SITE</th>
<th>INDEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.LITTLE BAY</td>
<td>7.3</td>
</tr>
<tr>
<td>2.COLEDALE</td>
<td>6.8</td>
</tr>
<tr>
<td>3.WENTWORTH FALLS</td>
<td>4.8</td>
</tr>
<tr>
<td>4.CBD</td>
<td>4.4</td>
</tr>
<tr>
<td>5.ILLAWONG</td>
<td>4.2</td>
</tr>
<tr>
<td>6.RICHMOND</td>
<td>4.2</td>
</tr>
</tbody>
</table>

As indicated in Chapter 3 the iron core / zinc wire couple is reputed to be more sensitive to marine environments and the copper core / zinc wire couple is believed to be more sensitive to industrial environments (Ganther, Cole & King 1999).
4.3.2 Corrosion Measured Using Copper / Steel Coupons

The extent of corrosion at each site measured using copper / steel coupons for the years December 1997 to December 1998 and December 1998 to December 1999 is shown in Figure 4.15. The total corrosion for both years is also indicated. It can be seen from the graph that the heaviest corrosion occurred at the coastal site and the lowest at the rural site of Wentworth Falls. The extent of corrosion at the exposed site of Richmond is slightly higher than that measured at the sheltered site of Illawong.

![Figure 4.15 Corrosion Measured Using Copper / Steel Coupons](image)

4.3.3 Extent of Corrosion Measured Using Zinc Plates

The extent of corrosion measured at the sites using zinc plates is shown in Figure 4.16

![Figure 4.16 Corrosion Measured Using Zinc Plates](image)
Corrosion at the coastal sites was the highest and it was very similar at all other sites.

4.4 Timber Moisture Content

4.4.1 Timber Surface Moisture Content

The calculated mean surface moisture content of the timber specimens mounted in the test enclosure at each site is shown in Table 4.6

Table 4.6 Mean Surface Moisture Content of Timber - December 1997 to December 1999 (%)

<table>
<thead>
<tr>
<th>RANK / SITE</th>
<th>CALCULATED AIR MOISTURE CONTENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. LITTLE BAY</td>
<td>25</td>
</tr>
<tr>
<td>2. COLEDALE</td>
<td>21</td>
</tr>
<tr>
<td>3. RICHMOND</td>
<td>20</td>
</tr>
<tr>
<td>4. ILLAWONG</td>
<td>18</td>
</tr>
<tr>
<td>5. WENT. FALLS</td>
<td>17</td>
</tr>
<tr>
<td>6. SYDNEY CBD</td>
<td>13</td>
</tr>
</tbody>
</table>

4.4.2 Timber Near Surface Moisture Content

The mean near surface moisture content of the six species of timber mounted in the test enclosure at each site over the two years of the field work is shown in Figures 4.17 to 4.22. The moisture content readings were corrected for each species in accordance with the instructions of the manufacturer of the moisture meter used. Where correction factors were not available from the manufacturer the adjustments were made using data published by the Forestry Commission of New South Wales (Hartley & Marchant 1989).
Figure 4.17 Mean Near Surface Moisture Content of Timber - Wentworth Falls (December 1997 to December 1999)

Figure 4.18 Mean Near Surface Moisture Content of Timber - Richmond (December 1997 to December 1999)

Figure 4.19 Mean Near Surface Moisture Content of Timber - Illawong (December 1997 to December 1999)
Figure 4.20 Mean Near Surface Moisture Content of Timber - CBD (December 1997 to December 1999)

Figure 4.21 Mean Near Surface Moisture Content of Timber - Little Bay (December 1997 to December 1999)

Figure 4.22 Mean Near Surface Moisture Content of Timber - Coledale (December 1997 to December 1999)
4.4.3 Timber Total Moisture Content

The minimum, maximum and mean total moisture content of the six species of timber exposed inside the test enclosure at each site over the period December 1997 to December 1999 are shown in Figures 4.23 to 4.28.

![Figure 4.23 Total Timber Moisture Content - Wentworth Falls (December 1997 to December 1999)](image1)

![Figure 4.24 Total Timber Moisture Content - Richmond (December 1997 to December 1999)](image2)
Figure 4.25 Total Timber Moisture Content - Illawong (December 1997 to December 1999)

Figure 4.26 Total Timber Moisture Content - CBD (December 1997 to December 1999)
The mean total moisture content for all species of timber (exposed in the test enclosure) at each site combined is shown in Figure 4.29.
Figure 4.29 Mean Total Moisture Content of All Species of Timber Combined for Each Site (exposed in test enclosures)
4.4.4. Moisture Content of Painted Timber

The mean moisture content of the painted Radiata Pine mounted externally and exposed to the elements of rain, wind and direct sunlight at each site is shown in Figures 4.30 to 4.35. Results for boards with and without primer are shown in each graph. The mean moisture content of all boards aggregated for the region is shown in Figure 4.36.

![Figure 4.30](image)

**Figure 4.30** Moisture Content of Painted Radiata at Wentworth Falls (December 1997 to December 1999)

![Figure 4.31](image)

**Figure 4.31** Moisture Content of Painted Radiata Pine at Richmond (December 1997 to December 1999)
**Figure 4.32** Moisture Content of Painted Radiata Pine at Illawong (December 1997 to December 1999)

**Figure 4.33** Moisture Content of Painted Radiata Pine in the CBD (December 1997 to December 1999)
**Figure 4.34** Moisture Content of Painted Radiata Pine at Little Bay (December 1997 to December 1999)

**Figure 4.35** Moisture Content of Painted Radiata at Coledale (December 1997 to December 1999)

**Figure 4.36** Mean Moisture Content of Painted Radiata Pine Boards at all Sites (December 1997 to December 1999)

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4.5 Nail Corrosion

4.5.1 Laboratory Measurement of Nail Corrosion

The mean nail corrosion rates for galvanised, bright, copper and zinc nails in CCA Treated Pine, Mountain Ash, Douglas Fir, Radiata Pine and Spotted Gum exposed in three tanks where the timber surface moisture content was maintained at 16%, 20% and 25% are shown in Table 4.7. Corrosion of uncoated nails was rated on a scale of 0 to 5 and nails coated with zinc products were rated on an extended scale of 0 to 8.

<table>
<thead>
<tr>
<th>SPECIES</th>
<th>NAIL TYPE</th>
<th>16%MC</th>
<th>20%MC</th>
<th>25%MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>TREATED PINE</td>
<td>GALVANISED</td>
<td>36</td>
<td>69</td>
<td>171</td>
</tr>
<tr>
<td></td>
<td>BRIGHT</td>
<td>8</td>
<td>31</td>
<td>158</td>
</tr>
<tr>
<td></td>
<td>COPPER</td>
<td>25</td>
<td>44</td>
<td>62*</td>
</tr>
<tr>
<td></td>
<td>ZINC</td>
<td>20</td>
<td>33</td>
<td>106</td>
</tr>
<tr>
<td>MOUNTAIN ASH</td>
<td>GALVANISED</td>
<td>73</td>
<td>116</td>
<td>113</td>
</tr>
<tr>
<td></td>
<td>BRIGHT</td>
<td>15</td>
<td>151</td>
<td>205</td>
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<tr>
<td></td>
<td>COPPER</td>
<td>4</td>
<td>22</td>
<td>47</td>
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<tr>
<td></td>
<td>ZINC</td>
<td>20</td>
<td>59</td>
<td>125</td>
</tr>
<tr>
<td>DOUGLAS FIR</td>
<td>GALVANISED</td>
<td>29</td>
<td>47</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>BRIGHT</td>
<td>8</td>
<td>89</td>
<td>112</td>
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<td></td>
<td>COPPER</td>
<td>4</td>
<td>40</td>
<td>94*</td>
</tr>
<tr>
<td></td>
<td>ZINC</td>
<td>13</td>
<td>40</td>
<td>99</td>
</tr>
<tr>
<td>RADIATA PINE</td>
<td>GALVANISED</td>
<td>54</td>
<td>58</td>
<td>149</td>
</tr>
<tr>
<td></td>
<td>BRIGHT</td>
<td>4</td>
<td>19</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>COPPER</td>
<td>4</td>
<td>40</td>
<td>86*</td>
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<tr>
<td></td>
<td>ZINC</td>
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<td>20</td>
<td>40</td>
</tr>
<tr>
<td>SPOTTED GUM</td>
<td>GALVANISED</td>
<td>31*</td>
<td>281*</td>
<td>281*</td>
</tr>
<tr>
<td></td>
<td>BRIGHT</td>
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<td>487</td>
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<tr>
<td></td>
<td>COPPER</td>
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</tr>
<tr>
<td></td>
<td>ZINC</td>
<td>43*</td>
<td>113*</td>
<td>156*</td>
</tr>
</tbody>
</table>

* These results are based on 156 days exposure. All other results are based on 335 days exposure.

The mean corrosion rate of bright and galvanised nails in CCA Treated Pine, Mountain Ash, Douglas Fir, Radiata Pine and Spotted Gum at moisture contents of 16%, 20% and 25% are shown in the graphs at Figures 4.37 and 4.38.
Figure 4.37 Mean Corrosion of Bright Nails at Varying Moisture Content

Figure 4.38 Mean Corrosion of Galvanised Nails at Varying Moisture Content
Corrosion ratings for galvanised, bright, copper and zinc nails in CCA Treated Pine, Mountain Ash, Douglas Fir, Radiata Pine and Spotted Gum exposed in three tanks so that the timber moisture content was maintained at 16%, 20% and 25% are shown in Table 4.8.

**Table 4.8 Head and Shank Corrosion Ratings (Laboratory Measurement)**

<table>
<thead>
<tr>
<th></th>
<th>156 DAYS EXPOSURE</th>
<th>335 DAYS EXPOSURE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16% MC 20%MC 25%MC</td>
<td>16% MC 20%MC 25%MC</td>
</tr>
<tr>
<td></td>
<td>H  S  H  S  H  S  H  S  H  S</td>
<td>H  S  H  S  H  S  H  S  H  S</td>
</tr>
<tr>
<td></td>
<td>16% MC 20%MC 25%MC</td>
<td>16% MC 20%MC 25%MC</td>
</tr>
<tr>
<td></td>
<td>H  S  H  S  H  S  H  S  H  S</td>
<td>H  S  H  S  H  S  H  S  H  S</td>
</tr>
<tr>
<td>TREATED PINE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>2 2.5 3.5 3 3 2.5 3 3 3</td>
<td>2 2.5 3.5 3 3 2.5 3 3 3</td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>C</td>
<td>1 1.5 1 3 1 3.5 2 3 2 3 2 3.5</td>
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</tr>
<tr>
<td>Z</td>
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<tr>
<td>MOUNT. ASH</td>
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<tr>
<td>G</td>
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<td></td>
</tr>
<tr>
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</tr>
<tr>
<td>C</td>
<td>1 1.5 2.5 3 2 3.5 1 2 1 1 3 3</td>
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<tr>
<td>Z</td>
<td>2 1.5 3 6 6.3 7 4 5 6 6 8 8</td>
<td></td>
</tr>
<tr>
<td>DOUGLAS FIR</td>
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<td></td>
</tr>
<tr>
<td>G</td>
<td>2 2.5 NOT RATED</td>
<td>2 2 NOT RATED</td>
</tr>
<tr>
<td>B</td>
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<td>RADIATA</td>
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<td></td>
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<td>G</td>
<td>3 3 3.5 3 3 3 3 3 3 3 3 3</td>
<td></td>
</tr>
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<td>2 2 3.5 3.5 2.5 2.5 2 2 2.5 2.5 3 3</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>1 1 3 4 3 3 2.3 2.3 4.5 4.6 4.6</td>
<td></td>
</tr>
<tr>
<td>SPOTTED GUM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>3 1.5 3 2.5 2 2 2 2 3 2.5 3 3</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>2 2 4.5 5 4.5 4.5 2.5 3 5 5 5 5</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1 1.5 3.5 4.5 2.5 4 1.5 2 2.5 4 2.5 4</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>1 3.5 6.5 8 6.5 7 2 3 8 7 5 5</td>
<td></td>
</tr>
</tbody>
</table>
4.5.2 Field Measurement of Nail Corrosion

The mean nail corrosion rates at each of the sites for the five species of timber and four types of nails exposed inside the test enclosures at each site are shown in Figures 4.39 to 4.43.

**Figure 4.39 Mean and Maximum Nail Corrosion - Radiata Pine (December 1997 to December 1999)**

**Figure 4.40 Mean and Maximum Nail Corrosion - Treated Radiata Pine (December 1997 to December 1999)**

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Figure 4.41 Mean and Maximum Nail Corrosion - Spotted Gum (December 1997 to December 1999)

Figure 4.42 Mean and Maximum Nail Corrosion - Mountain Ash (December 1997 to December 1999)
4.5.3 Nail Corrosion Ratings

The corrosion ratings for the heads and shanks of the nails exposed inside the test enclosure at each of the sites are contrasted in Figures 4.44 to 4.48. Uncoated nails were rated on a scale of 0 to 5 and nails coated with zinc products were rated on an extended scale of 0 to 8.
Figure 4.45. Mean Corrosion Ratings - Treated Pine (December 1997 to December 1999)

Figure 4.46 Mean Corrosion Ratings - Spotted Gum (December 1997 to December 1999)
Figure 4.47 Mean Corrosion Ratings - Mountain Ash (December 1997 to December 1999)

Figure 4.48 Mean Corrosion Ratings - Douglas Fir (December 1997 to December 1999)
4.6 Climatic and Atmospheric Aspects in Building Spaces at Wentworth Falls

4.6.1 Temperature

A comparison of the mean hourly temperature in the external test enclosure (external covered conditions) at Wentworth Falls with the mean temperature in the roof space, wall cavity and sub floor space is shown in Table 4.9. Figure 4.49 demonstrates how the temperature changed over twenty four hours in the building spaces as the temperature outside in the test enclosure changed. The graph covers a sample period in the Spring of 1999.

Table 4.9 Relationship Between Mean Temperature in Test Enclosure (external) at Wentworth Falls and Mean Temperature in the Building Spaces (°C)

<table>
<thead>
<tr>
<th>TEST ENCLOSURE</th>
<th>ROOF SPACE</th>
<th>WALL CAVITY</th>
<th>SUB FLOOR SPACE</th>
<th>RATIO OF ROOF / EXTERNAL</th>
<th>RATIO OF WALL CAVITY / EXTERNAL</th>
<th>RATIO OF SUB FLOOR / EXTERNAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14.58</td>
<td>13.96</td>
<td>14.43</td>
<td>14.04</td>
<td>0.96</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Figure 4.49 Relationship of Building Space Temperature to Outside Temperature (Spring 1999, N = 1200)
4.6.2 Relative Humidity

Table 4.10 compares the mean relative humidity in the test enclosure at Wentworth Falls with the mean relative humidity in the roof space, wall cavity and sub floor space.

<table>
<thead>
<tr>
<th>TEST ENCLOSURE</th>
<th>ROOF SPACE</th>
<th>WALL CAVITY</th>
<th>SUB FLOOR SPACE</th>
<th>RATIO OF ROOF / EXTERNAL</th>
<th>RATIO OF WALL CAVITY / EXTERNAL</th>
<th>RATIO OF SUB FLOOR / EXTERNAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>74.24</td>
<td>74.94</td>
<td>71.67</td>
<td>73.12</td>
<td>1.01</td>
<td>0.97</td>
<td>0.98</td>
</tr>
</tbody>
</table>

4.6.3 Salt Deposition

Salt deposition measured in the roof space and sub floor area using vertical salt candles (traditional) indicated that the levels were, for practical purposes, the same as those measured outside the building. The rates of deposition measured during the period 24 October 1998 to 31 July 1999 were 6.56 mg/m².day outside, 6.22 mg/m².day in the roof space and 6.16 mg/m².day in the sub floor area. The sub floor area and roof space of this building were very well ventilated and this may account for the similarity of salt deposition levels measured in these locations to that measured outside.

It was not possible to use vertical salt candles in the wall cavity because of the limited space available. Hence canister type candles were placed in this location as well as in the sub floor, roof space to facilitate comparisons between these places. The results are shown in Table 4.11.
Table 4.11 Salt Deposition Rates within the Building at Wentworth Falls Measured using Canisters – 24 October 1998 to 31 July 1999

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>DEPOSITION (mg/m².day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUB FLOOR</td>
<td>20.22</td>
</tr>
<tr>
<td>WALL CAVITY</td>
<td>18.75</td>
</tr>
<tr>
<td>ROOM</td>
<td>16.83</td>
</tr>
<tr>
<td>ROOF</td>
<td>15.54</td>
</tr>
</tbody>
</table>

4.6.4 Sulphur Dioxide, Nitrogen Dioxide and HNO₃ Levels

The levels of these pollutants measured inside the building are contrasted to those measured outside in Table 4.12.

Table 4.12 Comparison of SO₂, NO₂ and HNO₃ Levels inside the Building at Wentworth Falls with those Mesured Outside - December 1997 to December 1999

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>SO₂</th>
<th>NO₂</th>
<th>HNO₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>INSIDE</td>
<td>0.53</td>
<td>2.74</td>
<td>0.70</td>
</tr>
<tr>
<td>OUTSIDE</td>
<td>0.92</td>
<td>2.32</td>
<td>0.81</td>
</tr>
<tr>
<td>INSIDE / OUTSIDE</td>
<td>0.57</td>
<td>1.18</td>
<td>0.86</td>
</tr>
</tbody>
</table>

4.6.5 Timber Surface Moisture Content

The ratio of the estimated surface moisture content of timber elements in the roof space, wall cavity and sub floor space in the building at Wentworth Falls to the estimated outside surface moisture content of timber in the test enclosure at the site is set out in Table 4.13.
Table 4.13 Ratio of Estimated Mean Surface Moisture Content of Timber Elements to the Estimated Mean Surface Moisture Content of Timber in the External Test Enclosure (N = 4216)

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>RATIO OF MEAN SMC IN LOCATION TO MEAN SMC EXTERNAL TEST ENCLOSURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROOF</td>
<td>0.94</td>
</tr>
<tr>
<td>TOP OF WALL CAVITY</td>
<td>0.77</td>
</tr>
<tr>
<td>CENTRE OF WALL CAVITY</td>
<td>0.81</td>
</tr>
<tr>
<td>BOTTOM OF WALL CAVITY</td>
<td>0.86</td>
</tr>
<tr>
<td>SUB FLOOR</td>
<td>1.02</td>
</tr>
</tbody>
</table>

4.6.6 Timber Near Surface Moisture Content

The mean and maximum near surface moisture content of moisture boards (six species) mounted in the roof space, wall cavity and sub floor area, measured with a moisture meter, are compared with the results for the timber in the external test enclosure in Figures 4.50 to 4.52. Also compared are the mean and maximum moisture contents for all species in these locations.

![Graph showing moisture content for different species and locations](image)

**Figure 4.50** Mean and Maximum Near Surface Moisture Content in Roof and Outside at Wentworth Falls (December 1997 to December 1999)
4.6.7 Total Timber Moisture Content

The mean and maximum total moisture content of moisture boards (six species) mounted in the roof space, wall cavity and sub floor area for the study period are
compared with the results for the test enclosure outside in Figures 4.53 to 4.55. Also compared are the mean and maximum moisture contents for all species.

*Figure 4.53 Mean and Maximum Total Moisture Content of Timber in the Roof Space and Outside at Wentworth Falls (December 1997 to December 1999)*

*Figure 4.54 Mean and Maximum Total Moisture Content of Timber in a Wall Cavity and Outside at Wentworth Falls (December 1997 to December 1999)*
Figure 4.55 Mean and Maximum Total Moisture Content in the Floor Space and Outside at Wentworth Falls (December 1997 to December 1999)

4.6.8 Moisture Content of Timber Building Members

The median moisture content of the timber building elements measured by the resistance between two screws placed approximately 10mm apart and recorded on the data loggers in the building are shown in Table 4.14.
Table 4.14 Median Moisture Content of Building Elements

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>MEDIAN MEASURED MOISTURE CONTENT (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLOOR BEARER</td>
<td>17</td>
</tr>
<tr>
<td>FLOOR JOIST</td>
<td>16</td>
</tr>
<tr>
<td>RAFTER</td>
<td>16</td>
</tr>
<tr>
<td>WALL BOARDS – MID HEIGHT</td>
<td>12</td>
</tr>
<tr>
<td>FLOOR BOARDS</td>
<td>10</td>
</tr>
<tr>
<td>WALL STUD – MID HEIGHT</td>
<td>8</td>
</tr>
<tr>
<td>WALL BOARDS – HIGH LEVEL</td>
<td>9</td>
</tr>
<tr>
<td>WALL BOARDS – LOW LEVEL</td>
<td>9</td>
</tr>
<tr>
<td>DOOR - NORTH</td>
<td>9</td>
</tr>
<tr>
<td>WINDOW - SOUTH</td>
<td>9</td>
</tr>
</tbody>
</table>

4.7 Statistical Analysis of Nail Corrosion

Statistical analysis was carried out with a view to developing regression equations for estimating the corrosion rate of galvanised and bright steel nails. These nails have been used extensively in the study area for building purposes.

Correlation analysis was first used to determine the aspects measured in the study at the test sites having a strong relationship with nail corrosion. Then stepwise regression analysis and the calculation of F ratios were used with a view to confirming the choice of these aspects for inclusion in prediction models.
It was found that the aspect that had the strongest relationship with nail corrosion was near surface moisture content.

The correlation coefficients (Pearsons Product) for mean near surface moisture content, with the mean corrosion rates of bright and galvanised nails are shown in Table 4.15 below.

**Table 4.15** Correlation of Mean Near Surface Timber Moisture Content with Mean Annual Percentage Nail Corrosion Rate (Galvanised and Bright Nails)

<table>
<thead>
<tr>
<th>TIMBER TYPE</th>
<th>NAIL TYPE</th>
<th>CORRELATION COEFFICIENT FOR M.N.S.M.C. AND MEAN NAIL CORROSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>T. PINE</td>
<td>GAL.</td>
<td>0.951</td>
</tr>
<tr>
<td>T. PINE</td>
<td>BRIGHT</td>
<td>0.980</td>
</tr>
<tr>
<td>RADIATA</td>
<td>GAL.</td>
<td>0.875</td>
</tr>
<tr>
<td>RADIATA</td>
<td>BRIGHT</td>
<td>0.922</td>
</tr>
<tr>
<td>DOUGLAS FIR</td>
<td>GAL.</td>
<td>0.834</td>
</tr>
<tr>
<td>DOUGLAS FIR</td>
<td>BRIGHT</td>
<td>0.971</td>
</tr>
<tr>
<td>MOUNTAIN ASH</td>
<td>GAL.</td>
<td>0.771</td>
</tr>
<tr>
<td>MOUNTAIN ASH</td>
<td>BRIGHT</td>
<td>-0.338</td>
</tr>
<tr>
<td>SPOTTED GUM</td>
<td>GAL.</td>
<td>0.099</td>
</tr>
<tr>
<td>SPOTTED GUM</td>
<td>BRIGHT</td>
<td>0.157</td>
</tr>
</tbody>
</table>
Although there was a degree of correlation between other aspects and the mean rate of nail corrosion regression analysis revealed that the mean near surface moisture content accounted for the vast majority of variation in the mean rate of nail corrosion. Inclusion of other aspects as variables in the regression equations did not enhance them. Relatively robust equations were formulated for the softwoods used in the study (Radiata Pine, CCA Treated Radiata Pine and Douglas Fir). This proved not to be possible for the hardwoods used.

It should be noted that the equations developed have the limitation of only being applicable within the bounds of the data sets used to formulate them and they predict mean corrosion rates based on mean near surface moisture content. The regression equations for Radiata Pine, CCA Treated Radiata Pine and Douglas Fir are shown below:

Treated Pine

\[
C_{\text{nail,gal}} = -39.7 + 3.54MC_{\text{mns}}
\]  
(For MNSMC = 13.7% to 16.7%)  \hspace{1cm} (4.1)

SE=1.493 \hspace{0.5cm} R^2=90.5 \% \hspace{0.5cm} R^2 \text{ adj}=88.1 \% \hspace{0.5cm} F=37.94 \hspace{0.5cm} p=0.004

where;

\(C_{\text{nail,gal}}\) = corrosion rate of galvanised nails \((g/m^2\cdot\text{year})\); and

\(MC_{\text{mns}}\) = mean near surface moisture content of CCA Treated Pine (%)

\[
C_{\text{nail, bright}} = -31.7 + 2.56MC_{\text{mns}}
\]  
(For MNSMC = 13.7% to 16.7%)  \hspace{1cm} (4.2)

SE=0.5447 \hspace{0.5cm} R^2=97.4 \% \hspace{0.5cm} R^2 \text{ adj}=96.7 \% \hspace{0.5cm} F=148.82.11 \hspace{0.5cm} p=0.000

where;

\(C_{\text{nail, gal}}\) = corrosion rate of bright nails \((g/m^2\cdot\text{year})\); and

\(MC_{\text{mns}}\) = mean near surface moisture content of CCA Treated Pine (%)
Radiata Pine

\[ C_{nail\_gai} = -23.6 + 2.25MC_{mnsp} \]  \hspace{1cm} (For MNSMC = 13.7\% to 17.5\%) \hspace{1cm} (4.3)

SE=1.907 \hspace{1cm} R^2=79.5\% \hspace{1cm} R^2\text{ adj}=74.3\% \hspace{1cm} F=15.48 \hspace{1cm} p=0.017

where;

\[ C_{nail\_gai} \] = corrosion rate of galvanised nails (g/m².year); and

\[ MC_{mnsp} \] = mean near surface moisture content of Radiata Pine (%)

\[ C_{bright\_nail} = -15.9 + 1.37MC_{mnsp} \]  \hspace{1cm} (For MNSMC = 13.7\% to 17.5\%) \hspace{1cm} (4.4)

SE=1.133 \hspace{1cm} R^2=80.2\% \hspace{1cm} R^2\text{ adj}=75.3\% \hspace{1cm} F=16.25 \hspace{1cm} p=0.016

where;

\[ C_{nail\_bright} \] = corrosion rate of bright nails (g/m².year); and

\[ MC_{mnsp} \] = mean near surface moisture content of Radiata Pine (%)

Douglas Fir

\[ C_{nail\_gai} = -71.0 + 5.82MC_{mnadf} \]  \hspace{1cm} (For MNSMC = 13.7\% to 17\%) \hspace{1cm} (4.5)

SE=4.392 \hspace{1cm} R^2=67.5\% \hspace{1cm} R^2\text{ adj}=59.45\% \hspace{1cm} F=8.30 \hspace{1cm} p=0.045

where;

\[ C_{nail\_gai} \] = corrosion rate of galvanised nails (g/m².year); and

\[ MC_{mnadf} \] = mean near surface moisture content of Douglas Fir (%)

\[ C_{nail\_bright} = -44.2 + 3.23MC_{mnadf} \]  \hspace{1cm} (For MNSMC = 13.7\% to 17\%) \hspace{1cm} (4.6)

SE=0.7149 \hspace{1cm} R^2=96.0\% \hspace{1cm} R^2\text{ adj}=95.0\% \hspace{1cm} F=96.76 \hspace{1cm} p=0.001

where;

\[ C_{nail\_bright} \] = corrosion rate of bright nails (g/m².year); and

\[ MC_{mnadf} \] = mean near surface moisture content of Douglas Fir (%)

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4.8 Condition Surveys

Details of the outcomes of the building condition surveys are shown in Appendix 1. The observations of the surveys were consistent with the results of the field measurement of environmental aspects. For example:

- timber decay at Wentworth Falls was greatest in the floor area where the moisture content was highest and the drainage poor, otherwise as the climatic data suggested the floor was in a good condition;

- at Illawong there was decay in external timber elements where the detailing of the joints was poor and primer had not been used; appropriately detailed elements were in sound condition and

- nail head corrosion and consequent timber decay was evident on the wall lining boards on the southern and eastern walls of the building at Little Bay where an extension had been constructed and the boards had apparently been painted with acrylic paint only; in other locations where appropriate paint systems have been used nail corrosion was not evident.
CHAPTER 5
DISCUSSION OF RESULTS

5.1 Climatic Aspects During Study Period

5.1.1 Rainfall

It can be seen from comparing the results in Figure 4.1 (Chapter 4) and the data in Table 3.1 (Chapter 3) that the rainfall during the study period was consistent with the long term averages recorded by the Bureau of Meteorology. The elevated site at Wentworth Falls, and the coastal and near coastal sites of Illawong, the CBD, Little Bay and Coledale had relatively high rainfalls whilst the site at Richmond, in the Nepean – Hawkesbury Basin had approximately two thirds the rainfall of the other locations.

The number of sites used for this study was relatively small. To assist in making assessments of relative risk in relation to this aspect at other places the mean annual rainfall recorded at Bureau of Meteorology sites in the Sydney region was obtained and is shown in Table A2.1 in Appendix 2 (Bureau of Meteorology 2002).

5.1.2 Temperature

The results obtained were generally consistent with the long term Bureau of Meteorology data. For example the long term mean monthly temperatures recorded by the Bureau in the vicinity of Wentworth Falls and the CBD are 16.7°C and 21.5°C and the mean hourly temperatures recorded during the study period at the sites were 15°C and 20°C. It was also apparent from the similarity of the two sets of data that the test enclosures used in the study
did not have any undue influence on the results. They provided shelter to the test equipment and specimens in them from rain but were well ventilated.

Because of periodic data logger failures there appears to be little advantage in using this type of equipment over long durations rather than using Bureau data unless reliability can be improved. It could not be demonstrated that there is a sustainable accuracy advantage. The data loggers were found to be relatively useful in measuring very localised conditions for relatively short periods e.g., measuring and comparing conditions in the various building cavities.

The lowest winter temperature was recorded at the inland site of Richmond. The highest of the minimum temperatures was recorded at Coledale on the coast. The highest summer temperature was recorded at the Richmond site and the lowest maximum temperature was recorded at Coledale.

The moderating influence of the ocean on the temperature range near the coast was evident from the results. Similarly the effects of the geography at Richmond were apparent from the temperature extremes at that site. The effect of the cold air sliding down from the nearby mountains into the Nepean – Hawkesbury Basin was particularly apparent when contrasting the winter temperatures at this site with those at Wentworth Falls.

The relative extremes of temperature recorded at the Wentworth Falls and Richmond sites could be expected to result in greater stress in the surface fibres of exposed timber. This
may result in more extensive splitting of timber at these sites than at the other sites in the study area.

The number of sites used for this study was relatively small. To assist in making assessments of relative risk at other places in relation to this aspect long term Bureau of Meteorology data on mean 9 a.m. and 3 p.m. temperatures across the Sydney region was obtained and is shown in Tables A2.2 and A2.3 in Appendix 2 (Bureau of Meteorology 2002).

5.1.3 Relative Humidity

Comparison of the relative humidity results for the study period with the long term Bureau of Meteorology data indicated that the former was consistent with the latter. For example the mean monthly 9 a.m. relative humidity levels recorded by the Bureau in the vicinity of Wentworth Falls and CBD were 71% and 68 % respectively. The mean hourly relative humidity levels recorded in the study period were 74% and 66%. It was also apparent from comparing the two sets of data that the design of the test enclosure did not unduly distort the relative humidity results for the study and that they were a reasonable indicator of this aspect outside.

Although there were difficulties with the data loggers used due to the unpredictability of the battery life, it was not believed that this introduced a significant level of error as the number of successful readings was large and spread over a two year period.
The extremes of relative humidity were recorded in the CBD and at Little Bay. The CBD had the lowest recorded levels. This site was close to the marine influences of Sydney Harbour, which could have been expected at first glance to increase relative humidity; however on the other hand the site was in a very heavily developed environment, which may have had a strong diminishing effect.

Little Bay had significantly higher levels of relative humidity than all other sites including the other marine site of Coledale. Hence the timber decay and corrosion risk levels at this site were considered higher in respect of this aspect. This reinforced the proposition that risk levels can vary within relatively small geographic areas.

As a guide to the variation in relative humidity that can be expected across the region the map shown as Figure A2.1 in Appendix 2 (produced using the computer software Surfer and MapInfo) has been constructed using mean monthly 3 p.m. relative humidity data available from the Bureau of Meteorology internet site (Bureau of Meteorology 2002). Two sets of data are generally available for relative humidity at Bureau sites, 9 a.m. and 3 p.m.. The differences between the sites are more evident from the 3 p.m. data.

5.2 Corrosion Risk Aspects

5.2.1 ISO Time of Wetness

The highest time of wetness results (time that relative humidity exceeded 80%) were recorded at the marine sites of Little Bay and Coledale making this the highest risk
environment in relation to the effects of this aspect on corrosivity and timber decay. The risk level in the CBD was very low and at all other sites relatively moderate.

The low result for the CBD may have been attributable to the highly developed environment around the test enclosure.

Given the large number of relative humidity readings taken at each site the time of wetness results were considered to have a high order of accuracy.

The map shown as Figure A2.2 in Appendix 2 indicates the relative levels of time of wetness results at the test sites. There was insufficient data available to prepare a map indicating the time of wetness that might be expected at other locations within the region. The results of the study provide some guidance in relation to other locations of similar geography.

5.2.2 Rainwater pH

The differences in rainwater pH between sites were not great and the resulting levels of risk to corrosion were not considered high. The mean pH levels at the sites used in this study are indicated on the rainwater chemistry map shown as Figure A2.3 in Appendix 2. The similarity in mean pH levels at the sites despite the differences in geography is apparent from this map.
5.2.3 Rainwater Conductivity

Conductivity was greatest near the coast. It therefore appears reasonable to assume that the sea salt content of the water had a significant influence on this aspect. However it must be remembered that the areas of greatest development are also near the coast and resultant pollutants may have had an impact on rainwater conductivity.

If conductivity is used as a measure of risk in relation to corrosion then the area immediately adjacent to the coast might be rated as high risk, the area within approximately 10km of the coast could be regarded as being a moderate risk zone and beyond a low risk zone. The variation in rainwater conductivity in relation to the distance from the coast of the test sites is illustrated from the results shown marked on the rainwater chemistry map shown at Figure A2.3 in Appendix 2.

5.2.4 Rainwater Salt Content

The results indicated that (as was the case with conductivity) rainwater salt content was greatest adjacent to the coast, diminished rapidly within a short distance and then decreased slowly towards the western extreme of the study area.

In a similar way to conductivity, rainwater salt content levels, if used as a risk indicator for corrosion, might be categorised into three zones i.e., high near the coast, moderate from this zone to approximately 10 km inland and relatively low and constant towards the extremities of the region.
The rainwater was collected using a rain gauge. This water would have contained airborne salts that had been deposited on the funnel of the gauge and subsequently washed into the collection container. Hence the conductivity, pH and salt results might be considered to reflect total atmospheric levels rather than just rainwater levels. As the collection method used was the same for all the sites this influence/error would have been consistent. It was not considered to have adversely affected comparison of the risks at the various locations. The meter used to test the rainwater was calibrated using standard solutions before each occasion of use. Consequently the level of accuracy of the readings was considered relatively high. The map shown as Figure A2.3 in Appendix 2 shows the mean rainwater salt content at each of the sites. The relationship of the distance from the coast of the sites to the rainwater salt content is evident from this map.

5.2.5 Deposition of Salt from the Atmosphere

Figure 4.11 (Chapter 4) suggests that if this aspect were to be used as an indicator of corrosion risk, the region might be divided into three zones. The results indicated that the highest risk was immediately adjacent to the coast. The risk was moderate and relatively constant for the remainder of the region.

It was apparent from the results that local topography had a dampening effect on the level of deposition. The unsheltered site at Richmond experienced slightly higher risk levels than the sites at Illawong and the CBD, which had sheltering from natural and built landscape features, despite the Richmond site being further away from the coast than the other two sites. This is consistent with the findings of Paterson (Paterson 2001).
The level of accuracy of the air salt results was considered to be high due to the number of samples collected and the fact that the study was conducted over two years.

The measured levels of salt deposition at the sites were compared to estimates calculated using the equations (2.27) to (2.29) developed by Leicester et. al shown in Chapter 2 (Leicester 2000). Refer to Table 5.1.

**Table 5.1** Mean Daily Salt Deposition Measured at Study Sites Compared to Estimates Calculated Using Models Developed by Leicester (2000). (mg/m².day)

<table>
<thead>
<tr>
<th>SITE</th>
<th>MEAN MEASURED SALT DEPOSITION</th>
<th>ESTIMATED SALT DEPOSITION</th>
<th>COAST COMPONENT OF ESTIMATE</th>
<th>OCEAN COMPONENT OF ESTIMATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>WENTWORTH FALLS</td>
<td>5.2</td>
<td>3.9</td>
<td>&lt;0.1</td>
<td>3.9</td>
</tr>
<tr>
<td>RICHMOND</td>
<td>13.3</td>
<td>4.6</td>
<td>&lt;0.1</td>
<td>4.6</td>
</tr>
<tr>
<td>ILLAWONG</td>
<td>6.5</td>
<td>5.5</td>
<td>&lt;0.1</td>
<td>5.5</td>
</tr>
<tr>
<td>CBD</td>
<td>5.8</td>
<td>6.8</td>
<td>1.0</td>
<td>5.8</td>
</tr>
<tr>
<td>LITTLE BAY</td>
<td>72.3</td>
<td>35.4</td>
<td>29.4</td>
<td>6.0</td>
</tr>
<tr>
<td>COLEDALE</td>
<td>71.0</td>
<td>38.1</td>
<td>32.1</td>
<td>6.0</td>
</tr>
</tbody>
</table>

It is evident from Table 5.1 that the equations developed by Leicester et.al. may underestimate the levels of salt deposition within the region. It is also apparent from review of Table 5.1 that this potential under estimate is attributable largely to the equation for estimating salt deposition due to wave action near the shoreline (equation 2.28). For example the mean measured daily salt deposition at Little Bay and Coledale, sites that are approximately 0.2 and 0.05 km respectively from the shoreline, were 72.3 and 71.6
mg/m².day whereas the estimates based on Leicester's equations were 35.4 and 38.1 mg/m².day.

In Table 5.2 below the measured levels of salt deposition at the sites used in the study are compared to estimates of salt deposition calculated using equations 2.3 and 2.4 developed by Cole et.al. (2002).

**Table 5.2 Mean Measured Daily Salt Deposition Levels Compared to Estimates Based on Equations Developed by Cole et. al. (2002) (mg/m².day)**

<table>
<thead>
<tr>
<th>SITE</th>
<th>MEAN MEASURED DAILY SALT DEPOSITION</th>
<th>ESTIMATED DAILY SALT DEPOSITION</th>
<th>RATIO OF MEASURED SALT DEPOSITION TO ESTIMATED SALT DEPOSITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>WENTWORTH FALLS</td>
<td>5.2</td>
<td>5.5</td>
<td>0.95</td>
</tr>
<tr>
<td>RICHMOND</td>
<td>13.3</td>
<td>10.0</td>
<td>1.32</td>
</tr>
<tr>
<td>ILLAWONG</td>
<td>6.5</td>
<td>20.9</td>
<td>0.31</td>
</tr>
<tr>
<td>CBD</td>
<td>5.8</td>
<td>26.7</td>
<td>0.22</td>
</tr>
<tr>
<td>LITTLE BAY</td>
<td>72.3</td>
<td>102.2</td>
<td>0.71</td>
</tr>
<tr>
<td>COLEDALE</td>
<td>71.0</td>
<td>257.5</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Cole et. al. (2002) have determined that salt deposition rates at sites that have sheltering similar to that at Little Bay (sheltered at the sides by adjacent structures) are approximately two thirds of what they might otherwise be without this sheltering. If the sheltering at Little Bay is taken into account as suggested by Cole when comparing estimates based on Cole’s and Leicester’s equations with measured levels, the estimates based on Cole’s equations appear to be more accurate for the near coastal margin.
A map showing estimated salt deposition rates across the region calculated using the equations developed by Cole et.al. is shown as Figure A2.4 of Appendix 2 (produced using the computer software Surfer and MapInfo). The map assumes there is no sheltering. It also assumes that the shoreline surf generated salt deposition rate is 355 mg/m².day and the ocean generated shoreline salt deposition rate is 30 mg/m².day. These values were consistent with the findings of Cole et.al. (2002) for sites to the north and south of Sydney and the measured results for Little Bay (taking into account the sheltering factor proposed by Cole for sites similar to Little Bay).

The ratio of measured to estimated salt deposition rates shown in Table 5.2 and / or the sheltering factors proposed by Cole et. al. (2002) might be used with the map shown as Figure A2.4 of Appendix 2 to prepare first pass estimates of deposition rates at sites having similar geography and sheltering. Table 5.3 sets out the type of sheltering at each of the study sites and reiterates the ratio of the mean measured daily salt deposition rate to the estimated daily salt deposition rate.
Table 5.3 Ratio of Measured Salt Deposition to Estimated Salt Deposition According to Site Topography and Sheltering

<table>
<thead>
<tr>
<th>SITE</th>
<th>DESCRIPTION OF SHELTERING AND TOPOGRAPHY</th>
<th>RATIO OF MEASURED SALT DEPOSITION TO ESTIMATED SALT DEPOSITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>WENTWORTH FALLS</td>
<td>VERY HILLY, WOODED</td>
<td>0.95</td>
</tr>
<tr>
<td>RICHMOND</td>
<td>FLAT PLAIN, RURAL/URBAN, LITTLE SHELTERING</td>
<td>1.32</td>
</tr>
<tr>
<td>ILLAWONG</td>
<td>HILLY, SUBURBAN, SHELTERED BY ADJACENT HOUSES AND VEGETATION</td>
<td>0.31</td>
</tr>
<tr>
<td>CBD</td>
<td>FLAT, HEAVILY DEVELOPED, HEAVILY SHELTERED BY ADJACENT COMMERCIAL BUILDINGS (SOME HIGH RISE)</td>
<td>0.22</td>
</tr>
<tr>
<td>LITTLE BAY</td>
<td>RISING, NEAR SHORELINE, SHELTERED TO THE SIDES BY STRUCTURES, OPEN TO OCEAN AND SURF AT FRONT</td>
<td>0.71</td>
</tr>
<tr>
<td>COLEDALE</td>
<td>STEEPLY RISING, SHELTERED AT FRONT AND SIDES BY NATURAL AND MAN MADE SMALL SCALE STRUCTURES AND LANDSCAPE FEATURES</td>
<td>0.28</td>
</tr>
</tbody>
</table>

It should be cautioned that the number of sites used for the study was relatively small and estimates based on the results should consequently be treated with caution.

The mean measured salt deposition rate at Richmond was somewhat higher than the estimate for this site calculated using the equations developed by Cole et. al. It is believed that this may be attributable to the very open nature of the site, local wind conditions and air movement patterns.
5.2.6 Sulphur Dioxide Levels

The results revealed a close relationship between the levels of sulphur dioxide measured and the extent of human activity taking place in the vicinity. The measured levels of SO$_2$ in the CBD were approximately four times those measured at the bushland site of Wentworth Falls. Generally SO$_2$ levels diminished as the distance from the CBD to the respective sites increased. However the level at Coledale was slightly higher than might have been expected. This site is approximately 21 km from the southern industrial centre of Port Kembla, which may also have influenced SO$_2$ levels. This underlines the importance of identifying local factors that can affect individual locations.

It would seem reasonable from the results to use the distance from the CBD as an indicator of relative risk in relation to the corrosive effects of SO$_2$.

Sources of potential error in the results for this aspect related mainly to the diffusion rate of the gas in the air and the geometry of the samplers used. For example the gauze, filter paper and geometry of the sampler tube causes resistance. Distortion of the gauze in samplers can also create error. The CSIRO Division of Atmospheric Research who produced and processed the samplers advised that the accuracy in respect of SO$_2$ measurements was approximately plus or minus 20%. This was considered acceptable for the purposes of this study.

The statistical analysis carried out did not indicate that this aspect posed a high corrosion risk in the study area generally. However the possibility of higher concentrations of this
pollutant having an effect on a material on a localised basis can not be ruled out. Table 5.4 lists sites in the Sydney region with annual reported emissions of SO₂ of 10,000 kg or more for the reporting year of 2000 to 2001 (Environment Australia 2002). The location of these sites is shown on a map at Figure A2.5 in Appendix 2. Figure A2.6 is a map showing SO₂ levels recorded at Environment Protection Agency air quality monitoring sites across the Sydney Region (Environment Protection Authority 1999). The levels measured at the sites used in this study are also indicated on the map. The table and maps may assist in identifying potential hot spots affecting material degradation.

Reported emission levels may have inaccuracies and are likely to vary from year to year. Hence discretion should be used in the use of Table 5.4 and Figures A2.5 and A2.6 and their inclusion in this document is not intended to indicate there is actual material degradation associated with particular sites.
Table 5.4 Sites in the Sydney Region Reporting SO₂ Emissions of 10,000 kg or Greater

(Reporting Year 2000 – 2001)

<table>
<thead>
<tr>
<th>No.</th>
<th>SITE</th>
<th>LATITUDE</th>
<th>LONGITUDE</th>
<th>EMISSIONS (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Shell Refinery, Durham St, Rosehill</td>
<td>-33.824</td>
<td>151.037344</td>
<td>6200000</td>
</tr>
<tr>
<td>2</td>
<td>Caltex Refinery, Solander St, Kurnell</td>
<td>-34.018447</td>
<td>151.201188</td>
<td>3100000</td>
</tr>
<tr>
<td>3</td>
<td>Continental Copper,Sir Joseph Banks Dr., Kurnell</td>
<td>-34.029025</td>
<td>151.21394</td>
<td>850000</td>
</tr>
<tr>
<td>4</td>
<td>ACI Glass Packaging, Adrews Rd, Penrith</td>
<td>-33.735131</td>
<td>150.716097</td>
<td>430000</td>
</tr>
<tr>
<td>5</td>
<td>Qenos Olefines &amp; Site Utilities, Beuchamp Rd, Matraville</td>
<td>-33.956085</td>
<td>151.220876</td>
<td>370000</td>
</tr>
<tr>
<td>6</td>
<td>Pilkington Australia, Williams Rd, Ingleburn</td>
<td>-33.988856</td>
<td>150.841016</td>
<td>320000</td>
</tr>
<tr>
<td>7</td>
<td>Austral Brick Company, Walgrove Rd Horsely Park</td>
<td>-33.825942</td>
<td>150.849205</td>
<td>240000</td>
</tr>
<tr>
<td>8</td>
<td>PGH Bricks and Pavers, Cecil Rd, Cecil Park</td>
<td>-33.869642</td>
<td>150.833517</td>
<td>120000</td>
</tr>
<tr>
<td>9</td>
<td>Boral Bricks, Greendale Rd, Bringelly</td>
<td>-33.93977</td>
<td>150.72356</td>
<td>56000</td>
</tr>
<tr>
<td>10</td>
<td>PGH Bricks and Pavers, Townsen Rd, Schofields</td>
<td>-33.766742</td>
<td>150.871285</td>
<td>54000</td>
</tr>
<tr>
<td>11</td>
<td>Australian Refined Alloys, Euston Rd, Alexandria</td>
<td>-33.905637</td>
<td>151.192043</td>
<td>38000</td>
</tr>
<tr>
<td>12</td>
<td>CSR Monier Wunderlich, Grand Ave, Rosehill</td>
<td>-33.827823</td>
<td>151.02905</td>
<td>37000</td>
</tr>
<tr>
<td>13</td>
<td>Austral Bricks, Midson Rd, Eastwood</td>
<td>-33.784321</td>
<td>151.072165</td>
<td>36000</td>
</tr>
<tr>
<td>14</td>
<td>PGH Bricks and Pavers, Walgrove Rd Horsley Park</td>
<td>-33.822164</td>
<td>150.826612</td>
<td>25000</td>
</tr>
<tr>
<td>15</td>
<td>P&amp;O Ports Port Botany Terminal, Friendship Rd, Matraville</td>
<td>-33.972272</td>
<td>151.217833</td>
<td>21000</td>
</tr>
<tr>
<td>16</td>
<td>CSR Emoleum, Unwin St, Rosehill</td>
<td>-33.825112</td>
<td>151.024517</td>
<td>19000</td>
</tr>
<tr>
<td>17</td>
<td>Maldon Cement Works, Maldon Bridge Rd, Picton</td>
<td>-34.189837</td>
<td>150.634523</td>
<td>17000</td>
</tr>
<tr>
<td>18</td>
<td>Dairy Farmers, Birnie Ave, Lidcombe</td>
<td>-33.855967</td>
<td>151.060915</td>
<td>12000</td>
</tr>
<tr>
<td>19</td>
<td>Thornleigh Malthouse, Pioneer Ave, Thornleigh</td>
<td>-33.725881</td>
<td>151.083292</td>
<td>10000</td>
</tr>
</tbody>
</table>
5.2.7 Nitrogen Dioxide Levels

The statistical analysis carried out did not indicate that this aspect posed a high risk in the study area.

The sources of potential error in the results for this aspect were the same as those for SO₂. The CSIRO advised that the accuracy in respect of NO₂ was approximately plus or minus 15%.

The measured levels of NO₂ diminished proportionately as the distance from the CBD increased in an almost straight-line relationship. The distance from the CBD is therefore considered to be a reasonable overall risk indicator in relation to the level of NO₂ and the consequent risk of corrosion from this aspect. However when considering a particular site it must be emphasised that local sources of this pollutant that might create hot spots need to be identified.

Tables 5.5.a and 5.5.b list sites in the Sydney region with annual reported emissions of NO₂ of 10,000 kg or more for the reporting year of 2000 to 2001 (Environment Australia 2002). The location of the sites is also shown on the map at Figure A2.7 in Appendix 2. The map shown as Figure A2.6 indicates the NO₂ levels recorded at Environment Protection Agency air quality monitoring sites across the Sydney Region (Environment Protection Authority 1999) along with the levels measured at the sites used for this study. These tables and maps may assist in identifying potential hot spots affecting material degradation.
Reported emission levels may have inaccuracies and are likely to vary from year to year. Hence discretion should be used in their use. Inclusion in this document is not intended to indicate there is actual degradation associated with particular sites.

**Table 5.5(a) Sites in the Sydney Region Reporting NO₂ Emissions of 10,000 kg or Greater**

(Reporting Year 2000 – 2001)

<table>
<thead>
<tr>
<th>No.</th>
<th>SITE</th>
<th>LATITUDE</th>
<th>LONGITUDE</th>
<th>EMISSIONS (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Caltex Refinery, Solander St, Kurnell</td>
<td>-34.018447</td>
<td>151.201188</td>
<td>1700000</td>
</tr>
<tr>
<td>2</td>
<td>Maldon Cement Works, Maldon Bridge Rd, Picton</td>
<td>-34.189837</td>
<td>150.634523</td>
<td>1500000</td>
</tr>
<tr>
<td>3</td>
<td>ACI Glass Packaging, Andrews Rd, Penrith</td>
<td>-33.735131</td>
<td>150.716097</td>
<td>1200000</td>
</tr>
<tr>
<td>4</td>
<td>Qenos Olefins &amp; Site Utilities, Beauchamp Rd, Matraville</td>
<td>-33.956085</td>
<td>151.220876</td>
<td>620000</td>
</tr>
<tr>
<td>5</td>
<td>Shell Refinery, Durham St, Rosehill</td>
<td>-33.824</td>
<td>151.037344</td>
<td>620000</td>
</tr>
<tr>
<td>6</td>
<td>Continental Copper, Sir Joseph Banks Dr., Kurnell</td>
<td>-34.029025</td>
<td>151.21394</td>
<td>440000</td>
</tr>
<tr>
<td>7</td>
<td>P&amp;O Ports Port Botany Terminal, Friendship Rd, Matraville</td>
<td>-33.972272</td>
<td>151.217833</td>
<td>270000</td>
</tr>
<tr>
<td>8</td>
<td>Austral Brick Company, Walgrove Rd Horsely Park</td>
<td>-33.825942</td>
<td>150.849205</td>
<td>200000</td>
</tr>
<tr>
<td>9</td>
<td>Amcor Packaging Mill, Botany Rd, Matraville</td>
<td>-33.967882</td>
<td>151.226042</td>
<td>160000</td>
</tr>
<tr>
<td>10</td>
<td>EDL Operations, LFG Power Station 2 Lucas Heights</td>
<td>-34.046331</td>
<td>150.969684</td>
<td>100000</td>
</tr>
<tr>
<td>11</td>
<td>Patrick Container Terminal, Penrhn Rd, Port Botany</td>
<td>-33.964278</td>
<td>151.215003</td>
<td>71000</td>
</tr>
<tr>
<td>12</td>
<td>Capral Aluminium, Unwin St, Granville</td>
<td>-33.830024</td>
<td>151.02068</td>
<td>57000</td>
</tr>
<tr>
<td>13</td>
<td>PGH Bricks and Pavers, Cecil Rd, Cecil Park</td>
<td>-33.869642</td>
<td>150.833517</td>
<td>56000</td>
</tr>
<tr>
<td>14</td>
<td>QANTAS Base, Coward St, Mascott</td>
<td>-33.927507</td>
<td>151.1782</td>
<td>49000</td>
</tr>
<tr>
<td>15</td>
<td>Boral Quarry, Railway St, Emu Plains</td>
<td>-33.746985</td>
<td>150.671686</td>
<td>43000</td>
</tr>
<tr>
<td>16</td>
<td>EDL Operations LFG Power Station 1, Lucas Heights</td>
<td>-34.02957</td>
<td>151.000549</td>
<td>41000</td>
</tr>
<tr>
<td>17</td>
<td>KaaL Australia., Kiora Cr, Yenora</td>
<td>-33.862869</td>
<td>150.966094</td>
<td>26000</td>
</tr>
<tr>
<td>18</td>
<td>Boral Bricks, Greendale Rd, Bringelly</td>
<td>-33.93977</td>
<td>150.72356</td>
<td>25000</td>
</tr>
<tr>
<td>19</td>
<td>PGH Bricks and Pavers, Townsen Rd, Schofields</td>
<td>-33.766742</td>
<td>150.871285</td>
<td>25000</td>
</tr>
</tbody>
</table>
Table 5.5(b) Sites in the Sydney Region Reporting NO₂ Emissions of 10,000 kg or Greater

(Reporting Year 2000 – 2001)

<table>
<thead>
<tr>
<th>No.</th>
<th>SITE</th>
<th>LATITUDE</th>
<th>LONGITUDE</th>
<th>EMISSIONS (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>CSR Emoleum, Unwin St, Rosehill</td>
<td>-33.825112</td>
<td>151.024517</td>
<td>25000</td>
</tr>
<tr>
<td>21</td>
<td>EDL Operations LFG Power Station, Crozier Rd, Belrose</td>
<td>-33.714309</td>
<td>151.208505</td>
<td>24000</td>
</tr>
<tr>
<td>22</td>
<td>HCExtractions, Chisolm Rd Kurnell</td>
<td>-34.019741</td>
<td>151.203497</td>
<td>22000</td>
</tr>
<tr>
<td>23</td>
<td>Austral Bricks, Midson Rd, Eastwood</td>
<td>-33.784321</td>
<td>151.072165</td>
<td>22000</td>
</tr>
<tr>
<td>24</td>
<td>West Cliff Colliery, Wedderburn Rd, Appin</td>
<td>-34.113305</td>
<td>150.816752</td>
<td>20000</td>
</tr>
<tr>
<td>25</td>
<td>One Steel Mini Mill, Kellog Rd, Rooty Hill</td>
<td>-33.763445</td>
<td>150.76896</td>
<td>20000</td>
</tr>
<tr>
<td>26</td>
<td>CSR Monier Wunderlich, Grand Ave, Rosehill</td>
<td>-33.827823</td>
<td>151.02905</td>
<td>16000</td>
</tr>
<tr>
<td>27</td>
<td>Solvay Interox,20 McPherson St, Banksmeadow</td>
<td>-33.955946</td>
<td>151.213409</td>
<td>16000</td>
</tr>
<tr>
<td>28</td>
<td>Lidcombe Liquid Waste Plant, Hill Rd Lidcombe</td>
<td>-33.843193</td>
<td>151.060037</td>
<td>15000</td>
</tr>
<tr>
<td>29</td>
<td>Pioneer Quarry, Wallgrove Rd, Eastern Creek</td>
<td>-33.796223</td>
<td>150.821738</td>
<td>15000</td>
</tr>
<tr>
<td>30</td>
<td>CUB Brewery, Broadway, Sydney</td>
<td>-33.884625</td>
<td>151.201137</td>
<td>14000</td>
</tr>
<tr>
<td>31</td>
<td>PGH Bricks and Pavers, Walgrove Rd, Horsley Park</td>
<td>-33.822164</td>
<td>150.826612</td>
<td>13000</td>
</tr>
<tr>
<td>32</td>
<td>Tooheys, 29 Nrang St., Lidcombe</td>
<td>-33.848958</td>
<td>151.047662</td>
<td>12000</td>
</tr>
<tr>
<td>33</td>
<td>Kellog, Swinbourne St., Botany</td>
<td>-33.948722</td>
<td>151.20745</td>
<td>12000</td>
</tr>
<tr>
<td>34</td>
<td>CSR Quarry, Castlereagh Rd, Penrith</td>
<td>-33.726809</td>
<td>150.66697</td>
<td>11000</td>
</tr>
<tr>
<td>35</td>
<td>Austral Tiles, 62 Belmore Rd, Punchbowl</td>
<td>-33.937389</td>
<td>151.057902</td>
<td>10000</td>
</tr>
</tbody>
</table>
5.2.8 HNO₃ Levels

HNO₃ levels at the sites on the boundaries of the study area (Wentworth Falls and Coledale) were approximately half those found at the other sites. The risk of corrosion from this aspect was considered consistent and moderate across the region but low at non urban boundaries.

HNO₃ levels measured at the test sites are shown on the map at Figure A2.6.

The sources of potential error in the results for this aspect were the same as those for SO₂ and NO₂. The CSIRO advised that the accuracy in respect of HNO₃ was approximately plus or minus 20%.

5.2.9 Summary of Site Corrosion Risk Factor Levels

Statistical analysis indicated that the aspects that had the strongest correlation with corrosion levels were those relating to marine salt deposition i.e., salt deposition, rainwater salt content and rainwater conductivity. The correlation between the levels of corrosion measured and the pH, SO₂, NO₂ and HNO₃ levels was not significant.

Table 5.6 sets out the correlation coefficients for the mean corrosion rates of zinc wire on iron core zinccorr units at the study sites and the mean measured levels of marine salt related aspects, SO₂, NO₂ and HNO₃.
Table 5.6 Correlation of Mean Atmospheric Pollutant Levels at Test Sites with Mean Corrosion Levels of Zinc Wire on Iron Core Zincorr Units (Correlation Coefficient)

<table>
<thead>
<tr>
<th>POLLUTANTS</th>
<th>CORRELATION WITH ZINCORR CORROSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt Deposition</td>
<td>0.966</td>
</tr>
<tr>
<td>Rainwater Salt Content</td>
<td>0.950</td>
</tr>
<tr>
<td>Rainwater Conductivity</td>
<td>0.957</td>
</tr>
<tr>
<td>SO₂</td>
<td>0.016</td>
</tr>
<tr>
<td>NO₂</td>
<td>-0.159</td>
</tr>
<tr>
<td>HNO₃</td>
<td>0.320</td>
</tr>
</tbody>
</table>

The correlation of the time of wetness measured at the sites with the mean levels of corrosion was only moderate. For example the correlation coefficient for the time of wetness and the mean level of zinc wire on iron core zincorr units was 0.531. This suggested that the difference in the time of wetness between the sites was not significant in explaining the difference in mean corrosion levels. This was not interpreted to mean that the time of wetness did not contribute to corrosion.

5.3 Relative Corrosivity of the Sites

5.3.1 Corrosivity Measured with Zincorr Units

Corrosivity measured at the marine sites was highest with all three types of cores used (nylon, iron and copper). The levels measured at all other sites were very similar. In the cases of the iron and copper cores the results at the non marine sites were approximately half of those obtained at the marine sites.

The results suggest that corrosivity risk measured using this method might be divided into two risk zones, marine and non marine.
5.3.2 Corrosivity Measured using Copper / Steel Coupons

Corrosion at the coastal sites was found to be approximately twice that at other sites. The corrosion levels at these sites would be classified as Medium, C3 – Marine at Little Bay in terms of the ISO corrosivity categories set out in AS/NZS 2312/1994 and at the high end of Low, C2 at Coledale.

All other sites would be classified as Low, C2 – Arid/Urban. The corrosion levels were approximately at the mid point in the range used to describe this classification i.e., 1.3 to 25 μm/year.

The results were consistent with data published for similar sites in AS/NZS 2312. They were also reasonably consistent with the results for rainwater salt content, conductivity and salt deposition.

The rate of corrosion at Richmond was slightly above that for Illawong despite the former being further from the principal sources of atmospheric pollutants, the ocean and the city.

Two risk zones were evident; marine and non marine. The risk at the marine sites was approximately twice that at non marine sites.

Duplicate plates were used at each site to reduce the level of error in the results. The mean error across the sites was 0.14μm/year which was considered acceptable for the purposes of the study.
5.3.3 Corrosion of Zinc Plates

The corrosion rates at the coastal sites were the highest and two to three times that measured at the non-marine sites. The rates of corrosion were of similar magnitude at the non-marine sites.

Duplicate plates were used at each site to reduce the level of error in the results. The mean error across the sites was 0.004µm/year, which was considered acceptable for the purposes of the study.

5.3.4 Summary of Corrosivity Risk Levels

It was evident that if the region was to be classified in terms of corrosivity there would be two broad classifications, marine and non-marine. These classifications would be approximately equal to ISO 9223 classifications C3 (medium, 25 to 50µm corrosion of mild steel per year, coastal) and C2 (low, 1.3 to 25µm corrosion of mild steel per year, arid / urban) (Standards Australia 1994).

It was observed that sites very close to the shoreline, particularly those that are not afforded shelter by nearby natural or manmade structures are likely to have higher levels of corrosion than suggested by the corrosion rates measured during the study.

A comparison was made between the estimated corrosion rate for mild steel calculated using the equation developed by Cole (2000) for this purpose (equation 2.1) and the levels of corrosion measured at the study sites (refer to Table 5.7 below). It was apparent from
the comparison that the equation developed by Cole under estimated mild steel corrosion rates in the Sydney region.

**Table 5.7** Comparison of Estimated Corrosion of Mild Steel (based on equation 2.1 developed by Cole) and Measured Corrosion at the Study Sites (μm/year)

<table>
<thead>
<tr>
<th>SITE</th>
<th>ESTIMATED CORROSION</th>
<th>MEAN MEASURED CORROSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>WENTWORTH FALLS</td>
<td>2.0</td>
<td>9.0</td>
</tr>
<tr>
<td>RICHMOND</td>
<td>3.6</td>
<td>13.0</td>
</tr>
<tr>
<td>ILAWONG</td>
<td>2.4</td>
<td>10.5</td>
</tr>
<tr>
<td>CBD</td>
<td>4.0</td>
<td>13.5</td>
</tr>
<tr>
<td>LITTLE BAY</td>
<td>12.8</td>
<td>28.5</td>
</tr>
<tr>
<td>COLEDALE</td>
<td>12.5</td>
<td>23.0</td>
</tr>
</tbody>
</table>

Examination of the data set used by Cole (2000) to formulate equation 2.1 indicated that it was very heavily biased towards South East Asian sites where marine salt deposition levels tend to be low and have less influence on the relative levels of corrosion and SO₂ levels tend to be much higher than in Sydney and influence the corrosion rates to a greater extent.

The following regression model was developed from the mean levels of corrosion of the copper steel coupons and salt deposition measured in the study:

\[ C_{steel, mean} = 0.228 \times S_{air} + 9.47 \]  \hspace{1cm} (5.1)

\[ S = 2.565 \hspace{1cm} R^2 = 91.6\% \hspace{1cm} R^2(adj) = 89.4\% \hspace{1cm} p = 0.003 \hspace{1cm} F = 43.36 \]

where;

\[ C_{steel, mean} = \text{mean corrosion rate of mild steel coupons (μm/year); and} \]

\[ S_{air} = \text{salt deposition measured using salt candles (mg/m}^2\cdot\text{day).} \]
This equation and estimated salt deposition rates calculated using equations 2.3 and 2.4 in Chapter 2 (Cole 2000) were used to estimate corrosion rates for copper steel coupons (mild steel) at various distances from the shoreline in the Sydney region. The corrosion rates are set out in Table 5.8 below.

**Table 5.8** Estimated Mean Copper Steel Corrosion Rates at Various Distances from the Shoreline in the Sydney Region (µm/year)

<table>
<thead>
<tr>
<th>DISTANCE FROM THE SHORELINE (km)</th>
<th>ESTIMATED CORROSION (µm/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>96.2</td>
</tr>
<tr>
<td>0.2</td>
<td>32.7</td>
</tr>
<tr>
<td>0.5</td>
<td>21.7</td>
</tr>
<tr>
<td>1</td>
<td>19.3</td>
</tr>
<tr>
<td>5</td>
<td>15.9</td>
</tr>
<tr>
<td>10</td>
<td>15.3</td>
</tr>
<tr>
<td>30</td>
<td>13.4</td>
</tr>
<tr>
<td>60</td>
<td>11.8</td>
</tr>
<tr>
<td>90</td>
<td>10.9</td>
</tr>
</tbody>
</table>

The estimates in Table 5.8 indicate that for the sites very close to the shoreline the applicable ISO 9223 corrosivity classification would be C5 (very high, 80 to 190 µm/year, seashore) (Standards Australia 1994).

The estimates shown in Table 5.8 have been used to prepare the map at Figure A2.8 in Appendix 2 (produced using the computer software Surfer and MapInfo) which might be used as a guide to the corrosivity of the Sydney region in respect of mild steel.

A regression equation was also formulated from mean measured zinc wire on iron core zinccorr unit corrosion results and mean salt deposition rates at test sites to facilitate
estimating zincorr corrosion rates at other locations within the Sydney region. Iron core zincorr units were selected as they are reported to be more sensitive to marine influences (found to be the predominant aspect in relation to corrosion in the region).

The regression equation was:

\[ C_{r,\text{zincorr, iron mean}} = 0.0741S_{\text{air}} + 3.44 \]  \hspace{1cm} (5.2)

\[ S = 0.7354 \quad R^2 = 93.3\% \quad R^2(\text{adj}) = 91.6\% \quad F = 55.59 \quad p = 0.002 \]

where:

- \( C_{r,\text{zincorr, iron mean}} \) = mean rate of corrosion of zinc wire on iron core zincorr units (index number); and
- \( S_{\text{air}} \) = salt deposition measured using salt candles (mg/m².day).

The estimated zincorr indices for zinc wire on iron core zincorr units at sites at various distances from the shoreline are set out in Table 5.9.

**Table 5.9** Estimated Mean Zinc Wire on Iron Core Zincorr Corrosion at Various Distances from the Shoreline in the Sydney Region (index number)

<table>
<thead>
<tr>
<th>DISTANCE FROM THE SHORELINE (km)</th>
<th>ESTIMATED CORROSION (index number)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>0.2</td>
<td>11</td>
</tr>
<tr>
<td>0.5</td>
<td>7</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>60</td>
<td>4</td>
</tr>
<tr>
<td>90</td>
<td>4</td>
</tr>
</tbody>
</table>
A map of the Sydney region (produced using the computer software Surfer and MapInfo) prepared using the data set out in Table 5.9 is shown as Figure A2.9 in Appendix 2. This map might be used as a general indication of corrosivity of locations across the region.

A comparison of the measured corrosion of zinc plates at the test sites was made with corrosion rates estimated for those sites using equation 2.2 developed by Cole (2000).

In calculating the estimates the measured levels of rainwater pH, salinity and SO₂ obtained at the sites in the study were used. The estimates and measured corrosion rates are shown in Table 5.10.

**Table 5.10** Comparison of Estimated Zinc Plate Corrosion using equations developed by Cole (2000) and Mean Measured Rates of Corrosion at Test Sites (μm/year)

<table>
<thead>
<tr>
<th>SITE</th>
<th>ESTIMATED CORROSION</th>
<th>MEASURED CORROSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>WENTWORTH FALLS</td>
<td>4.2</td>
<td>3.05</td>
</tr>
<tr>
<td>RICHMOND</td>
<td>4.4</td>
<td>2.25</td>
</tr>
<tr>
<td>ILAWONG</td>
<td>1.4</td>
<td>0.75</td>
</tr>
<tr>
<td>CBD</td>
<td>1.3</td>
<td>0.65</td>
</tr>
<tr>
<td>LITTLE BAY</td>
<td>2.6</td>
<td>0.6</td>
</tr>
<tr>
<td>COLEDALE</td>
<td>1.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>

It is apparent that the equation developed by Cole (2000) tends to over estimate the corrosion rate for zinc plates in the Sydney region. A possible explanation is that the data set used to formulate this model included very few for Australia and Australian conditions.
The regression equation below was developed from mean measured corrosion rates for zinc plates at the test sites and the mean salt deposition rates. It may be used to estimate zinc plate corrosion rates at other sites in the region.

\[
C_{r,zinc,mean} = 0.0301 \times S_{air} + 0.478
\]  

\[
S = 0.3392 \quad R^2 = 91.5\% \quad R^2(\text{adj}) = 89.4\% \quad F=43.06 \quad p=0.003
\]

where;

\(C_{r,zinc,mean}\) = Mean corrosion rate of zinc plates (\(\mu m/\text{year}\)); and

\(S_{air}\) = salt deposition measured using salt candles (mg/m\(^2\).day).

The estimated corrosion rates calculated using this model (fits) are compared to the measured rates at the study sites in Table 5.11.

**Table 5.11** Comparison of Zinc Plate Corrosion Estimated Using Regression Equations to Measured Rates in the Sydney Region (\(\mu m/\text{year}\))

<table>
<thead>
<tr>
<th>SITE</th>
<th>ESTIMATED CORROSION</th>
<th>MEASURED CORROSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>WENTWORTH FALLS</td>
<td>2.62</td>
<td>3.05</td>
</tr>
<tr>
<td>RICHMOND</td>
<td>2.65</td>
<td>2.25</td>
</tr>
<tr>
<td>ILAWONG</td>
<td>0.65</td>
<td>0.75</td>
</tr>
<tr>
<td>CBD</td>
<td>0.67</td>
<td>0.65</td>
</tr>
<tr>
<td>LITTLE BAY</td>
<td>0.88</td>
<td>0.6</td>
</tr>
<tr>
<td>COLEDALE</td>
<td>0.63</td>
<td>0.8</td>
</tr>
</tbody>
</table>
5.4 Site Timber Decay Risk Factors

5.4.1 Timber Surface Moisture Content

The calculated mean moisture content of the air surrounding timber (surface moisture) at the sites reflected their ranking in relation to time of wetness and relative humidity. The highest level was at Little Bay and the lowest in the CBD.

The calculated levels of surface moisture appeared high. However the calculation method used took no account of the properties of timber and hence was not considered to be as satisfactory as other indicators of potential decay.

5.4.2 Near Surface Moisture Content

The near surface moisture content of Mountain Ash, Douglas Fir and Radiata Pine at Little Bay were relatively high and somewhat close to the decay threshold. In the case of the other species and the other sites the results were similar and apparently not excessive. This suggested that the region could generally be divided into two risk level categories for timber in covered conditions i.e., near coastal moderate risk and urban/inland low risk.

Due to the natural variability within timber species the results for this aspect would not necessarily be representative of all timber within these species. However this potential error was minimised by using three replicates for each species. In addition the moisture meter used to measure near surface moisture was calibrated according to the manufacturers instructions.
5.4.3 Timber Total Moisture Content

None of the species exposed at any of the sites had mean total moisture contents in excess of 18%. However several of the species at some of the sites had periods when the maximum total moisture content approached the point where timber decay could be sustained if it developed. For example at Wentworth Falls and Illawong the Mountain Ash, Douglas Fir and Treated Radiata Pine boards had maximum total moisture contents of 18%. The results were similar for Little Bay where the same species had maximum total moisture contents of approximately 16% to 17%. These species have relatively low densities compared to the other species exposed i.e., Spotted Gum and Brush Box.

The results suggested that well detailed timber members are not likely to decay in the Sydney Region. However poor detailing which tends to amplify moisture content was considered very likely to result in decay. Timbers that have low densities would seem particularly susceptible.

It was apparent that the risks associated with total moisture content only varied slightly across the Region.

5.4.4 Moisture Content of Painted Timber

Boards at all sites tended to have significantly higher moisture contents where primer was not used. The mean moisture content was less than 18% at all sites. However moisture levels in boards without primer at Wentworth Falls, Illawong, Little Bay and Coledale
experienced periods where the moisture content exceeded 18%. None of the boards at any of the sites that had primer experienced moisture contents above 18%.

The mean total moisture content levels for all of the sites aggregated were 12% for primed Radiata and 14% for unprimed Radiata. The mean total timber moisture content for all of the Radiata Pine boards in the test enclosures at all of the sites was 12%. It was apparent therefore that timber prepared with oil based primer afforded an adequate level of protection from moisture penetration, whereas timber not prepared in this way was subject to significant additional risk.

It appeared reasonable to conclude that in the Sydney Region soft woods such as Radiata Pine that are not primed with oil based primer and used externally are likely to be subject to decay if prolonged periods of precipitation or high humidity are experienced.

In view of the higher levels of moisture in unprimed timber it was apparent that corrosion of fixings in this situation would be more extensive than in primed timber. The level of risk appeared to be greatest at sites very near the coast such as Little Bay. The level of risk at the other sites was relatively consistent and more moderate.

The paint used in the study was applied by hand hence there would have been some variation in the paint cover on the boards used. This would have resulted in some variation in the protection given to the boards from moisture penetration. However care was taken to apply the paint evenly and each board was given the same number of coats. These measures were considered to afford an adequate level of accuracy.
5.4.5 Timber Decay Risk Levels in the Sydney Region Generally

As timber moisture content levels were only measured at six sites across the Sydney region means of estimating moisture at a wider range of sites were explored. To this end long term mean 9 a.m. and 3 p.m. relative humidity data obtained from the Bureau of Meteorology (Bureau of Meteorology 2002) was used in conjunction with Bramhall’s equation (equation 2.8) to estimate the surface moisture content of timber at these times for the sites (Cole, Ganther & Norberg 1996). The Bureau data did not always cover the same period. However the size of the data set available for each site was sufficient to regard the mean levels of relative humidity as long term and reasonably representative for the locations.

Moisture content at the Bureau of Meteorology sites was also estimated using the 9 a.m. and 3 p.m. annual average relative humidity and average rainfall data for the sites in conjunction with the equations developed by Bragg (1986), (equations 2.15 and 2.16).

The results of this analysis were not directly comparable to the data collected by measurement during the study as they consisted of estimates based on data for specific times of the day (9 a.m. and 3 p.m.) whereas the measured moisture content data was obtained at different time intervals. For example the surface moisture contents calculated for the study sites were based on average hourly relative humidity. Similarly the measurements of near surface and total moisture content taken at the sites were collected monthly and presented as means for the study period. Further in most cases the Bureau of Meteorology sites were some distance from the study sites.
In relation to the moisture contents based on Bragg’s equations the range of timbers used in that study was somewhat different to the range monitored at the study sites.

The estimates of moisture content based on the Bureau of Meteorology data are shown in Table 5.12.
Table 5.12 Estimated Timber Moisture Content at Bureau of Meteorology Sites in the Sydney Region (%)

<table>
<thead>
<tr>
<th>SITE</th>
<th>EMC ESTIMATED USING BRAGG'S EQUATION (9 A.M. DATA)</th>
<th>EMC ESTIMATED USING BRAGG'S EQUATION (3 P.M. DATA)</th>
<th>9 A.M. EMC ESTIMATED USING BRAMHALL'S EQUATION</th>
<th>3 P.M. EMC ESTIMATED USING BRAMHALL'S EQUATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>BANKSTOWN</td>
<td>14.3</td>
<td>13.5</td>
<td>14.5</td>
<td>10.3</td>
</tr>
<tr>
<td>BOWRAL</td>
<td>14.7</td>
<td>14.2</td>
<td>15.5</td>
<td>11.4</td>
</tr>
<tr>
<td>CAMPBELLTOWN</td>
<td>13.6</td>
<td>13.0</td>
<td>13.6</td>
<td>9.8</td>
</tr>
<tr>
<td>GOSFORD</td>
<td>15.4</td>
<td>14.9</td>
<td>14.7</td>
<td>11.8</td>
</tr>
<tr>
<td>GLENFIELD</td>
<td>13.6</td>
<td>NO DATA</td>
<td>13.8</td>
<td>NO DATA</td>
</tr>
<tr>
<td>KATOOMBA</td>
<td>15.4</td>
<td>14.9</td>
<td>14.8</td>
<td>11.8</td>
</tr>
<tr>
<td>CAMDEN AIRPORT</td>
<td>14.3</td>
<td>13.2</td>
<td>15.0</td>
<td>10.0</td>
</tr>
<tr>
<td>WOLLONGONG UNI</td>
<td>14.5</td>
<td>15.1</td>
<td>12.7</td>
<td>12.0</td>
</tr>
<tr>
<td>PROSPECT RESERVOIR</td>
<td>14.6</td>
<td>13.3</td>
<td>15.3</td>
<td>10.2</td>
</tr>
<tr>
<td>RICHMOND UWS</td>
<td>13.8</td>
<td>13.7</td>
<td>14.0</td>
<td>10.8</td>
</tr>
<tr>
<td>RICHMOND RAAF</td>
<td>14.4</td>
<td>13.0</td>
<td>13.3</td>
<td>9.8</td>
</tr>
<tr>
<td>RIVERVIEW</td>
<td>14.8</td>
<td>14.6</td>
<td>14.2</td>
<td>11.6</td>
</tr>
<tr>
<td>SEVEN HILLS</td>
<td>14.6</td>
<td>14.2</td>
<td>15.0</td>
<td>11.2</td>
</tr>
<tr>
<td>SYDNEY (OBSERVATORY HILL)</td>
<td>14.7</td>
<td>14.6</td>
<td>13.8</td>
<td>11.4</td>
</tr>
<tr>
<td>SYDNEY AIRPORT</td>
<td>14.5</td>
<td>14.4</td>
<td>13.8</td>
<td>11.2</td>
</tr>
<tr>
<td>WOLLONGONG POST OFFICE</td>
<td>14.6</td>
<td>15.7</td>
<td>14.0</td>
<td>13.5</td>
</tr>
<tr>
<td>NORAH HEAD</td>
<td>15.8</td>
<td>16.2</td>
<td>16.0</td>
<td>14.1</td>
</tr>
<tr>
<td>PARRAMATTA</td>
<td>14.0</td>
<td>13.4</td>
<td>13.8</td>
<td>NO DATA</td>
</tr>
<tr>
<td>PARRAMATTA NORTH</td>
<td>14.5</td>
<td>14.0</td>
<td>14.5</td>
<td>10.8</td>
</tr>
<tr>
<td>PEATS RIDGE</td>
<td>15.4</td>
<td>15.1</td>
<td>15.0</td>
<td>12.2</td>
</tr>
<tr>
<td>PENNANT HILLS</td>
<td>14.3</td>
<td>NO DATA</td>
<td>13.6</td>
<td>NO DATA</td>
</tr>
<tr>
<td>PICTON</td>
<td>14.1</td>
<td>13.4</td>
<td>14.8</td>
<td>10.4</td>
</tr>
<tr>
<td>PORT KEMBLA</td>
<td>14.8</td>
<td>15.7</td>
<td>13.8</td>
<td>13.2</td>
</tr>
<tr>
<td>KULNURRA</td>
<td>15.1</td>
<td>14.6</td>
<td>14.8</td>
<td>11.5</td>
</tr>
<tr>
<td>LIVERPOOL</td>
<td>14.3</td>
<td>13.3</td>
<td>14.8</td>
<td>10.1</td>
</tr>
<tr>
<td>LUCAS HEIGHTS</td>
<td>14.3</td>
<td>14.3</td>
<td>13.8</td>
<td>11.3</td>
</tr>
<tr>
<td>MARSFIELD</td>
<td>14.5</td>
<td>14.0</td>
<td>13.6</td>
<td>10.7</td>
</tr>
<tr>
<td>MOSSVALE</td>
<td>14.5</td>
<td>14.0</td>
<td>14.7</td>
<td>11.0</td>
</tr>
<tr>
<td>MOUNT VICTORIA</td>
<td>14.7</td>
<td>14.5</td>
<td>14.8</td>
<td>11.9</td>
</tr>
</tbody>
</table>

The 3 p.m. estimates calculated using Bramhalls equation appeared to discriminate between the locations reasonably well in that although the values were different from the measured moisture content values at the closest sites used for this study they followed the
same general trend. They were slightly higher at the near coastal and elevated inland sites and relatively constant at the sites in between. This is illustrated in Table 5.13 where the moisture content estimated for Bureau of Meteorology sites is contrasted with measured near surface moisture content at the nearest study test site.

Table 5.13 Comparison of Estimated Moisture Content at Bureau of Meteorology Sites with Mean Near Surface Moisture Content at Study Test Sites (% moisture content)

<table>
<thead>
<tr>
<th>SITE</th>
<th>MEASURED MEAN NEAR SURFACE MOISTURE CONTENT</th>
<th>MOISTURE CONTENT ESTIMATED USING BRAMHALL’S EQUATION AND 3.P.M. R.H.</th>
<th>CLOSEST BUREAU OF METEOROLOGY SITE</th>
</tr>
</thead>
<tbody>
<tr>
<td>WENTWORTH FALLS</td>
<td>14</td>
<td>12</td>
<td>KATOOMBA</td>
</tr>
<tr>
<td>RICHMOND</td>
<td>13</td>
<td>11</td>
<td>RICHMOND UWS</td>
</tr>
<tr>
<td>ILLAWONG</td>
<td>13</td>
<td>11</td>
<td>LUCAS HEIGHTS</td>
</tr>
<tr>
<td>CBD</td>
<td>13</td>
<td>11</td>
<td>OBSERVATORY HILL</td>
</tr>
<tr>
<td>LITTLE BAY</td>
<td>15</td>
<td>14 *</td>
<td>NO NEARBY SITE</td>
</tr>
<tr>
<td>COLEDALE</td>
<td>14</td>
<td>12</td>
<td>WOLLONGONG UNIVERSITY</td>
</tr>
</tbody>
</table>

* There was no Bureau of Meteorology site close to Little Bay so mean 3 p.m. relative humidity measured at the site has been used to estimate the moisture content.

A map (produced using the computer software Surfer and MapInfo) of the study region showing the moisture content of timber based on 3 p.m. relative humidity calculated using Bramhall’s equation (equation 2.8) is shown as Figure A2.10 in Appendix 2. This map might be used as a guide to the relative risk of timber decay across the region based on moisture content.
5.5 Nail Corrosion Due to Timber Selection and Changes in Moisture Content

It was observed from the laboratory humidity chamber tests that corrosion took place at 16% timber moisture content and generally increased as the moisture content increased. More detailed examination of the results for bright and galvanised nails which are of particular interest in buildings revealed that the corrosion rate of these nails in some timbers tended to increase as the moisture content approached 25% and it tended to decrease in others.

The mean corrosion rate of bright nails in Mountain Ash and Douglas Fir tended to decrease when the moisture content approached 25%. This was consistent with the findings of Cole, Ganther, Furman and Page (1999). The mean corrosion rate of bright nails in CCA Treated Radiata Pine tended to increase as the moisture content increased from 20% to 25%. This was also consistent with the findings of Cole et. al. (1999). Refer to Table 4.6 and Figure 4.37. The corrosion rate of bright nails in Radiata Pine and Spotted Gum tended to increase as the moisture content approached 25%. This was not consistent with the findings of Cole et. al. (1999). The difference between the findings may be attributable to natural variability within this species of timber, underlining the need to take this phenomena into account when considering corrosion of nails, particularly in species which tend not to be homogenous in their properties.

The corrosion rate of galvanised nails in Mountain Ash and Douglas Fir started to decrease within the range of 20% to 25% moisture content. In the case of Spotted Gum it was apparent that the corrosion rate started to decrease at or before 20%. The corrosion rate in
CCA Treated Radiata Pine started to increase slightly within the range of 20% to 25%.
However the corrosion rate of galvanised nails in Radiata Pine that was not treated did not change greatly between 16% and 20% but it increased between 20 and 25%.

Establishing the corrosion rates for various timber / nail combinations in controlled conditions where atmospheric influences other than moisture content were excluded and then contrasting them with the results of the field nail corrosion measurements confirmed that moisture content was the major contributing factor in determining the nail corrosion rate in a given species of timber. It also provided a basis for confirming that nothing untoward had influenced the field nail corrosion results.

Table 5.14 compares corrosion rates for bright nails in boards held at 16% moisture content with corrosion rates measured in the field at Wentworth Falls and Little Bay, noting the mean total moisture content recorded for these timbers at the sites involved. It can be seen from the table that the field results were not inconsistent with the laboratory results. The corrosion rates for the recorded moisture contents at Little Bay tended to be a little higher than the corrosion rates for the recorded moisture rates at Wentworth Falls. This suggested that factors other than moisture content at the former were influencing the corrosion rates. Given the proximity of Little Bay to the ocean the other influence was likely to have been atmospheric salt. The corrosion rate for bright nails in Mountain Ash at Wentworth Falls was inconsistent with the rates measured in the humidity chambers. This was likely to have been attributable to variability in the timber.
Table 5.14 Bright Nail Corrosion Rates at the Sites Compared to Corrosion Rates in Humidity Chambers (g/m².year)

<table>
<thead>
<tr>
<th>SPECIES</th>
<th>HUMIDITY CHAMBER</th>
<th>W. FALLS</th>
<th>LITTLE BAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>TREATED PINE</td>
<td>8 at 16% MC</td>
<td>5 at 15%MC</td>
<td>11 at 13%MC</td>
</tr>
<tr>
<td>MOUNTAIN ASH</td>
<td>15 at 16% MC</td>
<td>23 at 15%MC</td>
<td>8 at 13%MC</td>
</tr>
<tr>
<td>DOUGLAS FIR</td>
<td>8 at 16% MC</td>
<td>4 at 15%MC</td>
<td>11 at 13%MC</td>
</tr>
<tr>
<td>RADIATA GUM</td>
<td>4 at 16% MC</td>
<td>4 at 13%MC</td>
<td>8 at 11%MC</td>
</tr>
<tr>
<td>SPOTTED GUM</td>
<td>23 at 16% MC</td>
<td>8 at 11%MC</td>
<td>8 at 11%MC</td>
</tr>
</tbody>
</table>

It was also apparent that the differences in corrosion rates between species at the same moisture content can be significant and can in fact be greater than differences in corrosion rates brought about in some species by variations in moisture content.

The corrosion rating results suggested that shank corrosion tends to increase as the moisture content of timber increases from 16% to 25%. Nail head corrosion also tended to increase, but this trend was not as obvious as it was with shank corrosion.

A possible application of results of this type is the estimation of the corrosion rate of nails in timber in atmospheres where pollutants are at extremely low levels but where the average moisture content of the timber and the species used are known. They may also assist in the selection of suitable species for particular applications, as the difference in the corrosivity of the species is apparent. For example the corrosion rate for bright nails in
Radiata Pine at moisture content of 16% was 4gm/m².year compared to 23gm/m².year with Spotted Gum.

The exposure period for the nails was relatively short compared to the life that might be expected of nails in use. A consequence of this is that in the case of the coated nails the initial corrosion that took place related mainly to the zinc products used (refer to Table 4.8). This two stage corrosion process would need to be taken into account when estimating service life. Further the corrosion rate has been demonstrated by others to diminish in general after the initial exposure period (Cole, Trinidad & Chan 1999).

5.6 Levels of Nail Corrosion at the Sites

Nail corrosion overall tended to be highest at the coastal sites of Little Bay and Coledale, in that order. Across the remainder of the sites it was relatively even. However there was variability in the results which appeared to be attributable to natural variability in the timber but minor differences caused by positioning within the test enclosures and the like could not be ruled out as a possible cause.

Of the non-coastal sites Wentworth Falls generally had slightly higher levels of nail corrosion.

The hardwoods tended to have higher levels of corrosion than the softwoods. The differences in corrosion rates between species were in some cases equal to or greater than
the differences in corrosion rates between sites. The choice of timber appeared to be of fundamental concern in minimising nail corrosion.

CCA Treated Pine had mean and maximum corrosion rates that were generally above those for untreated Radiata Pine. It was apparent that if the results were to be used to predict nail life in the vicinity of the sites it would be appropriate to use the maximum corrosion rates recorded for near coastal sites and for hardwoods generally. It was also apparent that the mean corrosion rates could be used for the softwoods at the non marine sites i.e., for the nail / timber combination used in the study. This would provide a reasonably conservative estimate that not only took into account the environmental aspects but also the natural variability of the timber. A factor would of course have to be introduced into the estimate to take into account the diminishing rate of corrosion that generally occurs over an extended period of time (Cole, Trinidad & Chan 1999).

The results for the coated nails related mainly to the coating material as the exposure period was not sufficient to measure corrosion of the base material.

It was observed during processing of the nails that the extent of coating on the zinc nails, particularly on the heads, was variable and that this variability needs to be considered when assessing service life.
The nail corrosion rating results revealed that for the non coated nails (bright and copper) the head corrosion rate was greater than the shank corrosion rate and the former is an early onset phenomena. In the case of the coated nails the situation was less clear. At the non coastal sites the heads and shanks corroded relatively evenly or the shanks corroded to a greater extent than the heads. At the coastal sites the reverse tended to be the case; head corrosion ratings tended to be higher than the shank ratings.

The nail corrosion ratings overall tended to be consistent with the weight loss results in that the ratings for the coastal sites were higher than those for the inland sites. However the effects of natural variability within species and between species was evident.

5.7 Relationship of Key Climatic Conditions and Risk Factors in Timber Buildings to External Climatic Conditions and Risk Factors

5.7.1 Climatic Conditions

It can be seen from Table 4.10 that the mean temperature in the cavities of the building at Wentworth Falls was very close to the mean recorded in the test enclosure for external covered conditions. For practical purposes they could be regarded as the same. This building was constructed substantially of timber and very well ventilated in areas where measurement took place. However the building appeared to have a delaying effect on the prevailing external conditions. Figure 4.49 illustrates the time lag effects of the building on the temperature in the building spaces (spring 1999)
The closeness of the outside and inside results appeared to indicate that the measurements taken in the test enclosure provided a reasonable estimate of the mean temperatures in the cavities of timber framed and clad buildings with suspended floors and tiled roofs (assuming good ventilation and no major internal heating source).

The results in Table 4.11 indicated that a similar situation existed with relative humidity i.e., the mean relative humidity results in the building cavities were very similar to those for outside covered conditions as measured in the test enclosure. Therefore it appeared that it would be reasonable to use the latter as an estimate of the former providing the building was designed and constructed so as to provide adequate ventilation of the cavities.

5.7.2 Relationship of Salt Deposition in Building Cavities to Outside Salt Deposition

At Wentworth Falls salt deposition in the floor and roof spaces was very similar to that measured outside on the test enclosure when measured with vertical (traditional) salt candles. When salt deposition was measured using horizontal (canister) salt candles there were differences between the deposition rates in the cavities. This suggested that the air circulation patterns were different in each of the spaces and that the deposition pattern is complex.

It was evident that the most appropriate and conservative assumption to make when assessing the corrosion risk in building cavities in timber framed and clad buildings which are very well ventilated and located at non marine sites is that the salt deposition rate in them is the same as that measured immediately adjacent to the building i.e., the level of
risk in the building cavity is the same as the level of risk for the site generally. However in
the case of buildings at marine sites the building fabric is likely, as discussed in Chapter 2,
to have a sheltering effect in respect of the heavy salt particles generated by the surf.
Hence this reduction needs to be taken into account when assessing the risk of corrosion of
nails and other metal elements in building cavities.

5.7.3 Comparison of Inside and Outside Levels of SO₂, NO₂ and HNO₃

It can be seen from Table 4.13 that the levels of SO₂, NO₂ and HNO₃ at Wentworth Falls
were very similar inside and outside. The level of NO₂ inside was slightly higher than
outside. However the order of magnitude was very similar. It consequently appeared that
the building envelope in a very well and naturally ventilated building at a site where
pollutant levels are generally of a low level does not greatly affect the levels of these
pollutants measured over an extended period of time and that levels measured externally
provide a reasonable estimate of levels inside building spaces.

5.7.4 Comparison of Estimated Surface Moisture Content inside Building Spaces with
those in Outside Covered Conditions

Table 4.14 suggests that the surface moisture content of timber in a floor cavity is likely to
be equal to or greater than that measured in outside covered conditions (as established in
the test enclosure) over an extended time period. The extent to which it exceeds the outside
level will be influenced by the adequacy of the ventilation and sub floor drainage and
ground conditions.
The building condition survey at Wentworth Falls supported this proposition. In areas where there was good drainage and ventilation the floor was in good condition. Where the drainage and ventilation were poor there was significant decay.

In relation to the wall cavity the calculated mean surface moisture content was greatest at the bottom of the wall and decreased slightly towards the top. The mean surface moisture content at all levels within the wall cavities was lower than outside in the test enclosure (covered conditions).

The calculated mean surface moisture content in the roof cavity was slightly below that prevailing in the outside in the test enclosure (covered conditions).

It was apparent that calculated surface moisture estimates based on conditions in the test enclosure provided a reasonable (and conservative) approximation of the surface moisture content of timber in wall and roof spaces for timber framed and clad buildings with good ventilation. However in the case of sub floor spaces it was considered that the influence of the ground conditions would need close scrutiny and that estimates based on outside covered conditions (such as those existing in the test enclosure) might not be appropriate.

5.7.5 Comparison of Timber Near Surface Moisture Content in Building Cavities with those in External Covered Conditions

Except in the case of CCA Treated Radiata Pine, the mean near surface moisture content of the timber specimens mounted in the test enclosure (outside covered conditions) at
Wentworth Falls was within the range of 0-1% greater than the measured mean moisture content of the same species mounted in the roof space and wall cavity. The difference between the maximum near surface moisture content outside in the test enclosure and in the roof space and wall cavity was also of that order. In the case of the CCA Treated Radiata Pine it is probable that there was variability within the timber which distorted the results. There was some visual difference between the boards.

When the mean near surface moisture content results for timber in the test enclosures (outside covered conditions) at other sites were adjusted by 0-1% to estimate the near surface moisture content that might be expected in the roof space and wall cavities of timber framed and clad buildings at these sites none of the adjusted means exceeded 18%. It therefore appeared appropriate to conclude that providing design and construction detailing is appropriate the Sydney climate does not pose a serious risk in terms of decay being sustained in timber members associated with these spaces.

It was also apparent from the closeness of the inside results and those for the test enclosure that near surface moisture content results gathered in outside covered conditions provided a reasonable estimate of conditions in roof spaces and wall cavities of buildings similar in design to the building at Wentworth Falls.

The results indicated that at the Wentworth Falls site the mean near surface moisture content in the sub floor space exceeded those experienced in the test enclosure (outside covered conditions) by approximately 1% on average. They also indicated that there were
periods when the maximum near surface moisture content exceeded 18% in some species (Mountain Ash, Douglas Fir, Radiata Pine and CCA Treated Radiata Pine). These were the less dense timbers used in the study. The denser timbers, Brush Box and Spotted Gum did not have near surface moisture contents that exceeded 18%.

Ground conditions and drainage arrangements may vary from site to site and can also vary at a particular site. These variations may cause differences in the moisture content of the timber members nearby. For example at Wentworth Falls the floor varied in height above the ground considerably. At the location where the measurements were taken the height was approximately 300mm above ground and the ventilation and drainage were reasonably good. There were no signs of timber decay in this vicinity. However at the north west corner of the building the floor was much closer to the ground and the ventilation and drainage were poor. There was considerable decay in this area. Hence it was concluded that near surface moisture content data gathered outside in the test enclosure might not be a reliable indicator of the near surface moisture content in adjacent sub floor spaces.

The differences between the outside results and sub floor results for each species exposed at Wentworth Falls were used to adjust outside results at other locations to estimate what the mean near surface moisture content in the sub floor space at those locations might be for buildings of similar design (assuming the same ground conditions to those at Wentworth Falls). The estimated mean near surface moisture contents for the less dense timbers, Mountain Ash, Douglas Fir, CCA Treated Radiata Pine and Radiata Pine at Little Bay were 19%, 18%, 18% and 19% respectively (moisture contents at which decay
causing fungi can be sustained). The estimates for the denser timbers, Spotted Gum and Brush Box were 13% and 12 % respectively. The estimates for other sites were below 18%. The estimates for Little Bay illustrated the critical importance of the selection of appropriate timbers and the provision of ample ventilation and drainage at similar sites.

5.7.6 Comparison of Total Timber Moisture Content in Building Cavities with Total Moisture Content in Timber in External Covered Conditions

When the mean total moisture content results for timber specimens in the roof, wall and floor cavities at Wentworth Falls were compared to the mean total moisture content results for timber in the test enclosure (covered external conditions) at the site it could be seen that the former were approximately 1% lower than the latter. There were minor differences according to the species concerned.

When this difference was used to adjust the mean total timber moisture content results recorded in the test enclosures (external covered conditions) at other sites to estimate the mean total moisture content that might be expected in timber members in the wall cavities, roof space and sub floor space in buildings of similar design at those locations the results indicated that the risk of timber decay from excessive total timber moisture content was relatively low.

5.7.7 Moisture Content of Timber Building Members Monitored by Data Logger

Table 4.14 shows the median moisture content of various timber members in the building at Wentworth Falls. The paint systems used on external members were not known. Hence
no accurate judgement could be made on their influence on the moisture content of these elements. Nevertheless the results provided some indication of the ranking of moisture contents and relative timber decay risk levels.

It was noted that the data logger arrangement used to record the moisture content of the various members did not permit the calculation of the mean moisture content, only the median moisture content. The system would not record moisture levels below approximately 8%, only that a reading below 8% had occurred. Further the system could not be calibrated during the measuring process as is possible with commercially available moisture meters. Consequently it was apparent that this method of measurement requires further development if it’s potential is to be achieved.

5. 8 Statistical Analysis of Nail Corrosion Results

This analysis was carried out to determine the aspects that could be conveniently measured at relatively low cost to use as predictors in equations for estimating the rate of corrosion at sites in the region.

The regression analysis of the aspects measured at the test sites revealed that reasonably robust equations could be developed for predicting corrosion rates for bright and galvanised nails in the softwoods CCA Treated Radiata Pine, Radiata Pine and Douglas Fir based on the mean near surface moisture content of the timber involved (Equations 4.1 to 4.6). However this was not possible in the case of the hardwoods, Mountain Ash and Spotted Gum. In the case of these two species the graph developed from the laboratory
measurement of nail corrosion might be used for estimating purposes (Section 4.5, Chapter 4).

The coefficients of determination ($R^2$ and $R^2$ adjusted) for the softwoods suggested strongly that the difference in nail corrosion rates in Sydney could be attributed to the differences in moisture content of the timber. In the case of the hardwoods used it was apparent from the results that natural properties and variability in the properties of the timber play a significant role in determining the extent of nail corrosion. The effects of these properties and variability masked the effects of subtle differences in climate and atmospheric pollution.

The regression equations developed could be used to estimate the nail corrosion rate for a particular building where the nail / timber combination was the same i.e., one of the softwoods covered by the study and either galvanised or bright nails. The near surface moisture content could be determined by regularly taking moisture meter readings and calculating the mean of the data set for use in the equation. Alternatively if access to the timber element concerned was not possible for the use of a moisture meter then it could be estimated by placing moisture boards of the same species in an outside covered enclosure adjacent to the building, taking regular readings with a meter and adjusting the results with the factors shown in the comparison of outside and inside moisture contents shown in Chapter 4 obtained at Wentworth Falls. Another approach would be to suspended moisture boards in the building cavities and measure the near surface moisture content indirectly using these boards on a regular basis for a suitable period.
As an example, estimates of bright nail corrosion in the roof, wall and floor cavities at each of the sites for Douglas Fir were compiled using the regression equation for this species (Equation 4.6). The near surface moisture content of the boards in the test enclosures were adjusted as suggested above and used in the equation. The results are summarised in Table 5.15.
Table 5.15 Estimated Corrosion Rates for Bright Nails in Douglas Fir in Roof, Walls, Sub Floors and Outside at Sites

<table>
<thead>
<tr>
<th>(1) SITE</th>
<th>(2) LOCATION</th>
<th>(3) OUTSIDE M.C.</th>
<th>(4) LOCATION CORRECTION FACTOR</th>
<th>(5) ADJUSTED M.C. (3)+(4)</th>
<th>(6) EQUATION CONSTANT</th>
<th>(7) COEFFICIENT FOR M.C.</th>
<th>(8) NAIL CORROSION RATE (g/m²/year) (7)=(6)+(7)*(5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WENTWORTH FALLS, RICHMOND ILLAWONG CBD AND COLEDALE</td>
<td>ROOF</td>
<td>15</td>
<td>-1</td>
<td>14</td>
<td>-44.2</td>
<td>3.23</td>
<td>1.02</td>
</tr>
<tr>
<td>WALL CAVITY</td>
<td>15</td>
<td>-1</td>
<td>14</td>
<td></td>
<td>-44.2</td>
<td>3.23</td>
<td>1.02</td>
</tr>
<tr>
<td>FLOOR</td>
<td>15</td>
<td>1</td>
<td>16</td>
<td></td>
<td>-44.2</td>
<td>3.23</td>
<td>7.48</td>
</tr>
<tr>
<td>OUTSIDE</td>
<td>15</td>
<td>0</td>
<td>15</td>
<td></td>
<td>-44.2</td>
<td>3.23</td>
<td>4.25</td>
</tr>
<tr>
<td>LITTLE BAY</td>
<td>ROOF</td>
<td>17</td>
<td>-1</td>
<td>16</td>
<td>-44.2</td>
<td>3.23</td>
<td>7.48</td>
</tr>
<tr>
<td>WALL CAVITY</td>
<td>17</td>
<td>-1</td>
<td>16</td>
<td></td>
<td>-44.2</td>
<td>3.23</td>
<td>7.48</td>
</tr>
<tr>
<td>FLOOR</td>
<td>17</td>
<td>1</td>
<td>18</td>
<td></td>
<td>-44.2</td>
<td>3.23</td>
<td>13.94</td>
</tr>
<tr>
<td>OUTSIDE</td>
<td>17</td>
<td>0</td>
<td>17</td>
<td></td>
<td>-44.2</td>
<td>3.23</td>
<td>10.71</td>
</tr>
</tbody>
</table>
The estimates obtained might be adjusted to take into account the diminishing rate of corrosion that usually occurs over an extended period using Equation 2.34 developed by Cole, Trinidad and Chan (1999).

It should be noted that if equations 4.1 to 4.6 are used they are only applicable for moisture contents within the ranges indicated with the equations. An alternative approach would be to use the equations (2.32 and 2.33) developed by Cole et. al. (1999) that are applicable to a wider range of moisture contents.

If the prediction equations developed in this study are used for engineering purposes it should be recognised that nail corrosion is unlikely to occur evenly across the surface of the nail; hence the cross section will vary. An appropriate allowance needs to be made for this factor. Further the condition of the timber around the nail should be taken into account as it could affect the capacity of the nailed joint to withstand the loads placed on it.

Although equations 4.1 to 4.6 have reasonable coefficients of determination they have several limitations. Firstly they only cover a narrow range of moisture content values, they estimate mean nail corrosion based on mean near surface moisture content and were formulated from relatively small data sets. On the other hand equations 2.32 and 2.33 developed by Cole et. al. cover a wider range of moisture contents and were formulated using larger data sets and rigorous laboratory work. Further they deal satisfactorily with a wider range of timbers. They were therefore considered superior to equations 4.1 to 4.6.
Estimates of nail corrosion were calculated using Cole’s equations (2.32 and 2.33) for bright nail corrosion in Radiata Pine. The calculations utilised mean near surface moisture content results for Radiata Pine measured at the study sites, the dry density of the Radiata Pine moisture boards used at the study sites and typical Radiata Pine acid and pH values documented by Cole et. al. (1999). These estimates were compared to the bright nail corrosion rates for Radiata Pine measured at the study sites, adjusted to provide one year corrosion values (using equation 2.34) This comparison is set out in Table 5.16.

Table 5.16 Comparison of Estimated Bright Nail Corrosion in Radiata Pine with Corrosion Rates Measured at the Study Sites (g/m².year)

<table>
<thead>
<tr>
<th>SITE</th>
<th>ESTIMATED CORROSION</th>
<th>FIRST YEAR</th>
<th>MEAN MEASURED NAIL CORROSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>WENTWORTH FALLS</td>
<td>6</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>RICHMOND</td>
<td>6</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>ILLAWONG</td>
<td>6</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CBD</td>
<td>6</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>LITTLE BAY</td>
<td>8</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>COLEDALE</td>
<td>6</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

The results of this analysis indicated there was a reasonable, although not complete, similarity between the measured and estimated nail corrosion values. Cole’s equations produced a slightly conservative estimate when compared to the measured values.

To illustrate the slight variation in nail corrosion risk across the region Cole’s equations for estimating bright nail corrosion in Class 2 timbers (Radiata Pine, Douglas Fir and Mountain Ash) were used in conjunction with estimates of timber moisture content at Bureau of Meteorology sites to estimate the rates of nail corrosion at those locations. The timber moisture content was estimated using Bragg’s equation (2.15) and Bureau of
Meteorology mean 3 p.m. relative humidity and mean annual rainfall data. A map was then produced (using the computer software Surfer and MapInfo) indicating the estimated rates of nail corrosion across the region. This map is shown as Figure A2.11 in Appendix 2.

5.9 Building Condition Surveys

A number of observations were made during these surveys and the study generally on degradation risks. The outcomes of the condition surveys and tables summarising degradation risks are set out in Appendix 1. Risk mitigation measures are also suggested.
CHAPTER 6
CONCLUSIONS

6.1 Climatic Aspects

The temperature, relative humidity and rainfall data gathered was consistent with the long term averages recorded by the Bureau of Meteorology and therefore the study period was considered relatively representative.

Due to the similarity of the results of the study to those of the Bureau in relation to climatic aspects it was also considered that the former were not distorted significantly by the methods of measurement or housings used for the study and could be regarded as typical of outside conditions. However reliability problems were encountered with the data loggers used for recording relative humidity and temperature in relation to the predictability of battery life and it was concluded that this would need to be taken into account if they were being considered for future research. Battery failures occurred even though the software used in the loggers indicated the batteries had a long residual life. They were felt to be most suitable for projects where uninterrupted monitoring for periods of up to approximately one month was required.

The study confirmed that there were significant differences in the extremes of temperature and relative humidity at sites across the Sydney region which were principally determined by proximity to the coast, proximity to the mountain range to the west and the topography. The highest levels of humidity were experienced at sites very close to the ocean, which caused them to have the highest levels of risk in the region of
timber decay and atmospheric corrosion of metals in respect of this aspect. The study also identified that the longest times of wetness were experienced very close to the coast which also indicated that this area had a higher risk of corrosion.

6.2 Corrosion Risk Factors

In respect of the rainwater tests conducted it was found that the differences in mean rainwater pH across the region were relatively insignificant and that this aspect did not pose a significant risk in relation to corrosion.

Rainwater conductivity was relatively high near the coast, diminished in an approximately proportionate manner to a distance of approximately 10 km inland and then remained relatively constant to the western sector of the region. It was apparent that the primary influence on rainwater conductivity in the region was sea salt. Rainwater salt content was also identified as being highest near the coast and observed to diminish at a relatively constant rate to a distance of approximately 10km inland. It remained at a fairly constant level to the west of the region. The rainwater conductivity and salt content results reinforced the view that sites in close proximity to the coast had the highest risk levels in relation to atmospheric corrosion.

Air salt content measured using salt candles also indicated that the greatest level of risk of corrosion was at the marine sites and that it was similar elsewhere.
It was observed that the local topography tended to have a dampening effect on salt deposition rates. Open unsheltered sites had higher rates of deposition than sites with shelter provided by the built or natural environment.

SO\textsubscript{2} levels were relatively high in the CBD and tended to diminish the further the site was away from this area. NO\textsubscript{2} levels tended to diminish according to the distance from the CBD and HNO\textsubscript{3} levels were relatively consistent across the region except at the extremes from the CBD where they were considerably lower. It was concluded that the levels of these pollutants were generally not significant enough to pose a major risk of corrosion in the region. Notwithstanding this conclusion it was noted that care needs to be taken when assessing particular sites to determine whether there are any local factors creating pollution hot spots that may increase corrosion risk.

6.3 Corrosion Levels

Measurements made with zinccorr units indicated that the corrosion rate very close to the coast was relatively high and that the level of corrosion at non coastal sites was very similar.

The copper/steel coupon results indicated that the marine sites would be classified in the range of C2 Low (high end of the scale) to C3 Medium according to the ISO corrosivity categories set out in AS/NZ 2312/1994. Estimates of corrosion prepared indicated that shoreline corrosion levels would be classified C5, very high. All other sites would be classified as C2 Low – arid/urban.
The corrosion risk levels at marine sites measured using copper / steel coupons were approximately twice that at the non marine sites.

Corrosion measured using zinc plates was highest at the coastal sites and similar at all other sites.

6.4 Timber Decay Risk Aspects

High mean near surface moisture contents which were near the decay sustaining threshold were experienced in Radiata Pine, CCA Treated Radiata Pine, Douglas Fir and Mountain Ash at sites close to the coast. At non coastal sites or in the case of Brush Box and Spotted Gum the timber decay risk factor was found to be more moderate.

It was found that the total moisture content of timber in the region entered the decay sustaining threshold for short periods which highlighted the need for thoughtful design and construction detailing.

Field tests revealed that softwoods which were placed outside and subject to the elements of rain, wind and direct sunlight at near coastal sites and which were not primed with an oil based primer experienced periods when the moisture content exceeded the decay sustaining threshold and were considered to be at risk. Priming of external timber members with oil based primer was highly recommended.
6.5 Relationship of Key Climatic Conditions and Risk Factors in Well Ventilated Timber Framed and Clad Buildings to External Climatic Conditions and Risk Factors

The study revealed that key climatic and pollutant conditions in well ventilated cavities of timber framed and clad buildings at non marine sites were very similar to those outside.

The mean temperatures in the roof space, wall cavity and sub floor area were very similar to those encountered externally in covered conditions, albeit the building created a time delay factor. A similar situation existed with mean relative humidity. However it was observed that if there were sources of excessive moisture such as poor sub floor drainage or inadequate ventilation the relative humidity could increase significantly.

Atmospheric salt levels in the cavities were found to be very similar to those measured externally adjacent to the building, therefore the latter was considered a reasonable estimate of the former. However it was noted that in buildings very close to the coast external levels were likely to exceed those in the cavities significantly because of the shielding the building fabric afforded in relation to heavy surf generated salt particles present in such environments.

Levels of SO$_2$, NO$_2$ and HNO$_3$ measured inside were for practical purposes the same as the levels measured immediately adjacent to the building.
The study revealed that timber decay risk levels in well ventilated building cavities of timber framed and clad buildings varied slightly from those in external covered conditions (as measured in the test enclosures). It was concluded that in buildings of the same type the surface moisture content of timber in sub floor areas is likely to be higher than in other building spaces and covered external conditions (the extent being determined by the properties of the ground under the floor, the extent of ventilation and the quality of the drainage), hence it was also concluded that the risk of decay is greater in this location.

The results for the mean and maximum near surface moisture content of timber tended to be slightly lower in the wall cavities and roof space than in external covered conditions as measured in the test enclosures used (of the order of 0 to 1%) hence the risk of decay in appropriately detailed timber members in these spaces in the Sydney region was concluded not to be excessive.

On the other hand it was determined that the mean and maximum near surface moisture contents of low density timbers (such as Mountain Ash, Radiata Pine, Treated Radiata Pine and Douglas Fir) in sub floor spaces in high humidity marine locations are likely to exceed those of the same species in outside covered conditions by 1% or more posing a risk of timber decay and greater nail corrosion in poorly detailed buildings.

The mean total moisture content of timber in the roof space and wall cavities was found to be slightly lower than that measured externally in the test enclosures (on average approximately 1%);
6.6 Nail Corrosion

The natural variability within timber species and between species was found to have a considerable influence on the corrosion rate of nails. It was observed that the difference in the corrosion rate attributable to the natural properties and variability of timber can be greater than the difference attributable to relatively subtle changes of environmental conditions between sites, making the choice of a timber fundamental when attempting to minimise nail corrosion.

Nails in the hardwoods used in the study (Spotted Gum and Mountain Ash) tended to have higher corrosion rates than those in the softwoods (Radiata Pine, CCA Treated Pine and Douglas Fir). Nails in CCA Treated Pine had higher Corrosion rates than nails in untreated Radiata Pine.

It was found that the most significant influence on the rate of nail corrosion was the timber moisture content.

Nail corrosion rates were generally found to be highest near the coast and tended to be relatively even across the remainder of the region. The statistical analysis of the relationship between nail corrosion and climatic and pollutant risk aspects confirmed that the natural properties of timber and moisture content are the most important influences on the nail corrosion. Although pollutants such as atmospheric salt would have had some effect on nail corrosion, this was concluded to be relatively minor. The high relative humidity levels adjacent to the coast were considered to be the main cause of the higher levels of nail corrosion in this area.
The nail corrosion rating results indicated that in general head corrosion was greater than shank corrosion for uncoated nails. In the case of coated nails the same phenomena was evident at non coastal sites but the reverse was the case for coastal sites.

There were visible differences in the extent of cover of zinc coated and galvanised nails and it was apparent that this would afford different levels of protection to the base material which would need to be taken into consideration when assessing probable nail life.

Development of regression equations proved possible for the softwoods used in the study. The most satisfactory predictor of the nail corrosion rate was the near surface moisture content of the timber involved. Development of suitable regression equations for the hardwoods used was not possible as variation in the aspects measured in the study did not account for a significant proportion of the variation in corrosion.

6.7 Building Condition Surveys

The building condition surveys tended to support the conclusions drawn from the field measurement of environmental aspects and underscored the importance of appropriate design, construction detailing and maintenance.
6.8 Measures to Mitigate Higher Level Risks in the Region and Prevent Defects

6.8.1 Corrosion

The general measures identified from the research and review of the related literature for mitigating the risk of corrosion attributable to extended times of wetness and atmospheric salts, which were found to be the higher level risks in the region, were:

- selecting corrosion resistant materials and appropriate coating systems;
- ensuring surfaces are well drained and cleaned on a regular basis; and
- providing shielding to collect large salt particles if the site is marine

6.8.2 Timber Decay

The general measures identified from the research and review of the related literature for mitigating the risk of timber decay attributable to high timber surface moisture, high near surface moisture content and high levels of total moisture content in lower density timbers were:

- provide shelter to timber elements where possible;
- provide ample ventilation and suitable separation from the ground;
- ensure surfaces are self draining;
- use preservative treated or decay resisting timbers externally;
- use appropriate protective coating systems externally including oil based primer and;
- clean external surfaces regularly.
6.8.3 Nail Corrosion

The general measures identified for reducing the risk of nail corrosion in the region were:

- selecting timber species that are not inherently corrosive to nails;
- take timber variability into account when selecting a suitable timber;
- minimise timber moisture content;
- use galvanised nails for external applications;
- protect against nail head corrosion (by, for example, punching nail heads used in external applications, filling holes and painting with the timber coating system used); and
- avoid creating crevices but where this is unavoidable prime and paint all surfaces; and maintain paint systems regularly.

6.9 Recommendations for Further Research

In view of the relatively small number of data sets available for use in the regression analysis of nail corrosion it was concluded that a worthwhile area for further research would be to expose larger numbers of nails boards across the study area and statistically analyse the corrosion rate results with a view to testing and enhancing the regression models developed in this study.

A further area of possible research would be exploring the application of the general approach taken with this study to characterise the degradation of other materials in the Sydney region, including the development of regression models for predicting degradation rates.
LIST OF REFERENCES


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Malhotra, K. 198-, Effect of Environmental Factors on the Performance of Wood as a Construction Material, Technical University of Novascotia, Canada.


Noel Bell Ridley Smith, January 2000, *Queen Victoria Nursing Home Wentworth Falls – Conservation Plan*.


APPENDIX 1.

BUILDING CONDITION SURVEYS AND DEGRADATION RISKS OBSERVED DURING THE STUDY

A1.1 Building Condition Surveys and Observed Degradation Risks

Building condition surveys were carried out in buildings at three of the sites to ascertain whether the defects present were consistent with the degradation risk factors observed during the study and/or whether there were other influences giving rise to failures or partial failures. It was found that the defects were consistent with the risk factor identified. A number of observations were made during these surveys and the study generally on degradation risks. The outcomes of the condition surveys and tables summarising degradation risks are set out below. Risk mitigation measures are also suggested.

A1.2 Observations made during the Building Condition Surveys

A1.2.1 Wentworth Falls

This building forms part of a hospital constructed in c1903 (Noell Bell Ridley Smith 2000). It has been used primarily as a nurses residence although in recent years it has been used for storage purposes.

The timber floor members were found to be in a satisfactory condition except in the north west corner of the building where there is a bathroom. In this location the floor was observed to be close to the ground and there was evidence of past leaks in the drainage system. The result of these factors has been very substantial decay. Evidence of termite activity was also found in this corner.
The walls (except for several minor extensions) were noted to be timber framed and clad externally with timber weather boards. There was some mechanical damage to the boards and a number had been removed. Termite damage was found in the walls at the north west corner in the weather boards and the framing. The framing and the external cladding were in contact with the ground in this area there was extensive leaf litter which touched the lower parts of the walls. Further this part of the building was heavily shaded by nearby trees.

The roof drainage was noted as being heavily corroded and it was evident that rainwater had been spilling onto the ground adjacent to the building. The drainage was satisfactory on the south and east ends but there was poor drainage on the western side and to lesser extent on the northern side. This has added to the decay on the north west corner.

In areas where the external wall lining was missing the nails in the studs that remained were moderately corroded. The corrosion material covered all of the surface area of the nails and there was a small amount of knecking on the shanks.

The roof framing in the roof space did not display any evidence of decay. There was a section of ceiling missing in one of the minor extensions. The reason for it’s removal was not apparent. Its removal has resulted in increased ventilation of the roof space.

Externally the rafters were seen to be exposed under the eaves and there were no signs of significant decay.
There was a half gable vent on the north side of the building and there were signs of decay in the trim on the outside and one piece was missing.

The window and doorframes were constructed of timber. There was decay in one of the window frames on the north west corner. There was extensive mechanical damage to the doors but little evidence of decay.

The ceiling and wall linings were a mixture of hardboard and lining boards. These elements were worn but there no major signs of decay were apparent.

**A1.2.2 Illawong**

This building was constructed in 1984. And is the family home of the author.

The timber floor framing and particle board flooring appeared to be in sound condition except in the north east corner under the laundry. The particle board in this area was cracked. It was evident that this had been caused by moisture coming through the adjacent walls where there was a garden finishing above the damp proof course. There was also a paved path hard up against the doorstep to the laundry which was introducing moisture into the wall and door frame which had decay at the bottom. Water was then finding it's way through a hole in the door frame base and onto the bottom wall plate causing decay. There was no shelter over the door.

There was no decay evident in the wall framing other than in the north east corner as discussed above.
Access was available to the ceiling space above the ground floor in the kitchen and garage. There were no indicators of degradation in these places. Similarly there was no evidence of damage in the roof framing which consisted of Radiata Pine trusses and associated members. Visual inspection did not indicate any significant corrosion of the gang nails in the trusses.

Externally on the roof the timber on the gable ends was observed to be splitting where it protruded from the line of the building.

There were timber decks on the southern side of the building at the ground and first floors. The structure and the hand rails on these decks were constructed of Douglas Fir. The decking was hardwood of an unknown species. There was decay in the joints of the framing on the lower deck and in the joists at the joints with the decking. The decking was split from weathering and decay had commenced where water had entered the cracks. Some of the nails fixing the decking were proud of the top surface and there was decay around the nails. The hand rails were very badly decayed at the joints and where water had entered cracks on the top surface.
A1.2.3 Little Bay

This building is reported to have been constructed in c1915 as residence associated with the Prince Henry Hospital (Department of Health, NSW, 1990). It has subsequently been used as a sewing room for the hospital and during the period of this study was vacant.

The sub floor space was not accessible but an inspection from the perimeter did not reveal any defects.

The floor board ends on the eastern side and on the verandah to the north were exposed to the weather. They were split and there was some decay. The building was mostly lined externally with timber weather boards. There was decay in the ends of some of the boards on an extension on the southern side of the building and on the south east corner. Many of the nails fixing the boards to the framing were found to be corroded which was evident from discolouring coming through the painted finish. It was apparent that this extension had been painted with acrylic paint only. On the southeast corner there were corroded nails surrounded by timber decay.

The wall framing was constructed of timber. The cavities were not accessible but there was no indication of degradation except on the western side. There was a tank in the roof space on this side of the building that was leaking and had caused damage to the ceilings and wall linings both internally and externally.

The roof framing was of conventional design except that it was lined with planks above the rafters with planks of approximately 250mm x 50mm. There was no decay evident.
The rafters were exposed under the eaves but no significant damage was evident. Some of the barge boards had localised decay. The bargeboard on the eastern side was missing for reasons unknown.

There was a half gable roof vent, which was showing signs of decay. One of the trims was missing.

Horizontal surfaces on the external elements such as the window sills and verandah hand rails had peeling paint and splitting/cracking from weathering. One window frame on the southern side was decaying.

The observations of the building condition surveys were consistent with the results of the field measurement of environmental aspects. For example:

- timber decay at Wentworth Falls was greatest in the floor area where the moisture content was highest and the drainage poor, otherwise as the climatic data suggested the floor was in a good condition;

- at Illawong there was decay in external timber elements where the detailing of the joints was poor and primer had not been used; appropriately detailed elements were in sound condition and

- nail head corrosion and consequent timber decay was evident on the wall lining boards on the southern and eastern walls of the building at Little Bay where an extension had been constructed and the boards had apparently been painted with acrylic paint only; in other locations where appropriate paint systems have been used nail corrosion was not evident.
A1.3 Summary of Observed Risks and Suggested Mitigation Measures

Table A1.1 sets out higher level risks identified during the study and recommended mitigation measures. Tables A1.2 (a) to A1.2 (c) summarise potential defects identified by observation but less heavily evidenced by the research and recommend mitigation measures.
<table>
<thead>
<tr>
<th>RISKS</th>
<th>MITIGATION / PREVENTION MEASURES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CORROSION</strong></td>
<td></td>
</tr>
<tr>
<td>High time of wetness at marine sites.</td>
<td>Ensure external surfaces are adequately drained and cleaned on a regular basis.</td>
</tr>
<tr>
<td>High levels of atmospheric salt at marine sites.</td>
<td>Provide shielding to collect large surf generated salt particles. Use corrosion resistant metals and finishes which are easily cleaned for external elements</td>
</tr>
<tr>
<td><strong>TIMBER DECAY</strong></td>
<td></td>
</tr>
<tr>
<td>High timber surface moisture at marine sites.</td>
<td>Provide shelter where possible. Ensure surfaces are self draining and adequately coated.</td>
</tr>
<tr>
<td>Higher levels of near surface moisture content at marine sites.</td>
<td>Use preservative treated or decay resisting timbers externally. Ensure they are painted with oil based primer and good quality paint which is maintained.</td>
</tr>
<tr>
<td>Higher levels of total timber moisture content in lower density timbers.</td>
<td>Avoid using externally unless they are treated with suitable preservative.</td>
</tr>
<tr>
<td><strong>NAIL CORROSION</strong></td>
<td></td>
</tr>
<tr>
<td>Varying levels of nail corrosion in different species of timber.</td>
<td>Select appropriate species of timber for application.</td>
</tr>
<tr>
<td>Variability of nail corrosion rates due to natural variability within a timber species.</td>
<td>In considering nail corrosion take variability into account and use a suitable factor of safety that allows for this phenomena.</td>
</tr>
<tr>
<td>Higher levels of nail corrosion at marine sites.</td>
<td>Use galvanized nails in all external elements and cladding.</td>
</tr>
<tr>
<td>Higher levels of nail head corrosion at marine sites.</td>
<td>Use galvanized nails in external elements, punch nails, fill nail head holes with appropriate filler and paint element with oil based primer and two finish coats of external gloss paint. Repaint regularly to maintain protection.</td>
</tr>
<tr>
<td>Variability in the coating of zinc coated nails.</td>
<td>Avoid using zinc coated nails if possible. Use for internal applications only.</td>
</tr>
</tbody>
</table>
Table A1.2 (a) Measures Recommended to Mitigate Potential Defects Identified by Observation but Less Heavily Evidenced by the Research

<table>
<thead>
<tr>
<th>POTENTIAL DEFECTS</th>
<th>AVOIDANCE MEASURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timber decay in floors where they are very close to the ground.</td>
<td>Ensure that there is adequate well ventilated space between the floor and ground.</td>
</tr>
<tr>
<td>Timber decay in floors where the drainage system has not been maintained</td>
<td>Regularly check and maintain storm water drainage system. Ensure sub soil drainage</td>
</tr>
<tr>
<td>adequately.</td>
<td>is adequate.</td>
</tr>
<tr>
<td>Timber decay in floors where the sub floors ventilation is not adequate.</td>
<td>Ensure substantial sub floor ventilation. Provide large openings at the perimeter</td>
</tr>
<tr>
<td>of the sub floor space to ensure cross ventilation.</td>
<td>of the sub floor space to ensure cross ventilation.</td>
</tr>
<tr>
<td>Decay in floors and wall members where paths and gardens are too close or in</td>
<td>Ensure paths, paving, gardens and the like are not in contact with walls above</td>
</tr>
<tr>
<td>contact with the building above damp proofing.</td>
<td>membranes, weep holes and damp courses</td>
</tr>
<tr>
<td>Termite damage where timber elements are close to the ground.</td>
<td>Ensure there is adequate space between the ground and timber elements. Maximise</td>
</tr>
<tr>
<td></td>
<td>natural light and provide termite barriers (capping, mesh as appropriate to</td>
</tr>
<tr>
<td></td>
<td>construction detail)</td>
</tr>
<tr>
<td>Termite damage where the ground adjacent to timber members is moist.</td>
<td>Ensure ground is drained well. Use sub soil drainage if necessary. Ensure there is</td>
</tr>
<tr>
<td></td>
<td>ample air circulation and not excessive shading.</td>
</tr>
<tr>
<td>Termite damage where leaf litter is allowed to accumulate adjacent to buildings.</td>
<td>Clear litter and debris regularly and ensure that there no materials providing</td>
</tr>
<tr>
<td></td>
<td>cover for termite bridging of barriers.</td>
</tr>
<tr>
<td>POTENTIAL DEFECTS</td>
<td>AVOIDANCE MEASURES</td>
</tr>
<tr>
<td>--------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Decay in roof vents and other timber elements where there are small and</td>
<td>Ensure timber is painted with oil based primer before finish coats are</td>
</tr>
<tr>
<td>difficult members to paint and maintain that are heavily exposed to wind</td>
<td>applied (all sides), use galvanised nails or fixings, ensure all crevices at</td>
</tr>
<tr>
<td>driven rain.</td>
<td>connections are filled and painted and vents are repainted regularly. Use</td>
</tr>
<tr>
<td></td>
<td>preservative treated timber.</td>
</tr>
<tr>
<td>Cracking and decay on horizontal surfaces of timber elements such as</td>
<td>Use preservative treated timber. Ensure drainage from horizontal surfaces</td>
</tr>
<tr>
<td>window sills, hand rails and decking.</td>
<td>is adequate (sills, rails etc). Use oil based primer and good quality gloss</td>
</tr>
<tr>
<td></td>
<td>finish coats. Fill crevices and paint.</td>
</tr>
<tr>
<td>Decay in the bottom of softwood timber door frame members exposed to the</td>
<td>Provide shelter over doorways. Ensure threshold detail allows drainage</td>
</tr>
<tr>
<td>weather.</td>
<td>without it being excessive so as to cause a trip hazard. Use preservative</td>
</tr>
<tr>
<td></td>
<td>treated timber which is oil base primed and repainted regularly.</td>
</tr>
<tr>
<td>Splitting and decay in timber gable ends at their extremities where they</td>
<td>Use preservative treated or decay resistant timbers, oil based primer,</td>
</tr>
<tr>
<td>are very exposed to wind driven rain.</td>
<td>good quality paint and repaint regularly.</td>
</tr>
<tr>
<td>Timber decay in joints between decking and between decking and joists.</td>
<td>Use preservative treated timber. Ensure gaps are minimised. Paint all</td>
</tr>
<tr>
<td></td>
<td>surfaces very well at joints. Fill joints where possible.</td>
</tr>
<tr>
<td>Splitting of decking and decay in split areas.</td>
<td>Ensure timber is properly seasoned before use. Paint all surfaces with oil</td>
</tr>
<tr>
<td></td>
<td>based primer and good quality decking paint. Ensure paint cover is maintained.</td>
</tr>
<tr>
<td></td>
<td>Ensure adequate drainage from deck.</td>
</tr>
<tr>
<td>Nails in decking corroded and decay around nails.</td>
<td>Use galvanised nails. Punch nails and fill holes. Ensure timber is properly</td>
</tr>
<tr>
<td></td>
<td>seasoned before use. Paint all surfaces with oil based primer and good quality</td>
</tr>
<tr>
<td></td>
<td>decking paint. Ensure paint cover is maintained. Ensure adequate drainage.</td>
</tr>
<tr>
<td>POTENTIAL DEFECTS</td>
<td>AVOIDANCE MEASURES</td>
</tr>
<tr>
<td>---------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Splitting and decay in the ends of floor boards exposed to the weather.</td>
<td>Avoid this detail if possible. Ensure end grain is well sealed and maintained.</td>
</tr>
<tr>
<td>Decay in weather boards at their ends at the corners of buildings exposed to wind driven rain.</td>
<td>Provide shelter with wide eaves or verandah if possible. Paint all surfaces at the end of boards with oil based primer and good quality finishing paint. Fill all holes and gaps with low shrinkage filler and paint. Maintain paint on a regular basis.</td>
</tr>
<tr>
<td>Nail head corrosion in weather boards at marine sites.</td>
<td>Use galvanised nails in external elements, punch nails, fill nail head holes with appropriate filler and paint element with oil based primer and two finish coats of external gloss paint. Repaint regularly to maintain protection.</td>
</tr>
<tr>
<td>Nail corrosion and surrounding decay in weatherboards at the corner of buildings at marine sites.</td>
<td>Provide shielding from salt deposition. Use galvanised nails in external elements, punch nails, fill nail head holes with appropriate filler and paint element with oil based primer and two finish coats of external gloss paint. Clean down surface regularly. Repaint regularly to maintain protection.</td>
</tr>
<tr>
<td>Localised decay in bargeboards.</td>
<td>Use preservative treated timber. Use oil based primer and gloss finish coats. Fill and paint gaps. Clean and repaint regularly. Check condition of guttering regularly and repair as necessary.</td>
</tr>
</tbody>
</table>
APPENDIX 2

RISK ASPECT TABLES AND MAPS

A2.1 Tables and Maps Relating to Material Degradation Risk Aspects

Tables and maps referred to in Chapter 5 relating to material degradation risk aspects are set below.

**Table A2.1** Mean Annual Rainfall at Bureau of Meteorology Sites in the Sydney Region (mm/year)

<table>
<thead>
<tr>
<th>SITE</th>
<th>LATITUDE</th>
<th>LONGITUDE</th>
<th>RAINFALL (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BANKSTOWN</td>
<td>-33.9181</td>
<td>150.9864</td>
<td>917</td>
</tr>
<tr>
<td>BOWRAL</td>
<td>-34.4864</td>
<td>150.4021</td>
<td>939.4</td>
</tr>
<tr>
<td>CAMPBELLTOWN</td>
<td>-34.0833</td>
<td>150.8167</td>
<td>829.8</td>
</tr>
<tr>
<td>GOSFORD</td>
<td>-33.3949</td>
<td>151.329</td>
<td>1320.3</td>
</tr>
<tr>
<td>GLENFIELD</td>
<td>-33.9667</td>
<td>150.9</td>
<td>794.8</td>
</tr>
<tr>
<td>KATOOMBA</td>
<td>-33.7135</td>
<td>150.2983</td>
<td>1410.9</td>
</tr>
<tr>
<td>CAMDEN AIRPORT</td>
<td>-34.0391</td>
<td>150.689</td>
<td>828.8</td>
</tr>
<tr>
<td>WOLLONGONG Uni</td>
<td>-34.4033</td>
<td>150.8772</td>
<td>1373.5</td>
</tr>
<tr>
<td>PROSPECT RESERVOIR</td>
<td>-33.8193</td>
<td>150.9127</td>
<td>878.5</td>
</tr>
<tr>
<td>RICHMOND UWS</td>
<td>-33.6183</td>
<td>150.7483</td>
<td>807.1</td>
</tr>
<tr>
<td>RICHMOND RAAF</td>
<td>-33.6022</td>
<td>150.7794</td>
<td>810.3</td>
</tr>
<tr>
<td>RIVERVIEW</td>
<td>-33.8256</td>
<td>151.1556</td>
<td>1138.7</td>
</tr>
<tr>
<td>SEVEN HILLS</td>
<td>-33.7722</td>
<td>150.9303</td>
<td>945.1</td>
</tr>
<tr>
<td>SYDNEY (OBSERVATORY HILL)</td>
<td>-33.8607</td>
<td>151.205</td>
<td>1221.9</td>
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<tr>
<td>SYDNEY AIRPORT</td>
<td>-33.9411</td>
<td>151.1725</td>
<td>1102.4</td>
</tr>
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<td>WOLLONGONG POST OFFICE</td>
<td>-34.4333</td>
<td>150.8333</td>
<td>1135.6</td>
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<tr>
<td>NORAH HEAD</td>
<td>-33.2815</td>
<td>151.5759</td>
<td>1246</td>
</tr>
<tr>
<td>PARRAMATTA</td>
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<td>921.3</td>
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<tr>
<td>PARRAMATTA NORTH</td>
<td>-33.7917</td>
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<td>983.5</td>
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<tr>
<td>PEATS RIDGE</td>
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<td>PENNANT HILLS</td>
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<td>PICTON</td>
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<tr>
<td>KULNURRA</td>
<td>-33.2333</td>
<td>151.2</td>
<td>1207.1</td>
</tr>
<tr>
<td>LIVERPOOL</td>
<td>-33.9272</td>
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<td>869.5</td>
</tr>
<tr>
<td>LUCAS HEIGHTS</td>
<td>-34.0517</td>
<td>150.9</td>
<td>1047.3</td>
</tr>
<tr>
<td>MARSFIELD</td>
<td>-33.7744</td>
<td>151.1156</td>
<td>1149.3</td>
</tr>
<tr>
<td>MOSSVALE</td>
<td>-34.5444</td>
<td>150.3768</td>
<td>981.5</td>
</tr>
<tr>
<td>MOUNT VICTORIA</td>
<td>-33.5917</td>
<td>150.2544</td>
<td>1061.1</td>
</tr>
<tr>
<td>SITE</td>
<td>LATITUDE</td>
<td>LONGITUDE</td>
<td>MEAN 9A.M. TEMP</td>
</tr>
<tr>
<td>---------------------------</td>
<td>-----------</td>
<td>-----------</td>
<td>-----------------</td>
</tr>
<tr>
<td>BANKSTOWN</td>
<td>-33.9181</td>
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<td>16.7</td>
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<td>BOWRAL</td>
<td>-34.4864</td>
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<td>12.8</td>
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<td>-34.0833</td>
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<td>17.1</td>
</tr>
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<td>GOSFORD</td>
<td>-33.3949</td>
<td>151.329</td>
<td>17.3</td>
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<td>GLENFIELD</td>
<td>-33.9667</td>
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<td>16.7</td>
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<td>KATOOMBA</td>
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<td>150.2983</td>
<td>11.2</td>
</tr>
<tr>
<td>CAMDEN AIRPORT</td>
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### Table A2.3 Mean 3 P.M. Temperature at Bureau of Meteorology Sites in the Sydney Region (°C)

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Figure A2.1 Mean 3 p.m. Relative Humidity
**Figure A2.2** Time of Wetness at Study Sites

Source of Base Map of Sydney Region: Steve Parish Publishing 1997

Figure A2.3 Rainwater pH, Salt Content and Conductivity at Test Sites across Sydney Region
Figure 2.4 Estimated Salt Deposition
Source of Base Map of Sydney Region: Steve Parish Publishing 1997

Pollutant Levels Recorded by Environment Protection Authority and at Study Sites
Figure A2.8 Estimated Corrosion of Steel Coupons in the Sydney Region (μm/year)
Figure A2.9 Estimated Mean Zinc Wire on Iron Core Zinc Corr Corrosion in the Sydney Region (index number)
Figure A2.10 Timber Moisture Content in the Sydney Region (estimated % based on 3p.m. relative humidity)
Figure A2.11 Estimated First Year Corrosion Rate for Bright Nails in Radiata Pine, Douglas Fir and Mountain Ash in the Sydney Region (g/m².year)