DETERIORATION PROCESSES AFFECTING HISTORIC SITES IN ANTARCTICA
AND THE CONSERVATION IMPLICATIONS.

by

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A thesis submitted in fulfilment of the requirements of the
Degree of Doctor of Philosophy at the
University of Canberra.

September 2011
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ABSTRACT

Despite the widespread belief that deterioration is minimal or absent in Antarctica because of the ‘dry cold’, field research undertaken for this thesis at twelve Antarctic sites identified diverse deterioration problems, often related to moisture and salts. Accurate diagnosis of causes of deterioration is essential to ensure appropriate conservation treatments and rate measurements can help determine treatment priorities.

The main methods used in the research were field observations at 12 locations, various analyses of samples of materials and studies of temperature and relative humidity measurements and wind and other observational data from diverse sources. Temperature and humidity data measured by dataloggers inside of the AAE main hut at Cape Denison were used to assess potential changes in interior conditions following ice removal. Since exposure of sample materials to measure rates of deterioration by light and wind proved problematic, new methods based on repeated in situ observations of historic materials were developed, particularly to assess the damage to wood caused by wind. Modified ISO standard methods were used to measure salt deposition and corrosion rates and Raman microscopy and XRD were used to analyse salts. Visitor questionnaires and observations were employed to examine attitudes and awareness of conservation requirements relevant to site management. The outcomes of conservation treatments were assessed by field observations and reviews of site reports.

The main conclusions of the research were that diagnosis of some conservation problems has mis-attributed or over-stated the seriousness of some problems and under-estimated others.

Meltwater was found to be a greater risk than ice accumulation, except where the weight of ice is unsupported. Analysis of temperature and RH data at Cape Denison found hoarfrost formation on sensors indicate conditions are colder than in reality.

Removal of ice, a key conservation strategy at most huts, has not reduced high humidity as intended and treatments aimed at removing and continued exclusion of ice may not succeed unless mass transfer changes occurring in buildings are considered. These should determine whether internal cycles involving phase change (formation of hoarfrost and melting of ice from condensation occurring inside walls and ceilings) could continue to cause cyclic melting and re-freezing on structures and artefacts inside the building even if ice ingress is excluded. Melting of ice was often associated with corrosion and biodeterioration.

Corrosion rates at inland locations were the lowest measured on earth, but coastal corrosion rates exceeded predictions from ISO standard 9223 and were comparable to temperate rural Australia. Measurements found conditions for corrosion occurred above -10°C when RH exceeded 50%. Thus the ISO standard, widely used to estimate corrosion risks, underestimates these risks.

Inside Ross Island huts, analyses found sulphates were more prevalent than chlorides, despite proximity to the sea. The author identified defibring at some locations at Cape Denison and more extensively at Ross Island and Cape Adare and linked this to salts rather than ‘freeze-thaw’ cycles. Referring to more detailed subsequent research by others at Ross Island, the difficulties in diagnosing salt risks were identified since winds remove damaged fibres which may synergise surface loss.
Observations and measurements and surface damage to timber at Cape Denison showed location of damage is consistent with the boundary layer formed by katabatic winds, thus losses at edges and corners of buildings are high, but were overstated elsewhere. Plucking of wood fibres in the lee of the wind may be as damaging as particle impacts. Photodeterioration observations showed damage events occur relatively rarely over much of the building surfaces.

Observations at historic sites found significant variability in visitor impacts. Visitors’ attitudes generally supported retention of older buildings but were generally less supportive of retaining outdoor artefacts implying a need to improve interpretation. Analysis of selected site management plans identified information gaps in diagnosing deterioration and in evaluating treatments. Scientific resources of historic sites have been frequently overlooked and removal of dateable bio-artefacts and datum points in environmental clean ups could threaten opportunities to derive further historical and environmental information. The thesis proposes a framework for identifying and conserving these resources.

**Significance of the findings**
The research helps to provide a more holistic approach to understanding deterioration of Antarctic historic sites and provides a framework for assessing conservation strategies that could be applied in other locations with severe climates.
FORM B
CERTIFICATE OF AUTHORSHIP OF THESIS

Except where clearly acknowledged in footnotes, quotations and the bibliography, I certify that I am the sole author of the thesis submitted today entitled –

DETERIORATION PROCESSES AFFECTING HISTORIC SITES IN ANTARCTICA AND THE IMPLICATIONS FOR CONSERVATION.

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The material in the thesis has not been the basis of an award of any other degree or diploma except where due reference is made in the text of the thesis.

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Signature of Candidate

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DETERIORATION PROCESSES AFFECTING HISTORIC SITES IN ANTARCTICA AND THE IMPLICATIONS FOR CONSERVATION.

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The following publications are referred to in the chapters indicated in brackets.

A. Hughes, JD 1992 [chapters 2, 6, 7, 11]
Deterioration problems requiring investigation to develop methods for in situ preservation of cultural heritage at Mawson and Davis Stations.
Australian Antarctic Division, Hobart

B. Hughes, JD 1994 * [chapter 10]
Antarctic historic sites: the tourism implications.
Annals of Tourism Research (University of California) 21(2):281-294

C. Davis, BW and Hughes, JD 1995 * [chapter 10]
A Management Strategy for Tourism at Historic Sites and Monuments in Polar Tourism: Tourism in the Arctic and Antarctic Regions eds Hall, CM and Johnston, MJ: 235-255
Belhaven Press, Cambridge, UK

D. Hughes, JD King, GA and O’Brien, DJ 1996 * [chapter 6]
Corrosivity map of Antarctica - revelations on the nature of corrosion in the world's coldest, driest, highest and purest continent.
13th International Corrosion Conference, Melbourne, November 1996.
Australasian Corrosion Association publication; paper 24 (CD ROM)

E. Hughes, J; Pearson, C; Daniel, V and Cole, I 1999 * [chapter 4]
Monitoring of environmental conditions in a severe climate: how this can assist in development of conservation strategies for historic buildings and artefacts in Antarctica.
ICOM Committee for Conservation Triennial Conference, Lyon 29 August- 3 September 1999
Volume I: 57-63

F. Hughes, JD 2000 * [chapters 3, 4]
Ten myths about the preservation of historic sites in Antarctica and some implications for Mawson’s Huts at Cape Denison
Polar Record, Cambridge University Press 36(197): 117-130

G. Hughes, JD 2000 * [chapters 7, 8, 9]


J. Janet Hughes, George King and Wayne Ganther 2001 * [chapter 6] The application of corrosion information for the conservation of historic buildings and artefacts in Antarctica. NACE Northern Regions Conference, ‘Shining a light on Cold Climate Corrosion’, Fairbanks 26-28 February 2001


M. Janet Hughes, George King and Wayne Ganther 2004 * [chapter 6] Understanding cold climate corrosion: the need for basic corrosion research to improve conservation methodologies for historic artefacts in Antarctica. Metal 2001, 3-8 March 2001, University of Chile, Santiago

N. Calculation of AAE main hut volumes.

* Peer-reviewed publication.
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### GLOSSARY

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>AAE</td>
<td>Australasian Antarctic Expedition, led by Douglas Mawson, 1911-14</td>
</tr>
<tr>
<td>ablation (of ice)</td>
<td>“Combined processes (such as sublimation, fusion or melting, evaporation) which remove snow or ice from … a snow-field”. (US National Snow and Ice Data Center, NSIDC).</td>
</tr>
<tr>
<td>accumulation zone</td>
<td>An area in which the amount of snow and ice that is deposited exceeds that lost by deflation, evaporation, melting, or other means.</td>
</tr>
<tr>
<td>ANARE</td>
<td>Australian National Antarctic Research Expeditions</td>
</tr>
<tr>
<td>ANAN</td>
<td>Antarctic Non-Government Activity News, an Australian Antarctic Division publication</td>
</tr>
<tr>
<td>ASHRAE</td>
<td>American Society of Heating, Refrigeration and Airconditioning Engineers</td>
</tr>
<tr>
<td>AS/NZS</td>
<td>Australian and New Zealand Standard</td>
</tr>
<tr>
<td>ASOC</td>
<td>Antarctic and Southern Ocean Coalition</td>
</tr>
<tr>
<td>ATCM</td>
<td>Antarctic Treaty Consultative Meeting</td>
</tr>
<tr>
<td>ATS</td>
<td>Antarctic Treaty Secretariat</td>
</tr>
<tr>
<td>AWS</td>
<td>Automatic Weather Station</td>
</tr>
<tr>
<td>BANZARE</td>
<td>British Australian and New Zealand Research Expedition, 1927-30</td>
</tr>
<tr>
<td>BOM</td>
<td>[Australian] Bureau of Meteorology</td>
</tr>
<tr>
<td>Butynol, Butylclad</td>
<td>Trade names of butyl rubber sheeting roof membranes used at Ross Dependency huts.</td>
</tr>
<tr>
<td>CEP</td>
<td>Committee for Environmental Protection (of Antarctica), an Antarctic Treaty committee.</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CMP</td>
<td>Conservation Management Plan</td>
</tr>
<tr>
<td>corrosion (fig 7.1)</td>
<td>The US Navy Hydrographic Office publication No 609, 1952 definition: “wearing away of the surface of ice or other material through the friction of solid material transported by water or air”. Discussed in Chapter 7.</td>
</tr>
<tr>
<td>conservation</td>
<td>“all the processes of looking after a place so as to retain its cultural significance” (Burra Charter of Australia ICOMOS), thus inclusive of preservation, restoration, etc.</td>
</tr>
<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation, the Australian Government’s main research agency</td>
</tr>
<tr>
<td>defibring (fig 2.2)</td>
<td>Effect on the surface of wood of chemical action by salts, not ‘freeze-thaw’ processes. The same process is called ‘defibration’ by Blanchette et al (2002), see references. Discussed in section 2.5.3 and differentiated from ‘defibring’ used by Kaila (1988).</td>
</tr>
<tr>
<td>DEW Line</td>
<td>‘Distant Early Warning’ Line, a system of military bases in the Arctic during the Cold War of 1947-1991</td>
</tr>
<tr>
<td>EMC</td>
<td>Equilibrium Moisture content. See also MC. Moisture is released from the cell walls until it stabilises at an equilibrium moisture content (EMC) dependent on RH and ambient temperature. Thus EMC is the point at which wood is stable and in equilibrium with the humidity of its surroundings and is no longer gaining nor losing moisture.</td>
</tr>
<tr>
<td>EPF</td>
<td>Expeditions Polaires Francaises</td>
</tr>
<tr>
<td>EW</td>
<td>Early wood</td>
</tr>
<tr>
<td>fabric</td>
<td>“All the physical material of the place including components, fixtures, contents, and objects”. (Burra Charter of Australia ICOMOS)</td>
</tr>
<tr>
<td>firn</td>
<td>Rounded, well-bonded snow that is older than one year; firn has a density greater than 550 kilograms per cubic-meter (35 pounds per cubic-foot); called névé during the first year.</td>
</tr>
<tr>
<td>föhn</td>
<td>Wind warmed and dried by descent, in general on the lee side of a mountain.</td>
</tr>
<tr>
<td>freeze-thaw</td>
<td>This term was used by various authors to define a range of effects, discussed in Chapter 4.</td>
</tr>
</tbody>
</table>

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1 Detailed references to both scientific and vernacular Antarctic terminology are available in ‘The Antarctic Dictionary- a complete guide to Antarctic English’, by Bernadette Hince, CSIRO Publishing, Collingwood, Victoria Australia 2000 and the National Snow and Ice Data Center (US) website at [http://nsidc.org/arcticmet/glossary/permafrost.html](http://nsidc.org/arcticmet/glossary/permafrost.html)
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<tr>
<td>damage</td>
<td>but which are inconsistent or in some cases inaccurate (for example, defibring has often been mis-attributed to freeze-thaw damage). Freezing and thawing processes can both cause damage, but for different reasons. Freezing damage affecting rocks is caused by physical processes at the freezing front, whereas thawing damage is essentially water damage.</td>
</tr>
<tr>
<td>GOSEAC</td>
<td>Group of Specialists on Environmental Affairs and Conservation, a group within the Scientific Committee on Antarctic Research</td>
</tr>
<tr>
<td>HERCON criteria</td>
<td>Heritage Conservation criteria adopted by the [Australian] National Environment Protection and Heritage Council (EPHC) in 2008 to provide a consistent set of national criteria to identify and manage heritage across Australia.</td>
</tr>
<tr>
<td>hoarfrost</td>
<td>A deposit of interlocking ice crystals (hoar crystals) formed by direct sublimation on objects, usually those of small diameter freely exposed to the air, which surface is sufficiently cooled, mostly by nocturnal radiation, to cause the direct sublimation of the water vapor contained in the ambient air (NSIDC).</td>
</tr>
<tr>
<td>IAATO</td>
<td>International Association of Antarctic Tour Operators, a NGO.</td>
</tr>
<tr>
<td>ICOMOS</td>
<td>International Council on Monuments and Sites, a non-government body linked to UNESCO.</td>
</tr>
<tr>
<td>IGY</td>
<td>International Geophysical Year - an international program of scientific research conducted during 1956-57.</td>
</tr>
<tr>
<td>IPHC</td>
<td>International Polar Heritage Committee, a committee of ICOMOS</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standards Organisation</td>
</tr>
<tr>
<td>katabatic</td>
<td>“Any wind blowing down an incline; the opposite to anabatic wind. If the wind is warm, it is called a foehn; if cold, it may be a fall wind (bora), or a gravity wind (mountain wind)” (NSIDC). In Antarctica these are high velocity winds flowing from the polar plateau.</td>
</tr>
<tr>
<td>LW</td>
<td>Late wood</td>
</tr>
<tr>
<td>maintenance</td>
<td>The “continuous protective care of the fabric and setting of a place, …. distinguished from repair. Repair involves restoration or reconstruction”. (Burra Charter of Australia ICOMOS)</td>
</tr>
<tr>
<td>MC</td>
<td>Moisture content is the weight of water contained in a piece of timber, as a percentage of the weight of oven-dry wood. Newly cut wood has a high MC.</td>
</tr>
<tr>
<td>MHF</td>
<td>Mawson’s Huts Foundation, a non-government organisation undertaking conservation at the AAE site at Cape Denison.</td>
</tr>
<tr>
<td>nd</td>
<td>No date</td>
</tr>
<tr>
<td>NEPA</td>
<td>[US] National Environmental Protection Act</td>
</tr>
<tr>
<td>névé</td>
<td>One year old snow which is in the process of bonding together and compacting. It has a density greater than 550 kilograms per cubic-meter; see also ‘firm’.</td>
</tr>
<tr>
<td>NGO</td>
<td>Non Governmental Organisation</td>
</tr>
<tr>
<td>NSS</td>
<td>Non-sea salt, see Chapter 5</td>
</tr>
<tr>
<td>NZAHT</td>
<td>New Zealand Antarctic Heritage Trust, a non-government organisation undertaking conservation at historic sites in the Ross Dependency.</td>
</tr>
<tr>
<td>permafrost</td>
<td>“Layer of soil or rock, at some depth beneath the surface, in which the temperature has been continuously below 0 °C for at least some years. It exists where summer heating fails to reach the base of the layer of frozen ground”. (US National Snow and Ice Data Center, NSIDC)</td>
</tr>
<tr>
<td>ppb, ppm</td>
<td>Parts per million, parts per billion</td>
</tr>
<tr>
<td>preservation</td>
<td>“Maintaining the fabric of a place in its existing state and retarding deterioration”. (Burra Charter of Australia ICOMOS)</td>
</tr>
<tr>
<td>PVD</td>
<td>Peak-valley distance, the height difference between latewood and earlywood affected by corrosion</td>
</tr>
<tr>
<td>reconstruction</td>
<td>“Returning a place to a known earlier state and is distinguished from restoration by the introduction of new material into the fabric”. (Burra Charter of Australia ICOMOS)</td>
</tr>
<tr>
<td>restoration</td>
<td>“Returning the existing fabric of a place to a known earlier state by removing accretions or by reassembling existing components without the introduction of new material”. (Burra Charter of Australia ICOMOS)</td>
</tr>
</tbody>
</table>

2 The precise definitions in the Burra Charter are used interchangeably by many people in common usage.
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Term or Definition</th>
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</thead>
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<tr>
<td>RH</td>
<td>Relative humidity, the percentage of water in the air compared to that at saturation</td>
</tr>
<tr>
<td>SCAR</td>
<td>Scientific Council on Antarctic Research</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
</tr>
<tr>
<td>SMA</td>
<td>Specially Managed Area, also called ASMA (Antarctic SMA)</td>
</tr>
<tr>
<td>SPA</td>
<td>Specially Protected Area, also called ASPA (Antarctic SPA)</td>
</tr>
<tr>
<td>Sp, spp</td>
<td>Sp= species (singular); spp= species (plural)</td>
</tr>
<tr>
<td>SPRI</td>
<td>Scott Polar Research Institute, University of Cambridge</td>
</tr>
<tr>
<td>SS</td>
<td>Sea salt (as discussed in Chapter 5), distinct from non sea salt (NSS)</td>
</tr>
<tr>
<td>SSSI</td>
<td>Site of Special Scientific Interest. This designation was replaced by ASPA and ASMA.</td>
</tr>
<tr>
<td>sublimation</td>
<td>Phase change directly from the solid to the gaseous state without becoming liquid.</td>
</tr>
<tr>
<td>TAAF</td>
<td>Territoires Australes et Antarctiques Francaises</td>
</tr>
<tr>
<td>tin pest</td>
<td>Deterioration of tin caused by allotropic change, see Chapter 6.</td>
</tr>
<tr>
<td>Time of Wetness, TOW</td>
<td>The period (usually in hours per year) during which a metallic surface is covered by adsorptive and/or liquid films of electrolyte that are capable of causing atmospheric corrosion. (ISO 9223: 3.2)</td>
</tr>
<tr>
<td>TNB</td>
<td>Terra Nova Bay, Italian station in the Ross Sea area.</td>
</tr>
<tr>
<td>UKAHT</td>
<td>United Kingdom Antarctic Heritage Trust, non-government organisation undertaking conservation at UK Antarctic sites.</td>
</tr>
</tbody>
</table>
PREFACE

The author first travelled to Antarctica in 1985 to record the condition of artefacts and contribute to a conservation management plan for ‘Mawson’s Huts’, the abandoned base of the Australasian Antarctic Expedition (1911-14) at Cape Denison.

This initial visit revealed many conservation problems, such as unexpectedly extensive corrosion, although other problems, such as ‘timbers worn paper-thin’, appeared overstated. The favoured treatment strategy for the building was to remove the ‘damaging’ ice accumulation inside it and install vapour barriers to prevent further ingress and lower RH. Subsequent visits to other Antarctic historic sites revealed similar strategies had not lowered high RH, and additional problems had occurred.

Reasons for choosing this topic

These observations suggested that further materials conservation research was required to clarify causes and rates of deterioration to develop more effective conservation strategies.

Field observations prompted questioning of widespread assumptions, including:

- whether removing ice could reduce high RH;
- whether improved strategies to control temperature are needed to reduce meltwater-related problems; and
- whether corrosion can occur in below freezing and at RH below 80%.

Given the severe and unfamiliar conditions in Antarctica and the high costs of logistics, it was considered important to make best use scientific information already available in the literature and to use standardised methods to measure rates of deterioration. This enables comparison with data from other comparable locations (especially the Arctic) and facilitates evaluation of the efficacy of conservation treatments. Understanding the interaction of deterioration processes was also considered important.

The conservation of historic buildings requires a multidisciplinary approach involving consideration of historical significance, materials science, engineering, architecture and environmental management. This thesis therefore attempts to communicate the importance of integrating all these perspectives to improve management of Antarctic historic sites.

Limits of the scope of the thesis

Geographic and logistics constraints

The difficulty of obtaining travel and logistics support severely limited opportunities to examine Antarctic sites. There was also little funding to conduct analysis of materials or to obtain appropriate equipment. Travel costs to Antarctica are particularly high, and in the case of sea voyages, requires many weeks of travel for a few days ashore. Nevertheless the author visited 12 Antarctic historic sites dating from 1895 to 1961, including five of the six most significant ‘Heroic Age’ sites. This is unusual since few conservators have the opportunity to visit more than one or two locations in such a remote continent. Four voyages were undertaken over a 12 year
period, but it was not possible to visit Antarctic Peninsula sites, which have a warmer climate and more visitors, although information about these sites was included where possible.

**Coverage of historical significance of sites**
Space limitations precluded detailed discussion of the significance of the sites and artefacts, except when directly relevant to the understanding of deterioration processes or the development of treatment methods.

**Limited consideration of structural issues**
Structural problems of Antarctic historic buildings require professional assessment by an engineer, which is beyond the author’s skills as a materials conservator. However, where materials deterioration has structural implications these are discussed without detailed engineering calculations.

**Limitations on treatment of sites and artefacts**
The thesis focusses on causes and rates of deterioration and the implications for treatments, but treatments could not be carried out due to the scale of work and authorisation requirements.

**Structure of the thesis**
This thesis used the standard scientific approach (theory, hypothesis, methodology, results, statistical analysis, discussion and conclusions) to study the key deterioration processes affecting the Antarctic historic sites.

Chapter 1 analyses historical significance criteria for the sites and their climatic and political context.
Chapter 2 examines the scientific and heritage literature, and identifies overall gaps in knowledge.
Chapter 3 identifies an overall methodological approach for the thesis and provides the observations template used at each site and the risk assessment tool.
Chapters 4 to 9 each study a particular deterioration issue (temperature, humidity and ice; salts; corrosion; wind damage; photodeterioration and biodeterioration) using scientific methodologies to identify the deterioration process, measure deterioration rates and to consider treatment implications.
Chapter 10 uses a questionnaire to survey visitors about their visit and their views on preservation of the historic sites. Field observations were used to assess physical impacts of visitation and consider management requirements.
Chapter 11 examines the interactions of deterioration processes to and considers the implications for the effectiveness of conservation management plans.

**Benefits of the research**
The research provides new and more ‘holistic’ information on the deterioration of materials and buildings in extreme climates. By improving diagnosis of the cause of deterioration, rather than treating symptoms, treatments can be more effective. Improved quantification of affecting deterioration processes (eg minimum conditions for deterioration to occur) can have wider benefits applicable to managing environmental risks from deterioration of buildings and artefacts and in designing new infrastructure in Antarctica.
1. THE CLIMATIC, HISTORICAL AND POLITICAL CONTEXT OF ANTARCTIC HISTORIC SITES

Figure 1.1: Barents hut, Novaya Zemlya, Siberia, 1596 (Mirsky 1970: 40)

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INTRODUCTION

The survival of the hut of the 16th century Dutch Arctic explorer Willem Barents (figure 1.1) inspired the famous British Antarctic explorer Robert Falcon Scott to write:

"Wm Barents House in Novaya Zemlya built 1596, found by Captain Carlsen 1871 (275 years later) intact, everything inside as left! What of this hut!" (Scott 1913: 124).

A later commentator stated that at that time Scott was:

“very worried about his hut at Cape Evans and was upset to find the hut at Hut Point built ten years before, had filled with ice and snow. Little did he know that the snow and ice which eventually filled both of his huts would do so much to preserve them and their contents for another seventy years” (anon 1983).

Increasing numbers of people now visit Scott’s hut and other buildings used by the first explorers of the last-discovered continent. The buildings evoke the isolation and the hardships of the severe climate and seem ‘frozen in time’. But, what is the state of preservation of Barents’ hut today? Can the future of Scott’s hut be inferred from Barents’ hut? What is happening to the other huts of Antarctic explorers? What are the factors that affect preservation and how can these places be preserved for the future?

1.1 Aims and objectives

The overall aim of this thesis is to improve understanding of processes of deterioration affecting Antarctic historic sites and use this knowledge to improve conservation treatments by meeting the following objectives:

- Reviewing the condition of Antarctica’s historic sites, based on field studies at 12 sites and using published and unpublished reports to assess those not visited;
- Examining the cause of deterioration and measuring rates of deterioration and predict long term impacts and consider how climate change may influence deterioration rates;
1. THE CLIMATIC, HISTORICAL AND POLITICAL CONTEXT OF ANTARCTIC HISTORIC SITES

- Assessing the effectiveness of conservation treatments of buildings and artefacts (excepting structural repairs);
- Preparing a risk model and evaluating site management plans.

This chapter introduces Antarctica’s climate, the historical background of Antarctic exploration and its unique political context of the Antarctic Treaty, under which historic sites are protected. Since scientific research was a major activity at many of the sites, the scientific history of the sites is briefly considered since this is important in deciding conservation priorities, and in some cases, how sites should be conserved. Because of the widespread expectation that conservation problems of Antarctic historic sites have already been solved in the Arctic, some comparisons of the two regions are made.

1.2 Climatic conditions in Antarctica

Although both polar regions are obviously cold, they have significant climatic differences relevant to conserving their historic sites.

Figure 1.2: Geographic comparison of the Arctic and Antarctic (AAD website, downloaded 2009)
Temperatures are generally lower in Antarctica than the Arctic

The Arctic centres on an ocean surrounded by the Eurasian and North American landmasses with Greenland and archipelagos of smaller islands. Antarctica is a large, high altitude continent separated from other landmasses by huge expanses of ocean so its marine and atmospheric circulation is largely isolated from the rest of the planet. Antarctica is dominated by its extensive permanent ice cap up to 4,000 metres thick which reflects sunlight so temperatures do not increase markedly in summer whereas in the Arctic only Greenland and small areas of Novaya Zemlya, Svalbard, Ellesmere Island and Jan Mayen Island (figure 1.2) have permanent glaciers. The ice cover and oceanic isolation help maintain low temperatures in Antarctica.

At Resolute Bay (74°N), one of the coldest populated places in the Arctic, the monthly mean for the hottest month (July) is +4°C (Strub 1996: 169) whereas the monthly mean for the hottest month (January) at Scott Base (78°S), is -4.5°C (http://www.niwascience.co.nz/edu/resources/climate/antarctic/ downloaded on 1 December 2007).

Antarctica’s wind regime is more severe

The topography and size of the Antarctic ice cap promotes the formation of dense cold air masses which flow downslope producing severe ‘katabatic’ (down-flowing) winds. Katabatic winds occur in extensive areas of Antarctica, but are less frequent and more localised in the Arctic (e.g. the pitoraq winds of East Greenland).

The Southern Ocean is dominated by westerly airflows and low pressure 'depressions' that form and dissipate in a continuous cycle. These circulate around Antarctica in a clockwise direction at about the latitude of the Antarctic Circle so katabatic winds occur every few days.

Winds damage historic buildings throughout the world but it is the extreme speed and frequency of katabatic winds that makes them so problematic in Antarctica, discussed in greater detail in Chapter 7.
Only 2% of the total area of Antarctica is bare of ice and wildlife favour these areas since most species only breed on land. Bare rock (for building foundations) and proximity of wildlife (for food and study) were important in selecting bases for expeditions during the early exploration of Antarctica. The Australian explorer Mawson selected Cape Denison after unsuccessfully seeking an ice-free site along the ice cliffs of Terre Adelie for several weeks. The unusual period of calm weather when they landed gave no warning of the terrible conditions they later experienced (figure 1.4). After two years experiencing winds that averaged approximately 80km/hr he called it the ‘Home of the Blizzard’ and the expedition’s meteorological studies revealed it to be the windiest place on earth (Mawson 1915).
Low humidity and precipitation

Greater exposure to maritime climatic conditions in the Arctic results in generally higher precipitation than Antarctica, and the higher average temperatures means a greater proportion of that precipitation falls as rain rather than snow. Precipitation (snow) is less than 50mm per year in the interior of Antarctica and is highest in the warmest and most northerly part of Antarctica, the Antarctic Peninsula, which receives the equivalent of up to 900mm of water precipitation per year (McGonigal & Woodworth 2002: 52-53), comparable to Sydney, Australia. Rain is rare except in the northern part of the Antarctic Peninsula in summer. This means deposited salts are rarely washed from surfaces which increases corrosion risks (discussed in Chapter 6).
The strong effects of the circulating low pressure cells\(^1\) combined with the katabatic flow of cold air from the high polar plateau of the Antarctic cause strong periodic changes of humidity at coastal locations in Antarctica which are generally less pronounced in the Arctic. The effects of RH variation are discussed in detail in Chapter 4.

Climate change is a very significant issue for the polar regions as change is widely considered to be occurring there at a faster rate than elsewhere on earth (Steig et al 2009).

The generally colder, drier conditions of Antarctica have inhibited soil formation, whereas in the Arctic soils have formed from rock weathering and from biological decomposition of plants. Large areas of the Arctic are permafrost soils that are permanently frozen to a significant depth (often tens of metres deep) and only the surface melts in summer (figure 1.5). ‘Frost heave’ causes structural damage to buildings and extensive research in the Arctic is devoted to understanding the phenomena (Washburn 1979). Permafrost in Antarctica occurs in a fraction of the 2% of ice-free land surface and the active layer (the layer that freezes and thaws with the seasons) is usually thin and often contains little ice with little biological material.

These climatic differences imply that deterioration processes and rates may also differ so conservation strategies for Arctic historic sites may not be applicable in Antarctica.

Figure 1.5: Permafrost heave affecting a burial in Yukon (Chaplin & Barr 2004: 54)

\(^1\) These cells determine whether winds blow over sea or land, thus affecting moisture content of the air.
1.3 Historical context of polar sites

Arctic and Antarctic historic sites are compared to examine the historic values at risk and to consider implications for site management. The history of polar exploration and the technology of each era influenced the designs of buildings and the materials used, which therefore affects the types of conservation problems they experience.

Prehistoric sites

While there are numerous prehistoric sites throughout the Arctic there is no reliable evidence of indigenous populations in the Antarctic although Chilean research published evidence of Fuegan artefacts from natives who accompanied sealers to the South Shetland Islands during the nineteenth century (Stehberg & Lucero 1995). A Maori tribe established an independent settlement on the Subantarctic Auckland Islands in the nineteenth century (Smith 1910).

Many early Arctic sites have been excavated and extensively studied, such as the 500-year-old ‘mummies’ of Qilakitsoq in Greenland (Hart-Hansen et al 1991) and Norse sites in Greenland and North America. Most of these excavations are from soil or gravel, as shown in figure 1.6, rather than ice. The only Antarctic sites with comparable conditions are nineteenth century sealing sites on beaches in the Antarctic Peninsula (Stehberg and Luchero 1995).

Figure 1.6: Early twentieth century excavation in Greenland Hart-Hansen et al (1991: 21)
Seventeenth century Arctic sites

Fortifications, bridges and churches (figure 1.7) survive in Siberia and northern Russia dating from the seventeenth to nineteenth centuries (Opolovnikov and Opolovnikov 1989). Aspects of their condition and treatment are discussed in subsequent chapters when considering the natural condition of timber in cold conditions.

Figure 1.7: Siberian church (Opolovnikov & Opolovnikov 1989: 232)

In 1596 the Dutch explorer Barents attempted to find the north east passage to China. His ship became trapped in ice so he and his men were forced to build a hut ashore on the northeast coast of Novaya Zemlya. Barents’ hut is the oldest European-style hut in the High Arctic and was about 7.8 metres by 5.5 metres (Hacquebord & Blankenstein 1993), similar in size to several Antarctic timber huts. Carlsen visited the hut in 1871 (ibid) and stated it was in good condition. Artefacts from the expedition have been removed from the site over the past one hundred years, many by souvenir hunters, although some are in museums in Norway (Simonsen 1958), the Netherlands and Russia. A summary of Hacquebord’s analysis of causes of its current ruinous condition is given in Chapter 2.
The Norwegian archipelago of Svalbard, also known as Spitsbergen, has many sites from sixteenth to nineteenth century shore-based European whalers (Barr, S 1985). Burial in frozen peaty soils has produced exceptional preservation of human remains, clothing and equipment. The warmer, maritime climate of Svalbard, and the types of artefacts (trypots, tools and graves) are more comparable to Subantarctic islands or the Antarctic Peninsula, than most early Antarctic historic sites.

Figure 1.8: Tryworks on Svalbard (Hacquebord in Bjerck & Johannessen 1999: 9)

Figure 1.9: Body covered with cloth in grave, Svalbard (Bjerck and Johanessen 1999: 8)
Other Svalbard sites relate to coal mining, hunting by Russian fur trappers and various European explorers seeking routes to the North Pole (Barr 1985). Unfortunately no comprehensive list of historic sites is publicly available due to recent increases in human damage to sites (Barr, Riksantiksvaren Oslo, personal communication 2002). While Svalbard and Antarctic sites have some similarities (e.g., wooden buildings, maritime equipment) most Svalbard sites are much older and conservation of artefacts from peaty soil involves entirely different challenges to Antarctica.

**Nineteenth century Canadian sites**

Canadian Arctic historic sites that are historically and climatically comparable with Antarctica include Fort Magnesia (Barr, W & Blake 1990) at Payer Harbour on Pim Island, Nunavut (near Smith Sound); timber signposts erected by Peary at Cape Sheridan near the present-day military base of Alert; grave markers at Beechey Island and forts and caches such as Fort Conger and Northumberland, dating from the mid nineteen century when searchers were searching for Sir John Franklin's expedition, to the early twentieth century. Canadian researchers Hett and Weaver (1980) and Cross (1982) studied Captain Kellett’s storehouse at Dealy Island in detail (figure 1.10), discussed in subsequent chapters.

Figure 1.10: Kellett’s storehouse (photo by Martin Weaver in Harrowfield 1996)
Later Arctic sites

There are many wooden buildings in Alaska and the Yukon, mainly relating to gold mining and fur trading by the Hudson's Bay Trading Company, but these have much warmer climates than Antarctica.

Although there are no military sites in Antarctica (as military activity was prohibited under the 1959 Antarctic Treaty) North American military sites have some comparable conservation issues to Antarctic International Geophysical Year (IGY, 1957-58) sites due to similar construction styles and materials. DEW\textsuperscript{2} stations and weather stations such as Alert (Johnson 1990) on Ellesmere Island included barracks style accommodation similar to Antarctic ‘dongas’ with extensive use of plywood prefabricated panels with sandwich insulation. Despite the comparative remoteness of the Arctic it was strategically important during the 1945-1990 Cold War.

In the Russian Arctic Nansen’s refuge on Franz Josef Land (Barr 1991) and bases used by Sedov, the Duke of Abruzzi, Ziegler and Fiala; and Soviet-era meteorological bases are comparable to Antarctic historic sites in terms of climate, construction and materials and are discussed where relevant in subsequent chapters. Fedorov, a Russian scientist, gives fascinating diary descriptions of his visit in 1933 to the remains of huts and tents from these expeditions:

"Many expeditions left traces here. In effect it was a museum telling about the race to the Pole at the turn of the century. That museum should be put in order.” (Fedorov 1983: 106).

Fedorov’s observation, written in the 1930s, still awaits action although a joint Norwegian-Russian expedition (Barr 1991) made significant progress in recording sites which had not been visited for many years during the Cold War. Fedorov discussed the suitability of the buildings for the size of the earlier expeditions and pondered the navigational problems of the era from examining the equipment left behind and found flags intended by Fiala to claim undiscovered land. It is reassuring to find a scientist so respectful and interested in the possibilities of understanding history from the examination of the remains of former expeditions. This contrasts with the actions of Stefansson cited by Jenness (1990) who alleged gross damage and desecration at a Canadian site. Soviet weather stations were established along with military installations

\textsuperscript{2} Distant Early Warning (DEW) stations were used to detect intercontinental ballistic missiles.
(figure 1.12), some of which are still in use. A few concentration camps or 'gulags' (figure 1.11) in northern areas are climatically comparable with Antarctic buildings and used similar materials such as wood and metal sheeting (Philps 1997) although few conservation assessments are available.

Figure 1.11: Russian *gulag* (Brackman 2002: 38) showing typical infrastructure and environment
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Figure 1.12: Russian military base, Severnaya Zemlya (Chaplin & Barr 2004: 15)

Early Antarctic historic sites

As Antarctica was the last-discovered continent its historic sites are generally more recent than the Arctic. Table 1.1 lists sites, parties undertaking management, dates of construction/occupation, site type and significance. Figure 1.3 shows their locations.

While whaling and sealing were significant activities in the early exploration of Antarctica few land-based sites were established, located mostly in the Antarctic Peninsula (Torres & Aguayo 1993), (Simpson & Lewis Smith 1987) and on the South Shetland Islands (Pearson 2007). Sealing was undertaken in the Antarctic Peninsula from the early nineteenth century and the sites are characterised by ruined stone-walled walls with roofs made of whale ribs or timber, and work platforms for processing skins (for fur seals) or trypots for rendering blubber (elephant seals).
When whaling commenced in the Southern Ocean in the late nineteenth century, whales were hunted from ships and were processed on the ships. A Norwegian whaling station operated at Hector Station from 1906 to 1931 on Deception Island in the South Shetlands (figure 1.13). A whaler’s graveyard nearby was largely destroyed during a later volcanic eruption (Hacquebord 1992). The volcanic landscape and hot water beach have made this one of the most visited tourist locations in the Antarctic (Enzenbacher 1992).3

Figure 1.13: Hector Station (Hacquebord 1992)

Whaling, sealing and territorial claims (which could be done without landing) were ship-based so there was little incentive to establish shore bases. It was also difficult for wooden sailing ships of the mid-nineteenth century to break through the ice to shore without great risk. It is therefore not surprising that the first building on the continent, rather than an offshore island, was Borchgrevink’s hut at Cape Adare in 1895, built some 75 years after Bellinghausen’s first sighting of land in 1820. The Norwegian-style hut at Cape Adare was used for the first overwintering in Antarctica (1895) and was re-occupied during the Southern Cross expedition (1898-1900). Scientific work was undertaken and two Saami accompanied the expedition (figure 1.14) bringing traditional skills and clothing such as ‘finnesko’ shoes (Harrowfield 1981: 62). In

3 Tourism data published by IAATO available at www.iaato.org indicate this has been very popular for many years.
1912 the ‘Campbell Hut’ was erected close by for the Northern Party of the Scott’s *Terra Nova* expedition.

**Figure 1.14: Cape Adare ((Bernacchi 1901: 8))**

In the Antarctic Peninsula, Bruce’s Scottish National Antarctic expedition (1902-1904) and Nordenskjold’s Swedish Antarctic Expedition (1902-03) both established huts. Bruce’s building on Laurie Island (700 km east in the South Orkneys) is no longer extant. The Nordenskjold expedition built a hut at Snow Hill Island and a magnetic observatory in 1902. Their ship *Antarctic* sank and their party was separated with one group overwintering in a stone-walled shelter with a tarpaulin roof at Hope Bay and the other group built a stone shelter at Paulet Island.
Figure 1.15: Nordenskjold hut

Scott’s *Discovery* Hut was located as close as possible to the south of Ross Island but thick sea ice persisted until late in summer making access difficult. Thus subsequent South Pole expeditions such as Shackleton’s *Nimrod* expedition hut (1907-09) and Scott’s *Terra Nova* hut (1911-13), figure 1.16) were built further north on Ross Island, at Cape Royds and Cape Evans respectively.
Amundsen’s ‘Framheim’ hut was one of few early huts built on ice rather than rock but it vanished when the Bay of Whales ‘calved’ as icebergs several decades afterwards. Several other Antarctic expeditions also occurred around this time, but left no extant buildings.

The Australasian Antarctic Expedition (AAE) conducted scientific research in an unexplored part of the Antarctic coast directly south of Australia. One base was established at Cape Denison from two prefabricated wooden huts, joined when erected (see figure 1.17). The western base hut built on the Shackleton Ice shelf (Mawson 1915) disappeared when the ice shelf later broke up.
Early Antarctic building design

Pearson (1992) compared the design and performance of nine early Antarctic prefabricated timber buildings. Three were of Scandinavian design (traditional interlocking notched log construction), three were British designs with straight-sided walls and conventional roofs, and three were Australian with pyramidal roof shapes and closed-in verandahs. Six huts remain extant. Pearson integrated historical and archaeological information about the huts and assessed their suitability of in terms of insulation, heating efficiency, wind resistance and comfort.

Figure 1.18: Comparison of hut floor spaces\(^4\) (Pearson 1992: 275)

\(^4\) All huts are drawn to the same scale. Actual living spaces are hatched; other outlined areas were used for storage and work.
Increasing government involvement in Antarctic activities

Mawson’s orders for the British Australian and New Zealand Expedition (BANZARE) of 1928-30 included making territorial claims (figure 1.19). Several ‘Proclamation’ plaques are still extant and others are held in museum collections in Australia. BANZARE re-visited the AAE hut at Cape Denison in 1931.

Figure 1.19: BANZARE proclamation ceremony (Grenfell Price 1963: 225)

The competing territorial claims of France and Australia, arising from a mistake in publication of the eastern longitudes of Dumont d’Urville’s claim, were resolved just before the outbreak of the Second World War. France generously moved the border to allow Mawson’s Hut at Cape Denison to be included in the Australian Antarctic Territory because the French believed that Australians would wish to continue the research of the AAE and BANZARE using the original base (Bush 1988).

The establishment in 1939 of the US Antarctic Service, the first major government scientific program, set a trend for future programs by other nations. Two bases were established, West
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Base in the Bay of Whales, and East Base at Stonington Island in the Antarctic Peninsula. The bases were hastily evacuated at the outbreak of the Second World War resulting in large quantities of supplies and all the buildings being left behind (Broadbent 1992). The private Ronne Expedition Antarctic Research Expedition (1946-47) later established a hut on Stonington Island, well-known because of a popular book, ‘My Antarctic Honeymoon’ (Darlington 1957) written by one of the first women to overwinter on the Antarctic continent.

World War II curtailed Antarctic activity but the secret UK Operation Tabarin begun in 1943 (Russell & Taylor, Lamb 1945, anon no date) with 18 bases later used by the Falkland Islands Dependency Survey (FIDS) which took control after the war (Shears & Hall 1992).

The 1949-52 Norwegian-British-Swedish Expedition based in Dronning Maud Land was the first truly multi-national Antarctic expedition. It focussed exclusively on science rather than territorial assertions, which were becoming increasingly prevalent.

Australian National Antarctic Research Expeditions (ANARE) commenced in 1946 and established Australian government bases on Subantarctic Heard Island and on Macquarie Island in preparation for establishing bases on the Antarctic continent. Logistical difficulties were largely overcome by innovative use of war surplus materials, often originally designated for tropical use (Law 1983). These expedition bases are characterised by special huts built for scientific purposes such as upper atmospheric studies.

International Geophysical Year (IGY) of 1957-58

The IGY occurred during some of the most difficult years of the ‘Cold War’. Fogg (1992: 168-176) describes the political circumstances that broke the previous pattern of politically motivated expeditions and refocused the emphasis on science. A brief ‘thaw’ in the Cold War led to the inclusion of Soviet scientists and the insistence that members represented their science, and not their countries, helping avert some political problems.
The program included exchange of data and personnel between the stations of various nations. Eventually some 55 stations (figure 1.21) were established including an American station at the South Pole (thereby with a foot in each territorial claim), a Soviet base at the ‘Pole of Inaccessibility’ and a chain of stations on the polar plateau in the Australian-claimed sector (Dubrovnin & Petrov 1971). Many of these sites, such as Vostok, still exist but are rarely visited. The sheer volume of supplies and hazardous materials associated with scientific work at these and later sites has led to the present focus on removal of ‘rubbish’, which brings potential for conflict between environmental managers and cultural heritage specialists (Poland, Riddle & Zeeb 2003).

The 1957-58 Commonwealth Trans-Antarctic Expedition (TAE) crossed Antarctica and carried out scientific measurements including gravity determinations and seismic soundings of ice depth (Fogg 1992: 173). The TAE hut (figure 1.20) is now surrounded by New Zealand's Scott Base and its historic significance is recognised and protected.

Figure 1.20: TAE hut (author’s photo 1993)
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Figure 1.20: Map showing location of IGY bases (Fogg 1992: 170)

Fig. 6.5 Stations occupied in the Antarctic during the International Geophysical Year, 1957–58. Key: *Argentina*: 1 Orcadas, 2 Teniente Camara, 3 Decepción or Primero de Mayo, 4 Esperanza, 5 Melchior, 6 Almirante Brown, 7 General San Martín, 8 General Belgrano; *Australia*: 9 Macquarie Island, 10 Mawson, 11 Davis; *Belgium*: 12 Roi Baudouin; *Chile*: 13 Arturo Prat, 14 Pedro Aguirre Cerda, 15 General Bernardo O’Higgins, 16 Presidente Gabriel Gonzalez Videla; *France*: 17 Port-aux-Français, 18 Dumont d’Urville,
1.4 The political context of Antarctica

The most significant political events relevant to protection of historic sites are:

- the signing of the 1959 Antarctic Treaty, which requires protection of historic sites; and
- international ratification of the Madrid Protocol which extends that protection for designated sites, but forces the removal of non-historic sites for environmental protection reasons.

1.4.1 Antarctic Treaty

The Antarctic Treaty came into effect in 1961 and commits signatories to use Antarctica for peaceful purposes (Article I), suspends territorial claims (Article IV), seeks free exchange of scientific information and personnel (Article III), permits Treaty compliance inspections (Articles VII and VIII) and provides for periodic meetings (Article IX). The suspension of territorial claims helped overcome the difficulties imposed on scientific co-operation by the sector claims and tends to reduce the use of historic sites to bolster territorial claims.

The Antarctic Treaty meeting in Canberra in July 1961 led to the adoption of Recommendation I-IX (Historic Sites) in which governments were required to “adopt all adequate measures to protect such tombs, buildings or objects of historic interest from damage and destruction” (Harrowfield 1990). Recommendation VII-9 (Jackson 1992: 17) makes it the collective responsibility of the Treaty parties to ensure that a historic site is adequately protected. Historic sites are required to have signs in the four Antarctic Treaty languages (English, French, Russian and Spanish) denoting its protected status.

1.4.2 Madrid Protocol on Environmental Protection to the Antarctic Treaty Area Protection and Management (1991)

By 1991 the original 12 Treaty signatories increased to 39 nations. Increased scientific activity and logistical improvements resulted in general growth in the size and complexity of stations with extensive communication and accommodation facilities. Buildings were now larger, mainly
modular constructions of steel with complex insulation and vapour barrier systems such as the AANBUS system designed by Australian Construction Services (Incoll 1991). The growth in the number and size of stations and the increasing impact of human activities from waste and visual effects on the ‘last wilderness’ focussed attention on the protection of the Antarctic environment by both Non-Government Organisations (NGOs) such as Greenpeace as well as national governments.

The most significant features of the Madrid Protocol for historic sites are

- the system of Specially Protected Areas (SPAs) and Specially Managed Areas (SMAs) which improve the protection of environmental values through a permit system; and
- requirements for Management Plans for areas of special significance.

1.4.3 Definition and typology of Antarctic historic sites in the political context

Two key researchers (Barr and Warren) have developed typologies for Antarctic historic sites to help guide preservation decisions. Warren (1989) considered significance criteria and the need for a systematic evaluation process and she proposed criteria based on links to significant historic and scientific achievements; whether the site is representative of a particular era or activity in Antarctic history; architectural values; and ability to yield historic information.

Barr (2000: 46) compared Arctic and Antarctic historic sites identifying common traits that help define their significance:

- “They are the cultural remains of activity by individuals or groups who visited the polar area for a limited period of time, for commercial, exploratory or scientific purposes;
- The remains related historically both to the polar region itself and to the country of origin of those who left them behind;
- Their ‘dual nationality’ being located in one nation’s territory or administrative area while having their origin in another, raises questions of management;
- Their remoteness and difficulty of access have preserved remains that would have been removed or destroyed in more populated and accessible areas;
- They are better preserved by the polar climate than they would have been in warmer areas;
The various monuments and sites have more in common with similar monuments and sites in the circumpolar areas of both the Arctic and Antarctic, than with other cultural remains in less extreme part of the present country of situation;

Their often modest form and use of natural materials can lead to them being overlooked as monuments worthy of protection; and

Sites are often well documented in older written sources such as scientific or expedition reports”.

Both typologies can be used together although further development of criteria for recognising scientific values of historic sites is required, discussed in Chapter 11. While Barr and Warren focussed on typologies to clarify historic significance, clear criteria for historic significance are important in developing conservation plans.

Further common traits are found in the types of artefacts at Arctic and Antarctic historic sites:

- Whaling and sealing equipment (trypots, flensing tools, boilers);
- Scientific equipment (such as meteorological screens);
- Supplies such as food, clothing (furs, caribou sleeping bags, Burberry windproof ‘ventiles’);
- Polar equipment (skis, sledges and later mechanical transport such as ‘skidoos’); and
- Storage containers including barrels, tanks and tin-plated cans.

In 2000 Barr formed the International Polar Heritage Committee (IPHC) of the International Committee on Monument and Sites (ICOMOS) to help identify significant historic sites; discuss technical problems of preservation in polar climates; and develop site management strategies. A website at http://www.polarheritage.org provides information on its activities. It is important that information on conservation of Antarctic historic sites is shared to facilitate evaluation of the effectiveness of current treatment methods, to prevent repetition of errors and foster development of appropriate methods. Management Plans for SPAs and SMAs have been progressively developed and approved by the Committee for Environmental Protection (CEP) of the Antarctic Treaty, such as those for SPA 27 (Cape Royds), SPA 28 (Hut Point) and SPA 29 (Cape Adare) and SPA 25 (Cape Evans).
1.4.4 Analysis of characteristics of polar historic sites

The current list of historic sites recognised under the Antarctic Treaty (available at [http://cep.ats.aq/cep/MediaItems/HSM_list_2007_e.pdf](http://cep.ats.aq/cep/MediaItems/HSM_list_2007_e.pdf)) contains 82 sites. With two de-listings of sites no longer extant and amalgamation of the previously separate listing of the Cape Denison main hut (No. 13) and the Memorial Cross (No. 12) into a new separate listing (No. 77) this reduces to 78 sites. These were analysed by location, date and type as no such analysis has been undertaken since Warren’s thesis in 1989 and more sites have been added since that time, although numerous potential candidates remain.

*Distribution and location*

Since Antarctica was initially explored from ships and early land bases were located as close as possible to coastal re-supply, all but seven designated historic sites are located within 10 km of the coast. This implies significant conservation risks from salt deposition and katabatic winds. Sites on iceshelves and glaciers were either covered by ice accumulation (*eg* Vostok and Port Martin) or were lost when iceshelves broke away (*eg* Amundsen’s Framheim).

*Date categories represented*

A comparison of the numbers of listed sites by date categories is given in Table 1.2, noting that some sites (*eg* Whaler’s Bay No. 71) represent multiple date categories. This shows a high representation of early sites except sealing sites with few IGY sites.

*Table 1.2: Numbers of sites by date categories*

<table>
<thead>
<tr>
<th>Date category</th>
<th>Listed sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-1895</td>
<td>7</td>
</tr>
<tr>
<td>1895-1922 (‘Heroic Era’)</td>
<td>29</td>
</tr>
<tr>
<td>1922-1956</td>
<td>23</td>
</tr>
<tr>
<td>1957-58 (IGY)</td>
<td>3</td>
</tr>
<tr>
<td>Post IGY</td>
<td>16</td>
</tr>
</tbody>
</table>
Early sealing sites found on the South Shetland Islands by (Pearson 2007) have not yet been added to the CEP list of protected sites. Of the original nine timber buildings built before 1922 (so-called ‘Heroic Era’) six are extant; one building has collapsed; and two huts built on ice shelves have disappeared. Three of the extant ‘Heroic’ sites are located close together on Ross Island as a consequence of the British expeditions attempting to reach the South Pole by the shortest route. Borchgrevink’s hut and ruined Campbell’s hut are at Cape Adare, Mawson’s Huts (the site contains four huts, two conjoined and two small scientific huts) at Cape Denison and Nordenskjold’s hut in the Antarctic Peninsula.

The 23 sites dating between 1922 and 1955 are diverse in type (nationality, private, government, scientific purpose, etc) and exhibit trends in building development from simple wooden huts (eg East Base and some British Operation Tabarin huts) to more complex modern construction at Port Martin and Îles des Petrels. Two sites from this era, Îles des Petrels (at Dumont d’Urville) and Mawson Station are briefly discussed in this thesis.

Three of the five Treaty-designated IGY historic monuments (No. 4 Pole of Inaccessibility; Nos. 7 and 8 at Mirny) appear unrepresentative of the period, although Port Lockroy (No. 61) may be a better choice. Other IGY sites such as Wilkes (Clark & Wishart 1991) are not listed and suitable examples should be selected for conservation. The Dobrowolsky gravity pillar (No. 49) and magnetic observatory (No. 10) are of scientific significance, and the author believes that scientific significance should be incorporated into criteria used to evaluate historic sites (see Chapter 11). The author examined three locations with mid 1950s buildings at McMurdo, Davis and the New Zealand’s Scott Base.

The end of the IGY is commonly considered to be the last date at which an Antarctic site can be considered historically significant although evaluation of the significance of some recent sites in Svalbard (Barr, S 1991) could equally apply in Antarctica. The few Treaty-recognised sites later than 1958 are mainly memorials and cemeteries (see Table 1.1 at the end of the chapter).

Of the 16 post-IGY sites and monuments on the designated list, many do not meet the ‘historic’ criteria and no scientific stations or buildings representative of the era are included, although the
author considers that Platcha Hut near Davis Station may merit consideration (figure 1.22) since it typifies the era, is in good condition with few later inclusions and is associated with important scientific studies.

Figure 1.22: Platcha Huts, ‘old’ Platcha hut at right (photo by Rupert Summerson 1994)

Site types
Warren (1989) concluded there had been a lack of investigation to ensure that sites of each historic category are adequately represented in the list of designated historic sites, noting that sealing or whaling sites are either not listed at all, e.g. Borge Bay Whaling Station (ibid.: 220), and sealing remains at Coppermine Cove on Robert Island (ibid.: 232). There are only six designated sites (Nos. 57, 65, 70, 71, 72, 74 in Table 1.1) associated with whaling and sealing and most of these are either ruinous (such as those at Deception Island destroyed by volcanic activity) or are not adequately designated or recorded. Some ‘cleanups’ motivated by a desire to protect the Antarctic environment (Monteath 1992) may also have unwittingly removed sealing material.

There are numerous monuments such as graves, busts of political or expedition leaders (e.g. the bust of Lenin at the Pole of Inaccessibility (No. 4, ibid), plaques commemorating events and cairns that Warren categorises as ‘Cultural symbols’ or ‘Cultural properties’. She makes a
1. THE CLIMATIC, HISTORICAL AND POLITICAL CONTEXT OF ANTARCTIC HISTORIC SITES

convincing case for changing their status within the Antarctic Treaty system to provide more consistent identification and protection.

Warren’s pioneering thesis was written before the 1991 Madrid Protocol and therefore predates the system of SPAs and SMAs that are an integral part of the management of environmental protection in Antarctica. A UK Working Paper submitted to the CEP in 2001 recommended a review of the listing using the criteria listed above but no new significance criteria appear to have been produced.

1.4.5 Significance criteria for Antarctic sites

The Burra Charter of ICOMOS Australia (http://www.icomos.org/burra_charter.html) downloaded on 14 January 2008 and the Aotearoa Charter of New Zealand provide guidelines for assessing and documenting significance of national historic sites but do not provide specific detail needed for comparing and recording the significance of Antarctic historic sites.

The history of Antarctica is largely the history of exploration and science (Fogg 1992), and many archaeologists without specialist knowledge have difficulty in interpreting the significance of scientific activity in geology, meteorology, upper atmosphere physics, biology and other sciences that occurred at the sites. Most archaeological recording of sites has focussed on social history (eg Clark and Wishart 1991), although ‘history of science’ evaluation is also required to ensure comprehensive evaluation and documentation of the site. Warren developed general criteria for preserving scientific resources of historic sites (Warren 1989: 56-63) acknowledging the extent of ignorance about their significance. However, she concentrated on refuse studies, spatial distribution, examination of technological change and behavioural studies revealed from site analysis. An insightful study of scientific resources of historic sites is Lazer’s research on effects of iron alloy nails in the geomagnetic observatories at Cape Denison (Hayman, Hughes & Lazer 1998) to examine whether this could be a source of error in the AAE research.

A systematic approach should be developed for evaluation of historic scientific activities to ensure these are appropriately documented and that any relevant buildings and artefacts are
protected. This is discussed further in Chapter 11 where the idea of developing management guidelines based on site type and significance criteria is expanded.

Conservation issues of historic sites have strong links to current priorities of the Antarctic Treaty System, particularly management of SMAs and SPAs which include cultural heritage elements, and control of human impacts on the Antarctic environment, including tourism. Heritage specialists can contribute expertise to help address these issues and should be involved in Antarctic Treaty discussions on these matters. This interaction would also help scientists to understand the potential benefits of scientific study and preservation of these sites.

1.5 CONCLUSIONS

- Arctic and Antarctic historic sites have significant climatic differences and major differences in materials and construction of buildings, largely dependent when they were built. Even within Antarctica, conservation strategies that are suitable at one location may not be appropriate at a site with different building types or climatic conditions.
- There are major differences in the political context of Arctic and Antarctic historic sites: Arctic historic sites are on sovereign territory and a range of reasons have led to artefacts being relocated to museums with the exception of Svalbard, where an international approach to conserving historic sites has been developed. The Antarctic Treaty, however, requires conservation in situ and thus necessitates different conservation strategies.
- Despite these differences, there are sufficient similarities in the historic context and typology of Arctic and Antarctic sites so that bi-polar, multi-disciplinary cooperation via the International Polar Heritage Committee of ICOMOS can help to improve understanding of their historic values and conservation requirements, particularly improved significance criteria and specialised documentation requirements.
### Table 1.1: List of Antarctic Historic sites

<table>
<thead>
<tr>
<th>Date categories</th>
<th>Building types</th>
<th>Site categories</th>
<th>Non-building types</th>
</tr>
</thead>
<tbody>
<tr>
<td>#A= pre-1895 whaling, sealing and exploration</td>
<td>T= timber building (eg Nordenskjold hut)</td>
<td>X= memorials, graves and cemeteries, cross, religious monument</td>
<td></td>
</tr>
<tr>
<td>#B= 1895-1922, commonly called the ‘Heroic Era’</td>
<td>M= metal or composite materials building</td>
<td>P= plaque</td>
<td></td>
</tr>
<tr>
<td>#C= 1923-1956</td>
<td>S= stone building</td>
<td>C= cairn, including cairn with plaque</td>
<td></td>
</tr>
<tr>
<td>#D= IGY (1957-58)</td>
<td>R= ruined building (eg Campbell hut)</td>
<td>S= statue, or bust or stele</td>
<td></td>
</tr>
<tr>
<td>#E= post IGY</td>
<td>B= buried building (eg Port Martin)</td>
<td>F= flag post, message post</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sh= shelter or ruined shelter</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D= deport or supply cache</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### b. List of Historic Sites and Monuments approved by Antarctic Treaty Consultative Meetings

<table>
<thead>
<tr>
<th>ATCM No.</th>
<th>Description</th>
<th>Location</th>
<th>Party undertaking management</th>
<th>Date</th>
<th>Type</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flag mast erected in December 1965 at the South Geographical Pole by the First Argentine Overland Polar Expedition.</td>
<td>90°S</td>
<td>Argentina</td>
<td>#E</td>
<td>F</td>
<td>Cultural</td>
</tr>
<tr>
<td>2</td>
<td>Rock cairn and plaques at Syowa Station commemorates deceased expeditor, erected January 1961, includes funerary ashes.</td>
<td>69.00°S, 39.35°E</td>
<td>Japan</td>
<td>#E</td>
<td>X</td>
<td>Cultural</td>
</tr>
<tr>
<td>3</td>
<td>Rock cairn and plaque on Proclamation Island, Enderby Land, erected in January 1930 by Sir Douglas Mawson commemorating BANZARE landing.</td>
<td>65.51°S, 53.41°E</td>
<td>Australia</td>
<td>#C</td>
<td>C</td>
<td>Historic</td>
</tr>
<tr>
<td>4</td>
<td>Station building and attached bust of V.I. Lenin and plaque commemorating the conquest of the Pole of Inaccessibility in 1958.</td>
<td>83.06°S, 54.58°E</td>
<td>Russia</td>
<td>#D</td>
<td>X + unknown building materials</td>
<td>Cultural</td>
</tr>
<tr>
<td>5</td>
<td>Rock cairn and plaque at Cape Bruce, MacRobertson Land, erected in February 1931 by Sir Douglas Mawson. Commemorate landing by BANZARE.</td>
<td>67.25°S, 60.47°E</td>
<td>Australia</td>
<td>#C</td>
<td>C</td>
<td>Historic</td>
</tr>
</tbody>
</table>

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5 Devised by the author.
6 Devised by the author.
7 Sites shown in shading are discussed more extensively in this thesis.
8 The author adopted the end of the IGY as the primary criterion for considering automatic protection. These were further categorised by date and type to consider site significance, thus items after 1958 may be historic (eg Dobrowolsky Pillar) if associated with a major scientific or historic event. Items stated in Antarctic Treaty descriptions to have ‘symbolic significance’ are recorded as ‘cultural’ rather than ‘historic’ (in the last column). Graves earlier than 1958 are generally considered historic, while those later than 1958 are culturally significant. In effect, both ‘historic’ and culturally significant graves both require similar protection and management (eg protection from encroachment and damage, access for remembrance ceremonies, etc). Different management requirements for ‘historic’ and ‘cultural’ sites are discussed in Chapter 11.
### 1. THE CLIMATIC, HISTORICAL AND POLITICAL CONTEXT OF ANTARCTIC HISTORIC SITES

<table>
<thead>
<tr>
<th>ATCM No.</th>
<th>Description</th>
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<th>Date</th>
<th>Type</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Rock cairn at Walkabout Rocks, Vestfold Hills, Princess Elizabeth Land, erected in 1939 by Sir Hubert Wilkins.</td>
<td>68.22°S, 78.33°E</td>
<td>Australia</td>
<td>#C</td>
<td>C</td>
<td>Historic</td>
</tr>
<tr>
<td>7</td>
<td>Stone with inscribed plaque, erected at Mirny Observatory, Mabus Point, in memory of an expeditioner who died in 1956.</td>
<td>66.33°S, 93.01°E</td>
<td>Russia</td>
<td>#D</td>
<td>X</td>
<td>Cultural</td>
</tr>
<tr>
<td>8</td>
<td>Metal monument-sledge at Mirny Observatory, Mabus Point, with plaque in memory of an expeditioner.</td>
<td>66.33°S, 93.01°E</td>
<td>Russia</td>
<td>#D</td>
<td>X</td>
<td>Cultural</td>
</tr>
<tr>
<td>9</td>
<td>Cemetery on Buromskiy Island, near Mirny Observatory, 1960.</td>
<td>66°32′S, 93°01′E</td>
<td>Russia</td>
<td>#E</td>
<td>X</td>
<td>Cultural</td>
</tr>
<tr>
<td>10</td>
<td>Building (magnetic observatory) at Dobrowolsky Station, Bunger Hills, plaque commemorating opening of Oasis Station in 1956.</td>
<td>66°16′S, 100°45′E</td>
<td>Russia</td>
<td>#C</td>
<td>Building materials unknown</td>
<td>Historic (Scientific)</td>
</tr>
<tr>
<td>11</td>
<td>Heavy tractor at Vostok Station with plaque in memory of the opening of the Station in 1957.</td>
<td>78°28′S, 106°48′E</td>
<td>Russia</td>
<td>#D</td>
<td>Artefact and P</td>
<td>Cultural</td>
</tr>
<tr>
<td>12</td>
<td>Cross and plaque at Cape Denison, George V Land. (Removed from the Antarctic Treaty list of Historic Sites and Monuments subsumed with HSM 13 into HSM 77)</td>
<td>67°00′S, 142°39′E</td>
<td>Australia</td>
<td>#B</td>
<td>X</td>
<td>Historic</td>
</tr>
<tr>
<td>13</td>
<td>Hut at Cape Denison, George V Land. (Removed from the Antarctic Treaty list of Historic Sites and Monuments subsumed with HSM 12 into HSM 77)</td>
<td>67°00′S, 142°39′E</td>
<td>Australia</td>
<td>#B</td>
<td>T</td>
<td>Historic</td>
</tr>
<tr>
<td>14</td>
<td>Site of ice cave at Inexpressible Island, Terra Nova Bay, 1912. Campbell's Northern Party, British Antarctic Expedition, 1910-13. A wooden sign, plaque and seal bones remain at the site.</td>
<td>74°54′S, 163°43′E</td>
<td>New Zealand/Italy/UK</td>
<td>#B</td>
<td>Sh</td>
<td>Historic</td>
</tr>
<tr>
<td>15</td>
<td>Hut at Cape Royds, Ross Island, built in February 1908 by Sir Ernest Shackleton’s British Antarctic Expedition. Restored in January 1961 by NZ Department of Scientific and Industrial Research. Site incorporated within ASPA 157</td>
<td>77°33′S, 166°10′E</td>
<td>New Zealand/UK</td>
<td>#B</td>
<td>T</td>
<td>Historic</td>
</tr>
<tr>
<td>16</td>
<td>Hut at Cape Evans, Ross Island, built in January 1911 by Capt Scott’s British Antarctic Expedition (1910-1913). Restored in January 1961 by NZ Department of Scientific and Industrial Research. Site incorporated within ASPA 155</td>
<td>77°38′S, 166°24′E</td>
<td>New Zealand/UK</td>
<td>#B</td>
<td>T</td>
<td>Historic</td>
</tr>
<tr>
<td>17</td>
<td>Cross on Wind Vane Hill, Cape Evans, Ross Island, erected by Sir Ernest Shackleton’s Imperial Trans-Antarctic Expedition of 1914-1916, commemorates three members of the party. Site incorporated within ASPA 155</td>
<td>77°38′S, 166°24′E</td>
<td>New Zealand/UK</td>
<td>#B</td>
<td>X</td>
<td>Historic</td>
</tr>
<tr>
<td>18</td>
<td>Hut at Hut Point, Ross Island, built in February 1902 by Scott’s British Antarctic Expedition of 1901-04, Site incorporated within ASPA 158</td>
<td>77°50′S, 166°37′E</td>
<td>New Zealand/UK</td>
<td>#B</td>
<td>T</td>
<td>Historic</td>
</tr>
</tbody>
</table>
## 1. THE CLIMATIC, HISTORICAL AND POLITICAL CONTEXT OF ANTARCTIC HISTORIC SITES

<table>
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<tr>
<th>ATCM No.</th>
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<th>Party undertaking management</th>
<th>Date</th>
<th>Type</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>Cross at Hut Point, Ross Island, erected in February 1904 by the British Antarctic Expedition of 1901-04, commemorates Vince, a member of the expedition, who died nearby.</td>
<td>77°50'S, 166°37'E</td>
<td>New Zealand/UK</td>
<td>#B</td>
<td>X</td>
<td>Historic</td>
</tr>
<tr>
<td>20</td>
<td>Cross on Observation Hill, Ross Island, erected in 1913 by British Antarctic Expedition of 1910-13, in memory of Captain Robert F. Scott's party which perished returning from the South Pole.</td>
<td>77°51'S, 166°41'E</td>
<td>New Zealand/UK</td>
<td>#B</td>
<td>X</td>
<td>Historic</td>
</tr>
<tr>
<td>21</td>
<td>Remains of stone hut at Cape Crozier, Ross Island, built July 1911 by Edward Wilson's party of the British Antarctic Expedition (1910-13) during the winter journey to collect Emperor penguin eggs.</td>
<td>77°31'S, 169°22'E</td>
<td>New Zealand/UK</td>
<td>#B</td>
<td>S and R</td>
<td>Historic</td>
</tr>
<tr>
<td>22</td>
<td>Three huts and associated historic relics at Cape Adare. Two built in February 1899 during the British Antarctic (Southern Cross) Expedition, 1898-1900, led by Borchgrevink. The third was built in February 1911 by Scott's Northern Party, led by Campbell. Site incorporated within ASPA 159.</td>
<td>71°18'S, 170°12'E</td>
<td>New Zealand/UK</td>
<td>#B</td>
<td>T and R</td>
<td>Historic</td>
</tr>
<tr>
<td>23</td>
<td>Grave at Cape Adare of Norwegian biologist Nicolai Hanson, (British Antarctic (Southern Cross) Expedition, 1898-1900. Cross and plaque attached to boulder.</td>
<td>71°17'S, 170°13'E</td>
<td>New Zealand/ Norway</td>
<td>#B</td>
<td>X</td>
<td>Historic</td>
</tr>
<tr>
<td>24</td>
<td>‘Amundsen’s cairn’, on Mount Betty, Queen Maud Range erected by Roald Amundsen on 6 January 1912, on his way back to Framheim from the South Pole.</td>
<td>85°11'S, 163°45'W</td>
<td>Norway</td>
<td>#B</td>
<td>C</td>
<td>Historic</td>
</tr>
<tr>
<td>25</td>
<td>De-listed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Abandoned installations of Argentine Station ‘General San Martin’ on Barry Island, Debenham Islands, Marguerite Bay, with cross, flag mast, and monolith built in 1951.</td>
<td>68°08'S, 67°08'W</td>
<td>Argentina</td>
<td>#C</td>
<td>X + unknown materials</td>
<td>Historic</td>
</tr>
<tr>
<td>27</td>
<td>Cairn with a replica of a lead plaque erected on Megalestris Hill, Petermann Island, in 1909 by Charcot expedition. Original plaque repatriated to France.</td>
<td>65°10'S, 64°09'W</td>
<td>France /UK</td>
<td>#B</td>
<td>C</td>
<td>Historic and Scientific (?)</td>
</tr>
<tr>
<td>28</td>
<td>Rock cairn at Port Charcot, Booth Island, with wooden pillar and plaque inscribed with names of Charcot’ 1904 <em>Le Français</em> expedition which wintered aboard here.</td>
<td>65°03'S, 64°01'W</td>
<td>Argentina / France</td>
<td>#B</td>
<td>C</td>
<td>Historic and Scientific (?)</td>
</tr>
<tr>
<td>29</td>
<td>Lighthouse ‘Primero de Mayo’ on Lambda Island, Melchior Islands, by Argentina in 1942, the 1st Argentine lighthouse in the Antarctic.</td>
<td>64°18'S, 62°59'W</td>
<td>Argentina</td>
<td>#C</td>
<td>S</td>
<td>Historic</td>
</tr>
<tr>
<td>30</td>
<td>Shelter at Paradise Harbour erected in 1950 near the Chilean Base ‘Gabriel Gonzalez Videla’ to honour the first Head of State to visit Antarctica.</td>
<td>64°49'S, 62°51'W</td>
<td>Chile</td>
<td>#C</td>
<td>Sh</td>
<td>Cultural</td>
</tr>
<tr>
<td>31</td>
<td>De-listed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Concrete monolith, 1947, near Capitán Arturo Prat Base on Greenwich Island, South Shetland Islands. Point of reference for Chilean Antarctic hydrographic surveys.</td>
<td>62°28'S, 59°40'W</td>
<td>Chile</td>
<td>#C</td>
<td>S and R and X</td>
<td>Historic and scientific, datum for hydrographic surveys</td>
</tr>
<tr>
<td>ATCM No.</td>
<td>Description</td>
<td>Location</td>
<td>Party undertaking management</td>
<td>Date</td>
<td>Type</td>
<td>Significance</td>
</tr>
<tr>
<td>----------</td>
<td>------------------------------------------------------------------------------</td>
<td>---------------------------</td>
<td>------------------------------</td>
<td>------</td>
<td>-----------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>33</td>
<td>Shelter and cross with plaque near Capitán Arturo Prat Base (Chile),</td>
<td>62°29'S, 59°40'W</td>
<td>Chile</td>
<td>#E</td>
<td>X+ unknown materials</td>
<td>Cultural</td>
</tr>
<tr>
<td></td>
<td>Greenwich Island, South Shetland Islands.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Bust at Capitán Arturo Prat Base (Chile), Greenwich Island, South Shetland</td>
<td>62°50'S, 59°41'W</td>
<td>Chile</td>
<td>#C</td>
<td>X</td>
<td>Cultural</td>
</tr>
<tr>
<td></td>
<td>Islands, erected in 1947.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Wooden cross and statue of the Virgin of Carmen erected in 1947 near</td>
<td>62°29'S, 59°40'W</td>
<td>Chile</td>
<td>#C</td>
<td>X</td>
<td>Cultural</td>
</tr>
<tr>
<td></td>
<td>Capitán Arturo Prat Base (Chile), Greenwich Island, South Shetland Islands.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>Replica of a metal plaque erected by Eduard Dallmann at Potter Cove, King</td>
<td>62°14'S, 58°39'W</td>
<td>Argentina/Germany</td>
<td>#A</td>
<td>P</td>
<td>Cultural</td>
</tr>
<tr>
<td></td>
<td>George Island, commemorates visit of German expedition, 1874 on board</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Grönland.</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>37</td>
<td>Statue erected in 1948 at General Bernardo O’Higgins Base (Chile), Trinity</td>
<td>63°19'S, 57°54'W</td>
<td>Chile</td>
<td>#C</td>
<td>St</td>
<td>Historic</td>
</tr>
<tr>
<td></td>
<td>Peninsula, of Bernardo O’Higgins.</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>38</td>
<td>Wooden hut on Snow Hill Island built in February 1902 by the main party of</td>
<td>64°22'S, 56°59'W</td>
<td>Argentina/ Sweden</td>
<td>#B</td>
<td>T</td>
<td>Historic</td>
</tr>
<tr>
<td></td>
<td>the Swedish South Polar Expedition led by Otto Nordenskjöld.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>Stone hut at Hope Bay, Trinity Peninsula, built in January 1903 by a party of</td>
<td>63°24'S, 56°59'W</td>
<td>Argentina/ Sweden</td>
<td>#B</td>
<td>S</td>
<td>Historic</td>
</tr>
<tr>
<td></td>
<td>the Swedish South Polar Expedition.</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>40</td>
<td>Bust of General San Martin, grotto with a statue of the Virgin of Luján, and</td>
<td>63°24'S, 56°59'W</td>
<td>Argentina</td>
<td>#C</td>
<td>St and X</td>
<td>Historic (on basis of pre-IGY</td>
</tr>
<tr>
<td></td>
<td>a flag mast at Base ‘Esperanza’, Hope Bay, erected by Argentina in 1955;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>date only)</td>
</tr>
<tr>
<td></td>
<td>together with a graveyard and memorial stele.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>Stone hut on Paulet Island built in February 1903 by survivors of the</td>
<td>63°34'S, 55°45'W</td>
<td>Argentina/ Sweden</td>
<td>#B</td>
<td>St and R</td>
<td>Historic</td>
</tr>
<tr>
<td></td>
<td>Nordenskjöld’s Swedish South Polar Expedition led by Otto Nordenskjöld,</td>
<td></td>
<td></td>
<td></td>
<td>and X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>together with a grave of a member of the expedition and the rock cairn.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>Area of Scotia Bay, Laurie Island, South Orkney Island, includes stone hut</td>
<td>60°46'S, 44°40'W</td>
<td>Argentina/UK</td>
<td>#B</td>
<td>St and R</td>
<td>Historic and possibly Scientific</td>
</tr>
<tr>
<td></td>
<td>built by the Bruce Scottish Antarctic Expedition (1903); the Argentine</td>
<td></td>
<td></td>
<td></td>
<td>and X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>meteorological hut and Moneta House magnetic observatory, (1905); and a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>graveyard.</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>Cross erected in 1955, 1,300 metres north-east of the Argentine General</td>
<td>77°52'S, 34°37'W</td>
<td>Argentina</td>
<td>#C</td>
<td>X</td>
<td>Cultural</td>
</tr>
<tr>
<td></td>
<td>Belgrano I Station (Argentina) subsequently moved to Belgrano II Station</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Argentina) in 1979.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>Plaque erected at the temporary Indian station “Dakshin Gangotri”, Dronning</td>
<td>70°45'S, 11°38'E</td>
<td>India</td>
<td>#E</td>
<td>P</td>
<td>Cultural</td>
</tr>
<tr>
<td></td>
<td>Maud Land, listing the names of 1st Indian Antarctic Expedition, 1982.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>Plaque on Brabant Island, on Metchnikoff Point, built by the Joint Services</td>
<td>64°02'S, 62°34'W</td>
<td>Belgium</td>
<td>#B</td>
<td>P</td>
<td>Cultural, as plaque appears</td>
</tr>
<tr>
<td></td>
<td>Expedition 1983-85 to commemorate the first landing on Brabant Island by</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>to be a replica.</td>
</tr>
<tr>
<td></td>
<td>Gerlache’s Belgian Antarctic Expedition of 1897-99.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>All the buildings and installations of Port-Martin base, Terre Adélie</td>
<td>66°49'S, 141°24'E</td>
<td>France</td>
<td>#C</td>
<td>T and B</td>
<td>Historic</td>
</tr>
<tr>
<td></td>
<td>constructed in 1950 by the 3rd French expedition in Terre Adélie and partly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>destroyed by fire during the night of 23 to 24 January 1952.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATCM No.</td>
<td>Description</td>
<td>Location</td>
<td>Party undertaking management</td>
<td>Date</td>
<td>Type</td>
<td>Significance</td>
</tr>
<tr>
<td>---------</td>
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</tr>
<tr>
<td>47</td>
<td>Wooden building ‘Base Marret’ on the Ile des Pétrels, Terre Adélie, where seven men overwintered in 1952 following the fire at Port Martin Base.</td>
<td>66°40'S, 140°01'E</td>
<td>France</td>
<td>#C</td>
<td>T</td>
<td>Historic</td>
</tr>
<tr>
<td>48</td>
<td>Iron cross on Ile des Pétrels, Terre Adélie, commemorates meteorologist in the 3rd International Geophysical Year expedition who disappeared in January 1959.</td>
<td>66°40'S, 140°01'E</td>
<td>France</td>
<td>#E</td>
<td>X</td>
<td>Cultural</td>
</tr>
<tr>
<td>49</td>
<td>The concrete pillar erected by the First Polish Antarctic Expedition at Dobrowolsky Station on the Bunger Hill to measure acceleration due to gravity $g = 982.439.4$ mgal $\pm 0.4$ mgal in relation to Warsaw, according to the Potsdam system, in January 1959.</td>
<td>66°16'S, 100°45'E</td>
<td>Poland</td>
<td>#E</td>
<td>C</td>
<td>Historic on basis of scientific achievement</td>
</tr>
<tr>
<td>50</td>
<td>A brass plaque commemorating the landing of the first Polish Antarctic marine research expedition in February 1976.</td>
<td>62°12'S, 59°01'W</td>
<td>Poland</td>
<td>#E</td>
<td>P</td>
<td>Cultural</td>
</tr>
<tr>
<td>51</td>
<td>The grave of Włodzimierz Puchalski, who died in 1979, surmounted by an iron cross, near Arctowski station on King George Island.</td>
<td>62°13'S, 58°28'W</td>
<td>Poland</td>
<td>#E</td>
<td>X</td>
<td>Cultural</td>
</tr>
<tr>
<td>52</td>
<td>Monolith commemorating the establishment in 1985 of the ‘Great Wall Station’ on Fildes Peninsula, King George Island.</td>
<td>62°13'S, 58°58'W</td>
<td>China</td>
<td>#E</td>
<td>X</td>
<td>Cultural</td>
</tr>
<tr>
<td>53</td>
<td>Bust, monolith and plaques on Point Wild, Elephant Island, South Shetland Islands, celebrating the rescue of the survivors of the <em>Endurance</em> by the Chilean Navy cutter <em>Yelcho</em>. Erected by Chilean Antarctic Scientific Expedition in 1987-88.</td>
<td>61°03'S, 54°50'W</td>
<td>Chile</td>
<td>#E</td>
<td>St</td>
<td>Cultural</td>
</tr>
<tr>
<td>54</td>
<td>Richard E. Byrd Historic Monument, McMurdo Station, Antarctica. Bronze bust on black marble, on wood platform, erected in 1965.</td>
<td>77°51'S, 166°40'E</td>
<td>USA</td>
<td>#E</td>
<td>St</td>
<td>Cultural</td>
</tr>
<tr>
<td>55</td>
<td>Buildings and artefacts at East Base, Antarctica, Stonington Island, and environs, erected and used during two U.S. wintering expeditions: the Antarctic Service Expedition (1939-1941) and the Ronne Antarctic Research Expedition (1947-1948).</td>
<td>68°11'S, 67°00'W</td>
<td>USA</td>
<td>#C</td>
<td>T</td>
<td>Historic</td>
</tr>
<tr>
<td>56</td>
<td>The remains and immediate environs of the Waterboat Point hut Danco Coast, Antarctic Peninsula, occupied by the UK two-man expedition of Bagshawe and Lester in 1921-22. Only the base of the boat, foundations of doorposts and an outline of the hut and extension still exist.</td>
<td>64°49'S, 62°51'W</td>
<td>Chile/UK</td>
<td>#B</td>
<td>T and R</td>
<td>Historic</td>
</tr>
<tr>
<td>57</td>
<td>Commemorative plaque at ‘Yankee Bay’ MacFarlane Strait, Greenwich Island, South Shetland Islands. Commemorates Capt MacFarlane, who explored the Antarctic Peninsula in 1820.</td>
<td>62°32'S, 59°45'W</td>
<td>Chile/UK</td>
<td>#A</td>
<td>P</td>
<td>Location has historic value, plaque does not</td>
</tr>
<tr>
<td>58</td>
<td>De-listed.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>59</td>
<td>Cairn on Half Moon Beach, Cape Shirreff, Livingston Island, South Shetland Islands and plaque on ‘Cerro Gaviota’ commemorates those aboard Spanish vessel <em>San Telmo</em>, which sank in September 1819; Site incorporated within ASPA 149.</td>
<td>62°28'S, 60°46'W</td>
<td>Chile/Spain/Peru</td>
<td>#A</td>
<td>C</td>
<td>Location has historic value, plaque does not</td>
</tr>
<tr>
<td>ATCM No.</td>
<td>Description</td>
<td>Location</td>
<td>Party undertaking management</td>
<td>Date</td>
<td>Type</td>
<td>Significance</td>
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<tr>
<td>60</td>
<td>Wooden plaque and cairn at Penguins Bay, southern coast of Seymour Island placed on 10 November 1903 by the crew of a rescue mission of the Argentinian Corvette <em>Uruguay</em> where they met the members of Nordenskjöld’s Swedish expedition.</td>
<td>64°16’S, 56°39’W</td>
<td>Argentina/ Sweden</td>
<td>#B</td>
<td>C</td>
<td>Historic, if the wooden plaque is original; 1990 cairn not historic</td>
</tr>
<tr>
<td>61</td>
<td>‘Base A’ at Port Lockroy, Goudier Island, off Wiencke Island, Antarctic Peninsula. Operation Tabarin base (1944); scientific research including the first measurements of the ionosphere, and first recording of an atmospheric whistler, from Antarctica.</td>
<td>64°49’S, 63°29’W</td>
<td>UK</td>
<td>#C and #D</td>
<td>T</td>
<td>Historic and Scientific</td>
</tr>
<tr>
<td>62</td>
<td>‘Base F (Wordie House)’ on Winter Island, Argentine Islands, example of an early (opened 1947) British scientific base.</td>
<td>65°15’S, 64°16’W</td>
<td>UK/Ukraine</td>
<td>#C</td>
<td>T</td>
<td>Historic</td>
</tr>
<tr>
<td>63</td>
<td>‘Base Y’, Horseshoe Island, Marguerite Bay, western Graham Land. A relatively unaltered and completely equipped British scientific base of the late 1950s, also ‘Blaklock’ refuge hut nearby.</td>
<td>67°48’S, 67°18’W</td>
<td>UK</td>
<td>#C and #E</td>
<td>T</td>
<td>Historic</td>
</tr>
<tr>
<td>64</td>
<td>‘Base E’ Stonington Island, Marguerite Bay, Graham Land, represents early exploration (1946-1950) and later 1960s &amp; 1970s British Antarctic Survey history.</td>
<td>68°11’S, 67°00’W</td>
<td>UK</td>
<td>#C and #E</td>
<td>T</td>
<td>Historic</td>
</tr>
<tr>
<td>65</td>
<td>Message post, Svend Foyn Island, Possession Islands. A pole with a box attached placed on the island on 16 January 1895 during the whaling expedition of Henryk Bull and Captain Leonard Kristensen.</td>
<td>71°56’S, 171°05’W</td>
<td>New Zealand/ Norway</td>
<td>#A</td>
<td>F</td>
<td>Historic</td>
</tr>
<tr>
<td>66</td>
<td>Prestrud’s Cairn, Scott Nunataks, Edward VII Peninsula. The small rock cairn was erected in 1911 during the Norwegian Antarctic Expedition of 1910-1912.</td>
<td>77°11’S, 154°32’W</td>
<td>New Zealand/Norway</td>
<td>#B</td>
<td>C</td>
<td>Historic</td>
</tr>
<tr>
<td>68</td>
<td>Site of depot at Hells Gate Moraine, Inexpressible Island, Terra Nova Bay. Consisted of a sledge loaded with supplies and equipment placed by the British Antarctic Expedition, 1910-1913, removed in 1994.</td>
<td>74°52’S, 163°50’E</td>
<td>New Zealand/UK</td>
<td>#B</td>
<td>Depot</td>
<td>Historic</td>
</tr>
<tr>
<td>69</td>
<td>Message post at Cape Crozier, Ross Island, erected in 1902 by Scott's Discovery Expedition of 1901-04. Held a metal message cylinder, since removed. Site incorporated within ASPA 124</td>
<td>77°27’S, 169°16’E</td>
<td>New Zealand/UK</td>
<td>#B</td>
<td>F</td>
<td>Historic</td>
</tr>
<tr>
<td>70</td>
<td>Message post at Cape Wadworth, Coulman Island. A metal cylinder nailed to a red pole placed by Scott in 1902.</td>
<td>73°19’S, 169°47’E</td>
<td>New Zealand/UK</td>
<td>#B</td>
<td>F</td>
<td>Historic</td>
</tr>
<tr>
<td>71</td>
<td>Whalers Bay, Deception Island, South Shetland Islands, comprising all pre-1970 remains including early whaling period (1906-12); Hektor Whaling Station (1912) and all artefacts associated with its operation until 1931; cemetery and memorial; remains from British scientific and mapping activity</td>
<td>62°59’S, 60°34’W</td>
<td>Chile/Norway/UK</td>
<td>#B, #C, #D and #E</td>
<td>Mt and R and X</td>
<td>Historic and Scientific</td>
</tr>
</tbody>
</table>
1. THE CLIMATIC, HISTORICAL AND POLITICAL CONTEXT OF ANTARCTIC HISTORIC SITES

<table>
<thead>
<tr>
<th>ATCM No.</th>
<th>Description</th>
<th>Location</th>
<th>Party undertaking management</th>
<th>Date</th>
<th>Type</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>72</td>
<td>Mikkelsen Cairn, Tryne Islands, Vestfold Hills. Rock cairn and mast erected by landing party of Norwegian whalr Thorshavn.</td>
<td>68°22'S 78°24'E</td>
<td>Australia/Norway</td>
<td>#C C</td>
<td>Historic</td>
<td></td>
</tr>
<tr>
<td>73</td>
<td>Memorial Cross for 1979 Mount Erebus crash victims, Lewis Bay, Ross Island. A stainless steel cross erected in January 1987 three kilometers from the crash site commemorating 257 people died in the air crash.</td>
<td>77°25'S, 167°27'E</td>
<td>New Zealand</td>
<td>#E X</td>
<td>Cultural</td>
<td></td>
</tr>
<tr>
<td>74</td>
<td>The un-named cove on SW coast of Elephant Island in which the wreckage of a large wooden sailing vessel is located.</td>
<td>61°14'S, 55°22'W</td>
<td>UK</td>
<td>#A</td>
<td>Shipwreck site</td>
<td>Historic</td>
</tr>
<tr>
<td>75</td>
<td>The A Hut of Scott Base, sole existing Trans Antarctic Expedition 1956/1957 building in Antarctica, Ross Island.</td>
<td>77°51'S, 166°46'E</td>
<td>New Zealand</td>
<td>#C</td>
<td>Mt prefabricated panels</td>
<td>Historic</td>
</tr>
<tr>
<td>76</td>
<td>The ruins of the Chilean Base Pedro Aguirre Cerda Station, at Pendulum Cove, Deception Island, Antarctica, built 1955, destroyed by volcanic eruptions in 1967 and 1969.</td>
<td>62.59'S, 60.40'W</td>
<td>Chile</td>
<td>#C</td>
<td>R, unknown building materials</td>
<td>Historic and scientific</td>
</tr>
<tr>
<td>77</td>
<td>Cape Denison, Commonwealth Bay, George V Land, including Boat Harbour and the historic artefacts contained within its waters. Site is contained within ASMA No. 3, (Measure 1 (2004). Part of site is also contained within ASPA No. 162, (Measure 2 2004).</td>
<td>67°00''S, 142°39''E</td>
<td>Australia</td>
<td>#B</td>
<td>T and X</td>
<td>Historic</td>
</tr>
<tr>
<td>78</td>
<td>Memorial plaque at India Point, Humboldt Mountains, Wohltthat Massif, central Dronning Maud Land, 1990.</td>
<td>71°45'08''S, 11°12'30''E</td>
<td>India</td>
<td>#E</td>
<td>P</td>
<td>Cultural</td>
</tr>
<tr>
<td>79</td>
<td>Lillie Marleen Hut, Mt. Dockery, Everett Range, Northern Victoria Land, erected for the German Antarctic Northern Victoria Land Expedition, 1979/1980. Bivouac container made of prefabricated fibreglass units insulated with polyurethane foam.</td>
<td>71°12'S, 164°31'E</td>
<td>Germany</td>
<td>#E</td>
<td>Mt</td>
<td>Not able to be determined</td>
</tr>
<tr>
<td>80</td>
<td>Amundsen's Tent, erected at 90° by Amundsen’s expedition on their arrival at the South Pole in 1911. The tent is currently buried underneath the snow and ice in the vicinity of the South Pole.</td>
<td>90°S</td>
<td>Norway</td>
<td>#B</td>
<td>Buried artefact</td>
<td>Historic</td>
</tr>
<tr>
<td>81</td>
<td>Rocher du Débarquement (Landing Rock), a small island where Dumont d’Urville landed in 1840.</td>
<td>66° 36.30'S, 140° 03.85'E</td>
<td>France</td>
<td>#A</td>
<td>Landing site</td>
<td>Site is historic although no historic materials remain.</td>
</tr>
<tr>
<td>82</td>
<td>Monument to the Antarctic Treaty and Plaque near Frei, Bellingshausen and Escudero Bases at Filde Peninsula, King George Island.</td>
<td>62° 12' S; 58° 57' W</td>
<td>Chile</td>
<td>#E</td>
<td>P</td>
<td>Cultural</td>
</tr>
</tbody>
</table>

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10 Site is historic although it is unknown whether any historic material remains, but accords protection for any remains found
b. Sites considered to possess historic significance but not recognised under the Antarctic Treaty

<table>
<thead>
<tr>
<th>No.</th>
<th>Site Description</th>
<th>Coordinates</th>
<th>Country</th>
<th>Type</th>
<th>Status</th>
<th>Historic</th>
</tr>
</thead>
<tbody>
<tr>
<td>83</td>
<td>Mawson Station buildings- early buildings dating from the 1950s and early 1960s include scientific infrastructure and some accommodation designed for Antarctic conditions and illustrative of the period.</td>
<td>67.60°S 77.97°E</td>
<td>Australia</td>
<td>C</td>
<td>T and Mt</td>
<td>Historic</td>
</tr>
<tr>
<td>84</td>
<td>Old Paint Store, transferred from the first Australian ANARE base (Heard Island) is a rare surviving example of the use of polygonal, pre-fabricated buildings from this period. Old Dongas were part of the original station including accommodation, administration, radio and toilets of innovative design representing a comprehensive picture of life and work at an Antarctic station of this period.</td>
<td>68.58°S 77.97°E</td>
<td>Australia</td>
<td>C</td>
<td>T and Mt</td>
<td>Historic</td>
</tr>
<tr>
<td>85</td>
<td>Davis station (68°34’ S, 77°58’ E), established in 1957. It was inscribed on the (Australian) Register of the National Estate in 1999 and has been included on the Commonwealth Heritage List as an indicative place. Thirty-seven station buildings are included in the assessment including other sites and buildings in the region, including Platcha Hut, Brookes and Watts Huts, the Mikkelsen Cairn, Walkabout Rocks, and Law Cairn. A cultural heritage study has been prepared for the station and its environs (Rando and Davies 1996). Platcha Hut, 20km east of Davis Station, built in 1961, used for innovative scientific studies of katabatic winds over four years and subsequently for studies of the surrounding area.</td>
<td>68° 30’ S 78° 30’ E</td>
<td>Australia</td>
<td>E</td>
<td>T and Mt</td>
<td>Historic</td>
</tr>
<tr>
<td>86</td>
<td>Wilkes, former US IGY base transferred to Australia in 1958, consists of wooden and Jamesway (textile over timber framework) buildings and associated artefacts comprehensively representing IGY period.</td>
<td>66° 15’S 110° 36’E</td>
<td>Australia</td>
<td>D</td>
<td>T and other materials</td>
<td>Historic</td>
</tr>
<tr>
<td>87</td>
<td>Jamesway hut, McMurdo Base, used as part of US IGY activities and later retained as a bar for base personnel. Jamesway buildings were widely used during the IGY and in various US military expeditions in elsewhere, but few have survived. Possibly no longer extant.</td>
<td>77° 55’S 166° 40’E</td>
<td>US</td>
<td>D</td>
<td>T and other materials</td>
<td>Historic</td>
</tr>
</tbody>
</table>
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1. THE CLIMATIC, HISTORICAL AND POLITICAL CONTEXT OF ANTARCTIC HISTORIC SITES


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1. THE CLIMATIC, HISTORICAL AND POLITICAL CONTEXT OF ANTARCTIC HISTORIC SITES

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CHAPTER 2 LITERATURE REVIEW AND GAPS IN KNOWLEDGE

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2.1 Aim and introduction

2.1.1 Objectives and scope

The aims of this chapter are to:

- review the scope of the literature (detailed content being discussed in chapter 4-10); and
- identify gaps in knowledge.

Prior to the author’s first visit to Antarctica, advice given by Antarctic veterans about the condition and causes of problems\(^1\) included many statements that, through frequent repetition, had attained the status of self-evident truths (see Hughes 2000, Appendix F). Several were subsequently found to be incorrect when buildings and artefacts were later examined on-site (Hughes 1986). False diagnosis of the causes of deterioration can lead to inappropriate treatments, with ineffective or even harmful results. The conflicts between the ‘advice’ and the observations on the initial 1985 Antarctic visit prompted a literature review to compare conservation problems from other polar sites and analyse the effectiveness of any treatments undertaken.

\(^1\) The ten most common of these statements illustrate how pervasive the conventional wisdom was at the time (Hughes 2000).

- ‘Artefacts in the Ross Dependency huts are in a near-perfect state of preservation’ (Trevelyan 1996).
- ‘Damage is being done to the timbers by freeze-thaw cycles’ (Robert Headland, personal communication).
- ‘Corrosion is not a problem in Antarctica because of the dry cold’ (communication from Australian Antarctic Division to Professor Colin Pearson in 1970s).
- ‘It is terrible, Mawson’s Hut is full of ice’ (Smith 1991: 6).
- ‘If the ice is removed from Mawson’s hut, people will be able to see inside the hut just as it was during the AAE, similar to what can be seen in the Ross Dependency huts’ (Rod Ledingham, personal communication).
- Putting a dome over Mawson’s hut would protect the timbers from being worn away by ice particles carried by the wind’ anon 1992, ‘Mawson’s Hut plans icebound’, Australian Geographic, vol. 1992, no. October p. 12.
- ‘The only responsible and sensible thing to do is to bring it [Mawson’s main hut] back to Australia’ (Madigan, R 1986, ‘Comments to parliamentary committee’, paper presented to Antarctic Science Advisory Committee First Forum, not stated, October 1986.).
- ‘Conservators are expensive- it is better value to employ a carpenter’ (personal communication to the author by a member of the Mawson’s Huts Conservation Committee 1993).
- ‘The treatment of the Ross Dependency huts is a success and the approach there can be reproduced for Mawson’s huts. The use of a vapour barrier in the walls will stop snow from getting inside and will enable the huts to be kept ice-free’ (Bill Blunt, personal communication 1991).]
2. Literature review

The widespread expectation that historic materials in Antarctica are in a “near-perfect state of preservation” (Trevelyan 1996) seems often to have been the basis for questioning whether materials conservation research and treatments are even necessary in Antarctica. Conversely, others have stated that Antarctic historic sites and artefacts, such as Mawson’s main hut at Cape Denison, are in danger of immediate demise from the severe climate if urgent action is not taken (Smith 1991). A third expectation about Antarctic historic sites is that conservation problems in Antarctica will have already been successfully addressed at historic sites in the Arctic where research is presumed to have been conducted over a longer period. Related to this expectation is the assumption that research on a historic site in one part of Antarctica can be applied elsewhere in Antarctica on the basis of similar climates.

2.2 Methodology

2.3.1 Research questions

The research questions guiding the literature search were:
- What conservation issues were documented at Antarctic and (relevant) Arctic sites?
- How many sites have been assessed?
- Are the causes of deterioration accurately and comprehensively diagnosed?
- What patterns exist in any deterioration problems identified? Are these as expected?
- What conservation methods were used (if any) and were these successful?

Sources of information covered included:
- Site visit reports and any additional information from historic sites with comparable climates;
- Cold climate materials science publications;
- Materials conservation research undertaken at comparable sites; and
- Site management information including tourism publications.

2.2.2 Bibliographic search methods

The major internet resources included:
2. Literature review

- The Arctic and Antarctic bibliography of the Scott Polar Research Institute, which aims for a complete international coverage of polar scientific and cultural information covering all languages (http://www.spri.ac.uk).
- The Canadian Heritage Information Network (CHIN) provides access to the international materials conservation literature (http://www.chin.gc.ca).
- The Getty Conservation Institute provides extensive technical information on various types of materials and archaeological issues (http://aata.getty.edu/nps).
- The Cold Regions Bibliography provides information on cold regions science and technology including research from the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) (http://lcweb.loc.gov/rr/scitech/coldregions/welcome.html).

Other information, including unpublished reports, was obtained through personal visits to the Scott Polar Research Institute Library (Cambridge UK) and the Australian Antarctic Division library (Kingston, Tasmania) and through numerous professional contacts listed in the acknowledgements. It was often very difficult to identify the keyword that would yield useful information. For example, references to damage to timber surfaces by wind borne particles are found under different keywords including 'corrasion', 'aeolian erosion', 'ablation', and 'blowing snow'. Some references were available only in the original French, German, Norwegian, Russian and Spanish. The acknowledgements of this thesis record the author’s gratitude to many people who generously provided translations and identified information of potential interest. While recent specialist polar and cultural heritage literature is available through the internet, it remains difficult to obtain full copies of some older journals and field reports which are sometimes not systematically referenced according to date and location.

2.3 Analysis of the scope and extent of the literature

2.3.1 Materials science literature for polar conditions

*Temperature and Relative humidity including freezing-thawing and condensation processes*
Table 2.1 shows there is relatively limited monitoring information. Measurements at Dealy Island limited to one intermittently functioning thermohygrograph. In Antarctica, detailed monitoring undertaken at Ross Island sites by Mason (1999) and Held et al (2005) and Cape Denison and collaborative research by the author at Cape Denison is discussed in detail in Chapter 4.

Padfield (1998) studied complex problems of ice formation, thawing and condensation in Scandinavian buildings as part of his thesis on the stabilisation of relative humidity fluctuations in buildings. Although the annual temperature range studied was higher than in Antarctica, the physical processes described by Padfield are applicable to Antarctic historic sites including sublimation and condensation processes inside the wall spaces.

Everett (1961) published a classic study of freeze-thaw processes in stone and describes experiments that show that freezing damage of stone is not caused by the expansion of water at +4°C, as is often supposed. Florian (1987) and Peacock (1999) studied freezing and thawing processes affecting wood and textiles although both acknowledged additional research was required. Florian’s work was largely undertaken on dry material to investigate potential adverse effects on pest-infested museum collections treated by freezing, which differs from effects on buildings and artefacts that are immersed in water which then freezes. The use of vapour barriers, frequently proposed to prevent snow ingress in Antarctic historic buildings, is discussed by Strub (1996) and in greater technical detail by Trechsel and Bomberg (1989), who showed that vapour barriers can cause many problems.

Salt deposition

On commencing this thesis, surprisingly few publications reported Antarctic measurements of atmospheric deposition rates, excepting collaborative research led by Argentina Rosales & Fernandez 2001 (2001) on King George Island and Mason (1999) at Cape Evans. Clark and Wishart (1989: 5) attributed erosion by windborne particles to ‘wood fur’ (defibring, figure 2.2), illustrating both the need for a definitive terminology to guide field practice in Antarctica. Wilkins and Simpson (1988) produced a key paper on defibring in temperature climates from

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2 Discussed in further detail in Chapter 4.
which the author identified the problem in Antarctica. Blanchette *et al* (2003) studied severe defibring at Cape Evans\(^3\).

Figure 2.2: Defibring ((Blanchette, RA, Held & Farrell 2002: 320)

This shows SEM images of defibred wood.

A Exterior wall, Cape Evans.
B Exterior wall, Cape Royds.
C Outside of *Discovery* Hut, transverse section showing sound wood at bottom, separation of wood cells at the middle lamella (arrows) and continued fragmentation and erosion of fibres on exposed surface (arrowheads).
D Exterior of Cape Evans hut.

\(^3\) Discussed in further detail in Chapter 5.
Corrosion and other problems affecting metals

Divine and Perrigo (1986) comprehensively reviewed Arctic corrosion research, which is regularly discussed in conference publications of the National Association of Corrosion Engineers (NACE) on Cold Climate corrosion. Arctic corrosion research is more extensive than for Antarctica because of greater population and industrial activity such as pipelines. At the commencement of research some Antarctic personnel stated that corrosion cannot occur at temperatures below 0°C and was therefore not a problem in Antarctica (Hughes 2000: 121). King et al (1988) measured corrosion at Cape Evans and Lake Vanda and subsequent contact led to collaborative research that is presented in Chapter 6.

Damage by wind

Severe corrosion has been documented at Arctic sites, particularly the Fossil Forest site on Axel Heiberg Island (Grattan, D et al. 1996) and Barents’ hut on Novaya Zemlya (Hacquebord, L 1991). The only rate measurements found were measurement of ablation by Grattan (ibid) in the Arctic and Harrowfield's (1996, 2006) measurements of damage by windborne beach sand and pebbles affecting timbers at Cape Adare and insightful observations at other sites (figure 2.3).

Figure 2.3: Wind-abraded glass window on SE of Terra Nova hut (Harrowfield 2006: 304)

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4 See previous comments regarding different terminology.
There are many publications in the meteorological literature on ‘blowing snow’, of which Berg (1986), Budd (1966), Dietrich (1977) and Kodama et al (1985) are of the most practical benefit to conservators. Bagnold (1941) remains the classic reference on the theory of saltation and movement of particles in the boundary layer of winds, based on his study of sand dunes.

**Fungi and other biodeterioration**

Fungal problems are prevalent at most polar historic sites, discussed in detail in Chapter 9. McLean (1919) studied the fungi found inside the AAE hut at Cape Denison during its occupation. A joint US-NZ team continue to study fungi affecting wood at the Ross Dependency huts (Farrell et al 2004. There are, however, relatively few publications concerning the treatment of affected historic materials displayed *in situ* in buildings with rare exceptions.5

**Visitor impacts**

Clark and Wishart (1989), Spude and Spude (1993) and Harrowfield (1989) recorded problems caused by visitors trampling, touching, vandalising and removing artefacts or even whole buildings in Antarctica. There are extensive studies of more general tourism issues, as this is a major issue for national Antarctic program managers. Hall and Johnson (1995) and a special volume of Annals of Tourism Research (volume 21 (2) in 1994) cover aspects of tourism in polar regions, including the lengthy history of tourism in the Arctic. It is remarkable, for example that tourists were already visiting the ruined Wellman base at Virgohamn in 1906 (figure 2.4).

Although historic sites in the Antarctic Peninsula are some of the most frequently visited sites on the whole continent (Enzenbacher 1992) little visitor analysis exists specifically for historic sites excepting the Ross Island sites Harrowfield (1989).

Some strategies for visitor management were developed for the Ross Dependency sites (Harrowfield, DL 1990) and protective measures have been used, listed in Table 2.1. However, there is no detailed study of the *causes* of the errant behaviour at historic sites, indicating better

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5 None of the methods are applicable in Antarctic historic buildings due to safety and logistics reasons.
understanding of visitor interests and needs is necessary to develop better and more specific protective measures. These can then be incorporated into management plans as part of the SMA and SPA administration under the Antarctic Treaty, discussed in greater detail in Chapter 10.

Figure 2.4: Tourists at Virgohamn 1906 (A Wilse, in Bjerck and Johannessen 1999)
2. Literature review

2.3.1 Publications analysed by geographic location in both polar regions.

Types of conservation problems occurring and treatments applied are examined for each site in Table 2.1. Photographic examples selected from the literature are reproduced to illustrate the nature of some sites and their problems.

**Arctic sites**

**Alaska**

Most Alaskan literature concerns excavation and treatment of native sites such as the destructive excavation of wooden log buildings on Barter Island off the coast of Alaska during Stefansson’s Canadian Arctic Expedition 1913-18 (Jenness 1990). Jenness experimented with different methods of thawing the frozen ground but abandoned the method of lighting a fire on top “when he found the rapid change in temperature damaging the stone and bone implements”6. Some Alaskan papers discuss excavation techniques for frozen material although few details of field conservation methods are given (Newell 1984).

The Alaska State Historic Preservation Office maintains a database on historic and archaeological sites including site surveys and treatment reports (Spude 1986). Discussions with staff in Anchorage during February 2001 showed that most non-native sites are in climatic zones that are not comparable to Antarctica (i.e. forest zones). Alaska has high standards of statutory protection.

**Canada**

Nearly 100 relevant references were found on archaeological excavation, deterioration and/or conservation treatments of historic sites in High Arctic Canada including:

- Kodlunarn Island (latitude 62° 49' N, longitude: 65° 27' W), SE Baffin Island, occupied by Martin Frobisher in the sixteenth century;

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6 Jenness cited difficulties caused by native excavators who dug artefacts for sale and unscientific excavations by non-natives.
• Kerketen in southern Baffin Island, an Inuit and European whaling site that operated over many centuries until 1921, also the site of the 1882-83 German International Polar Year base;
• Kellett’s Storehouse (figure 1.10) on Dealy Island (Latitude 74° 58’ N, Longitude 108° 49’ W) which contains a unique collection of British Navy supplies for a mid-nineteenth century Franklin search expedition;
• Beechey Island (74° 43’ N, 91° 55’ W, figure 2.5), which has graves from a Franklin Expedition and the ruins of Northumberland House; and
• Fort Conger (81° 43’N, 64° 43’ W), a series of tar-paper covered timber buildings used intermittently between 1881 and 1935 for various explorations and research, associated with Peary and others.  

The author’s discussions with Canadian researchers and summary information in Table 2.1 revealed that human interference is their most urgent and difficult conservation problem. Most sites have been excavated and artefacts are usually relocated to museums to prevent looting. Some artefacts are considered to be too damaged or too fragile to survive in situ. Most of the conservator’s work is in stabilising wet, excavated artefacts for relocation and treatment offsite (Hett 1978, 1980). This limits the applicability to Antarctic sites since the Madrid Protocol requires that historic material should not be removed except when there is no alternative to protect or preserve the item. Furthermore, the air access widely available in Canada is generally not available in Antarctica.

Other Canadian conservation problems in coastal areas include meltwater, high humidity and salts, in common with many Antarctic sites. Objects in the active layer of permafrost are affected by biodeterioration and structures are also frequently damaged by permafrost movements and ice lens formation although this is rare in Antarctica.

Kellett’s Storehouse has been the most intensively investigated High Arctic Canadian site (Hett and Weaver 1980) and is the only major site where artefacts have been kept in situ, largely due to the volume of remains (Janes 1982). Reburial of artefacts in ice and protection with an insulated

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7 This site is perhaps the most comparable to Antarctic sites in terms of its age, materials, design and some of its conservation problems (Blanchette et al. 2008) although its climate is warmer in summer and supports grasses which are not present in Antarctica except the northerly Antarctic Peninsula.
floor has been the main conservation strategy used. A thermohygrograph was placed under the insulated floor to determine whether this is effective in keeping the store contents frozen to assist their preservation. Installation of an insulated floor has reduced and stabilised sub-floor temperatures and that the permafrost is causing no damage.

Figure 2.5: Beechey Island sites, Canada (Beattie & Geiger 1987)
2. Literature review

Other historic sites throughout Canada are less relevant to Antarctic historic sites either because of different climatic conditions or because the preservation problems are not priorities for Antarctic sites. Dawson City has significant problems with permafrost movement (Harrowfield 1996), whereas the Ross Dependency ‘permafrost’ problems are nowhere near as severe and are ice lens formation rather than permafrost heave related to the soils. Again, most artefacts are relocated to museums and the conservation problems are essentially those of waterlogged sites with no particular relevance to Antarctic sites. Other minor sites are climatically relevant, such as caches at Victory Harbour in Nunavut but no conservation information appears available.

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Research on erosion and site management problems undertaken at the Fossil Forest on Axel Heiberg Island is relevant to Antarctic sites, although this is a geological site rather than an historic site. Canadian Conservation Institute researchers (Bigras et al 1995, Grattan 1982) developed a coating method using ‘Parylene’ which consolidates the barely fossilised plant material enabling it to be examined by botanists and be displayed. Site management issues due to erosion and visitor interference are of great concern (Grattan et al 1996) and stabilisation of the permafrost in which the plant material is buried is the key to solving the preservation and management problems of the site. Geophysical investigations have been adapted for archaeological surveys including use of Ground Penetrating Radar (Vaughan 1986).

Mould growth is a significant problem (Hett 1987, Grant 1993) and both publications promote the use of sphagnum moss as a packing material for artefacts being transferred to laboratories for treatment. It is used in the Arctic since it grows naturally at the sites and is suitable for retaining moisture and minimising biological growth in waterlogged organic materials.

Complex artefact treatments are undertaken at the Canadian Conservation Institute in Ottawa, although some treatments such as cleaning and consolidation of metals and leather are also

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8 This approach was proposed for Antarctica (Harrowfield 1996: 43) although sphagnum moss is not found in Antarctica and may not be imported due to the potential to introduce alien micro-organisms. Australian Quarantine Inspection Service regulations prohibit its use for re-importation of objects to Australia and similar prohibitions are likely for other Antarctic Treaty nations. Other materials and methods are available should it be necessary to stabilise wet materials. Moreover, large scale removal of artefacts from Antarctica is not appropriate under Annexe 8 of the Madrid Protocol.
undertaken at the Prince of Wales Northern Heritage Centre in Yellowknife (letter to the author from Margaret Bertulli 1995).

A history and typology of food tins (Wade 1978) describes the manufacturing methods including labelling and its application for dating tin cans. This is relevant to the numerous tin cans found at Antarctic sites. Treatment of tinplate food cans for museum displays was undertaken on mid nineteenth century lead-soldered cans taken from Dealy Island and other locations (eg Fox 1979, Hawley 1981, Wright 1979 cited in Thorp 1986). Information from studies of the corroded food cans informed ensuing debate on whether lead from soldered cans killed Franklin’s men. Reports on medical studies of frozen bodies from Beechey Island (eg Beattie and Geiger, figure 2.6) and elsewhere discuss excavation methods.

Figure 2.6: Frozen body dating from 1846, Beechey Island (Beattie and Geiger 1987: 53)

Freeze drying using natural low temperatures to sublimate moisture was used to dry a canoe without the expense of freeze-drying chambers (Grattan et al 1980) although this method appears not to have been used again in Canada. Godfrey and Ambrose (1998) adapted this approach in Antarctica, using a venturi system to increase the rate of sublimation.
In summary, the significant conservation problems at Canadian High Arctic sites are human interference and trampling; wind erosion; coastal action; wildlife damage (particularly bears wherever food caches exist); corrosion; ice lens formation; permafrost movement, solifluction and biodeterioration in the active layer. Grattan et al (1996: 776) stated that lack of data on rates of deterioration processes is a significant limitation on further development of conservation strategies.

Greenland

Extensive information is available on the study and treatments of the 500 year old ‘freeze-dried’ bodies from Qilakitsoq which were taken to Denmark and then repatriated to Greenland after Home Rule (Hart-Hansen, Meldgaard & Nordqvist 1991). The bodies suffered fungal problems when taken to Denmark and required irradiation treatment and special cold display cases. Inuit and Viking sites have been excavated in southern Greenland but are not climatically comparable to Antarctic sites and have soil and permafrost rather than ice or frozen gravel.

Images of late nineteenth to early twentieth century fur-hunters’ huts (Barr, Susan 1998) show simple wooden buildings comparable in style to some early Antarctic buildings. Sod-roofed wooden buildings still exist in Greenland but no detailed information was available on their conservation. There are some nineteenth century historic sites from European exploration such as Peary's base at Qanaaq, the remains of the German North Polar Expedition of 1869-70 and Amdrup’s observatory and depot at Cape Dalton. However, information on these sites is scarce as the focus of archaeological activity by the relevant bodies such as the Greenland National Museum and Archive (Claus Andreasen, communication to the author by e-mail 7.5.02) and the Danish Polar Centre (e-mail communication to the author by Kirsten Caning, April 2002) is Norse and Inuit sites.

Norwegian trappers’ huts in North East Greenland National Park (NEGNP), dating from the early to mid twentieth century, are cared for by ‘Nanok’ (http://www.xsirius.dk/en/node/10), a private organisation. These huts were privately owned by the Danish and Norwegian trapping companies and when NEGNP was founded there was no plan for their preservation which led to
the current voluntary arrangement (personal communication to the author by e-mail from Peter Schmidt Mikkelsen on 27 April 2002). The huts are not listed as historic monuments and there are no formal requirements for documentation or reporting of work undertaken although Nanok Expeditioners prepare reports and photographs which are now available on their website (see figure 2.7). Mould (where wood is in contact with the ground) and polar bear damage are significant problems and the buildings are generally ice-free in summer and where felt covering is used the buildings remain ice-free in winter (ibid).

Figure 2.7: Antarctichavn hut, built 1930 (Barr 1993: 60) and under restoration in 2001 (Nanok website downloaded in 2002)
Norwegian territories - Svalbard, Jan Mayen and Bjornoya

Jan Mayen and Bjornoya are influenced by the Gulf Stream and are climatically more comparable to Subantarctic islands than Antarctica. Sites include wooden huts built on gravel or soil and experience biodeterioration of wood, meltwater and storm damage, corrosion (due to high RH) and coastal erosion similar to Subantarctic islands (see Barr 1985, 1987: 51).

Historic sites in Svalbard include many whaling stations dating from the sixteenth to eighteenth centuries with tryworks (figure 2.8) and graves built on permafrost, for example Smeerenburg (Barr, S 1987). Most experience warmer temperatures than Antarctica, although sites in the north and east of the archipelago experience temperatures more like Antarctica. RH is generally high. Nineteenth century trappers huts, built of planks and covered with tar paper, still stand although lower timbers suffer from meltwater and fungi and some replacement of planks and clearing of soil build up has been undertaken (Harrowfield 1996: 11-13).

Figure 2.8: Svalbard tryworks (Barr 1987)

Site reports and excavations from permafrost at Smeerenburg, one of the most studied sites, are given by Vons-Comis and Lutken in the Smeerenberg Seminar report (Barr 1987). Some conservation problems are similar to Antarctic sites, although generally closer to those at Canadian sites such as Beechey Island. Black polyethylene sheeting is widely used to aid melting
of permafrost, and hot water is used in excavations. Ground Penetrating Radar\textsuperscript{9} does not seem to have been used, possibly because salts are more extensive in sites close to the shoreline that makes the differentiation by radar impossible. Cross-disciplinary communication between historians, archaeologists and conservators and scientists (including geomorphologists interested in dating shorelines is well-developed between all the nations working on Svalbard sites, through international seminars as the Smeerenburg Seminar (Barr 1987).

Later North Pole expeditions by Wellman, Nobile and others resulted in sites that more closely resemble those in Antarctica, containing prefabricated wooden buildings, extensive steel structures, food supplies and other materials in common with locations such as Cape Denison and Cape Adare. Sites from the Andree (figure 2.9) and Wellman (figure 2.10) expeditions were extensively damaged by wind and artefacts are scattered and broken and corrosion is widely evident and serious in many locations (Capelotti 1994).

Figure 2.9: Andree’s house ((Bjerck & Johannessen 1999: 15)

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{andree_house}
\caption{Andree’s house ((Bjerck & Johannessen 1999: 15)}
\end{figure}

\textsuperscript{9} A geophysical method that uses radar to examine sub-surface layers.
Figure 2.10: Virgohamn maps and images (Bjerck and Johanessen 1999)
Aerial view of Virgohamn showing broken and scattered structures and artefacts

Table 2.1\textsuperscript{10} shows human interference is arguably the major concern at Svalbard sites with trampling, illegal interference with graves and vehicle tracks reported. Other conservation problems include solifluction, permafrost heave, coastal erosion, wind erosion and polar bear damage, including alleged opening of graves (Henrat 1984).

Field stabilisation problems discussed by Lutken (in Barr 1987) consider the conservation issues working on these sites, but again most artefacts are not conserved at the site. Research by Peacock (1999) on the effect of multiple freezing and thawing of both wet and dry textiles could be relevant to clothing outdoors at Antarctic sites where it is sometimes found partly buried outdoors under snowdrifts or inside buildings.

Despite extensive archaeological excavation and consequent conservation treatment, the literature from the Norwegian territories shows that while there are useful points of comparison with Antarctic sites no comprehensive suite of conservation treatments has been developed that can be applied in Antarctica. Nevertheless, the nature and scale of the conservation problems at the sites in the Norwegian territories have sufficient elements of comparability (as shown in Table 2.1) to

\textsuperscript{10} Placed at the end of the chapter due to its size.
support the case argued by Barr (1990) and others for international cooperation between conservators working on polar historic sites.

**Russia**

Barr (1995) provides brief descriptions of deterioration affecting Russian sites, particularly observations of the Nansen shelter showing its progressive deterioration including the rotting of the walrus hide roof and scattering of wooden elements. Other sites include Papanin's abandoned base, Leigh Smith's Eira House and some Soviet-era weather stations (abandoned, but now proposed for re-use). Correspondence with the Russian member of IPHC, Peter Boyarski (e-mail to the author 23.5.02), revealed that visits to historic sites in Franz Josef Land and other northern locations in Russia have been made over the past 15 years. Boyarski confirms the opinions of Barr that Eira House and Lee Smith’s overwintering hut at Cape Flora are in good original condition and no special conservation work has been required. Surface corrosion of nails are other metal fittings and artefacts has occurred but “the inner parts seem to be quite strong up to now” (*ibid*). Wire stays used on the buildings have however been destroyed by corrosion. These sites are not often visited due to their remote location. Some huts at Tichaya Buchta are “permanently full of pressed ice and snow” (*ibid*) and no conservation work has been undertaken.

Braat (1984) discusses the work of Kravchenko who found the remains of Barents’ ship on Novaya Zemlya. A later site visit to Barents' hut (Hacquebord 1991: 38) reports its current poor condition (shown in figures 2.11, 2.12) with extensive visitor damage at this site by comparison with Antarctic sites.

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11 The apparent contradiction in the good condition of nails and damage to stays may be due to low atmospheric corrosion of the former and stress cracking in the latter.
Figure 2.11: Barents’ hut deterioration, Hacquebord in Chaplin & Barr (2004: 74)

Figure 2.12: Barents’ hut (Hacquebord in Chaplin and Barr 2004: 74)
Antarctic sites

Sector Antartico Argentino

Argentina nominated Nordenskjold’s Snow Hill Island hut for protection under the Antarctic Treaty because of the participation of an Argentine (Sobral) in that expedition. Argentina has continuously managed the remains of the Scottish National Expedition on Laurie Island since transfer in 1904 (Comerci 1983). Comerci discusses the excavation of the Snow Hill Island hut detailing the condition of artefacts and extent of snow accumulation but discusses the deterioration problems only briefly. Excavation techniques includes block lifting or covering of areas containing artefacts encased in ice which were then wrapped in double layers of polyethylene (black outside, clear inside) using solar radiation to melt the ice.

Capdevila et al 1994) describe artefacts removed from the Snow Hill Island hut, many of which have been transferred to museums in Argentina (Comerci 1983). Capdevila et al (1994) discuss the replacement of a canvas roof on Nordenskjold’s Hope Bay refuge and describes an experiment with a polyester coating applied in situ to strengthen the repair material. There has been apparent controversy regarding unauthorised excavation and other activity at Snow Hill Island (IPHC website downloaded 8 December 2007).

No condition reports have been found in the literature that discuss the condition of Argentine IGY bases although San Martin base was considered by Warren (1989: 187) to be an historic resource.

Australian Antarctic Territory

The Australian Antarctic Division Library has a comprehensive collection of ANARE field reports including reports on examinations of Cape Denison and other sites at various dates from the 1950s onwards. Photographs and other image collections are held at the organisation’s multimedia centre.
As well as the early ANARE stations at Mawson Station, Davis Station, the Australian Antarctic Territory includes a former US IGY base at Wilkes and some remains of the Russian/Polish station at Oasis in the Bunger Hills (Table 1.1 No. 10). There are also some historic monuments at Vostok (Table 1.1 No. 11), an inland Russian station in the Australian sector, but no reports are available and it appears that no heritage or environmental assessments have been made (Viktor Pomelov, Russian Antarctic Expedition, personal communication to the author 1996).

Reports on the ANARE stations, which are mostly not designated historic sites under the Antarctic Treaty, show there are significant deterioration problems associated with snow drift formation and meltwater/condensation. Some buildings, however, are in very good condition, such as the Heard Island hut relocated to Davis Station (figure 2.13). A symposium held at the Australian Antarctic Division collated information about the ANARE buildings in 1992 and more recent reports are available in ‘State of the Environment’ reports by the Australian Government available on-line at http://www.environment.gov.au/about/publications/annual-report/06-07/outcome2-antarctica.html

Figure 2.13: Old Paint Store, author’s photo 1992
Clark and Wishart (1989) studied Wilkes Station and the ‘Tunnel’ (figure 2.14) at old Casey Station that was removed in the early 1990s due to structural failure caused by corrosion. While the main focus of the documentation was a study of the social history, their report clearly shows problems with corrosion. Problems with large quantities of hazardous chemicals, often covered by ice, and smashing of windows by errant expeditioners (allowing ice formation to obscure the previously clear view of interiors with meals still on the table) were also mentioned.

Figure 2.14: Casey Tunnel when new (Australian Antarctic Division, undated)

Ambrose and Godfrey (1998) used dataloggers to record temperature and relative humidity inside a (non-historic) building at Wilkes during experiments to remove ice from the interior of the building by sublimation using a venturi system. The building was covered with plywood and sealed with silicone (figure 2.15). This research, based on some presumptions about damage due to the presence of ice, was proposed to remove ice from the AAE main hut at Cape Denison, discussed in detail in Chapter 4.

Figure 2.15: Wilkes venturi project (Ambrose and Godfrey 1998)
The abandoned AAE base at Cape Denison, known as ‘Mawson’s Huts’ has particular archaeological significance being one of the least disturbed sites of the early exploration of Antarctica (Lazer 1986) and is the best known Australian Antarctic historic site. There are four buildings at the site, a Memorial Cross and numerous artefacts from the occupation of the site in 1912-13. During the brief visit in 1931 by the British Australian New Zealand Antarctic Research Expedition a formal sovereignty claim was made, (figure 1.19). The condition of the plaque in 1984 is shown in figure 2.16.

Ledingham (1979) described work undertaken in 1977 by a small party (without an archaeologist or conservator) including the removal of ice from the Living Hut and cladding of the Workshop roof with lead sheeting. The intended replacement of the weathered original cladding with new Baltic Pine timbers of the same dimensions was prevented by logistics problems. The original cladding was to be removed for a museum exhibition. The Memorial Plaque (attached to the Memorial Cross) was enclosed in the bronze box (figure 2.16) and the Proclamation Plaque (attached to the Puffometer Pole) was similarly enclosed in a bronze box with a plastic ‘window’.

Figure 2.16: AAE Proclamation plaque (Project Blizzard, 1984)
In 1984 Project Blizzard proposed an extensive program of work including removal of ice and lifting and replacement of weathered timbers, inserting vapour barriers to prevent further ice ingress (Blunt 1991). Blunt’s thesis includes extensive documentation and drawings including a large bibliography listing unpublished reports held by the Australian Antarctic Division. The proposed ice removal and recladding/vapour barrier was not approved by the Australian Heritage Commission and this work was not carried out, although excavations by archaeologists (Lazer 1986, McGowan 1988) were undertaken, and the initial condition survey was conducted by the author, a materials conservator (Hughes 1986). The Proclamation and Memorial Plaques (figure 2.17) were by this time stained blue from the effects of corrosion on the bronze containers and were also wet from melted snow and wood fibres were raised and detaching from the surface.

Figure 2.17: AAE Memorial plaque enclosed in bronze box (Project Blizzard 1984)

Controversy continued concerning ice removal but there were no further visits to carry out conservation treatments at the site until 1997. Various professionals have prepared assessments of the significance of the site, a Conservation Management Plan was written (Ashley 2000) and a revised plan was published by the Australian Antarctic Division in 2007 (available at http://www.aad.gov.au/default.asp?casid=33170 ).
Conservation work has been undertaken by the Mawson’s Hut Foundation including removal of ice (figure 2.18, figure 4.8) to carry out repairs to the Workshop, repair of windows and complete covering of the existing roof of the Workshop by new boards coated with an acrylic polymer. Monitoring of the hut has been conducted as part of the research for this thesis described in detail in Chapter 4. Work is ongoing at the site.

Figure 2.18: Memorial Plaque stained blue (author’s photo, 1985)
Note: the top row of letters is approximately 40mm high.

Figure 2.19: Ice-filled verandah C Denison (Ashley 1998 in Chaplin and Barr 2004: 46)
Note: the doorway is approximately 80cm wide.
Territorio Chileno Antartico

A series of archaeological studies led by Stehberg investigated alleged native stone tools found at sites on Greenwich Island, Cape Shirreff (Livingston Island) and other islands in the South Shetlands (Stehberg 1983). Some construed this as a bid for a territorial claim through prior discovery and occupation by Fuegan natives (Headland 1993 personal communication).

However, subsequent research (Torres & Aguayo 1993) discuss evidence of cooperation between Fuegans accompanying whalers and sealers in later periods. Photos and substantial descriptions are included of the types of objects found at 18th-19th century sealing sites on the island (ibid: 74-75). These are mainly bone, ceramics, glass bottles, some metals, leather fragments and some tools with metal tips on wood and string shafts. Excellent site maps are provided with photos showing a conventional excavation in gravel and sand, ie not frozen. Stehberg (personal communication to the author 2002) considers the stone projectiles shown in figure 2.20 (Stehberg 1983) to be ‘scientific fraud’ but that the skull and other artefacts are evidence of the participation of Fuegan natives on early British sealing Expeditions. Stehberg and Pearson, a Chilean-Australian team, are conducting ongoing research at Antarctic Peninsula sealing sites.

Figure 2.20: Alleged prehistoric tools found in Antarctica (Stehberg 1983)
2. Literature review

*Terre Adelie (France)*

Port Martin was established in the late 1940s and abandoned after a fire in 1951 and is now buried under substantial ice accumulation (Le Mouël personal communication). Base Marret (figure 2.21) at Île des Petrels (now part of Dumont d’Urville base) was established as a temporary base after the Port Martin fire. Brief observations of the Marret site were made by the author in 1997 although no other reports have been found on recent archaeological excavations or materials conservation work at these sites.

Figure 2.21: Base Marret, author’s photo 1993

*New Zealand Ross Dependency*

Harrowfield (1996) compared conservation problems of Arctic sites with those of the Ross Dependency (but not other Antarctic sites) and contains a useful summary of literature on Arctic sites which confirms that treatments of Arctic sites are in fact quite limited since there is a significant focus on field stabilisation and removal of artefacts to museums rather than *in situ* preservation.
Arguably the most extensive body of literature on the conservation of Antarctic sites comprises
the reports by New Zealand researchers on the huts on Ross Island and at Cape Adare since the
eyearly 1960s. Materials Conservation did not exist as a profession in New Zealand when
Quartermain 1963) first removed ice from Scott’s Terra Nova hut in 1960 (figure 2.22) and later
from the hut at Hut Point. Quartermain was an historian, not an archaeologist so "artifacts were
distributed throughout the hut where they seemed most appropriate”. Harrowfield (1981:52)
states that no record was made of their original locations. Unfortunately many artefacts were
considered to be rubbish and were disposed of in tide cracks and important early geomagnetic
buildings were demolished without their scientific or cultural values being assessed. There were
no real precedents for such work but it seems unfortunate in retrospect that so much work was
carried out without adequate time to assess whether any adverse effects were arising from the
work undertaken.

Figure 2.22: Cape Evans darkroom before removal of ice, 1960 (Quartermain 1963: fig 28)
Harrowfield noted that artefacts that had been in perfect condition shown in photos when first excavated were suffering from various deterioration problems by the early 1980s. Harrowfield (1991) states:

"The artefacts encased in ice were well-preserved. The preservation qualities of constant below zero temperatures on artefacts is exemplified by a zinc-plated canister from the 1899 Expedition containing an enamel plate, fry pan and teaspoon individually wrapped in brown paper in almost new condition."

Considerable maintenance was required to keep the huts clear of ice and some ice removal methods appear to have resulted in deep scoring of the wooden floors (anon 1983). Ice was excavated from Borchgrevink’s hut at Cape Adare in 1961 (Harrowfield 1991).

Corrosion is particularly evident on artefacts both inside and outside the Ross Island huts and is a significant concern with the numerous food tins because of the labour-intensive treatments that are required to treat corrosion and damage to paper labels. Pioneering measurement of corrosion rates at Cape Evans and Lake Vanda by King et al (1988), mentioned previously, found rates at Cape Evans were comparable to those of suburban areas in temperate Melbourne.

At Cape Adare strong and frequent katabatic winds have demolished Campbell’s Hut (Harrowfield 2006) and torn off the door of Borchgrevink’s hut. Damage to timber surfaces by windborne particles (scoria at the Ross Island huts and beach sand at Cape Adare), ranged from mild to severe, discussed in greater detail in Chapter 7.

Harrowfield (1991) also identified damage from ‘permafrost’, defibring, algae, meltwater, and fungi at all the sites cared for by New Zealand and from the accumulation of penguin guano at Cape Adare. Excavation methods included the use of black plastic to hasten melting of frozen ground. Harrowfield also examined visitor management issues and explained supervision arrangements by New Zealand government representatives. Monitoring of temperature and relative humidity inside the Cape Evans hut has been undertaken with varying success since the early 1990s. A thesis by Mason (1999) on environmental conditions in the Cape Evans hut is
discussed in detail in Chapter 4 along with later research by Held et al (2005) at Ross Island sites. The New Zealand Antarctic Heritage Trust has coordinated funding and treatment carried out at these sites and publishes regular news bulletins on conservation activities at the sites. Ongoing research on timber (Farrell et al 2004) has been mentioned previously.

Removal of ice from NZ huts has not been universally supported (see Chapter 4). Prevention of continued ice ingress, even with the controversial use of vapour barriers, has not been entirely successful, despite extensive annual maintenance, which is not possible at many other sites.

Conservation studies at the New Zealand sites, while extensive, are by no means comprehensive nor complete and are not necessarily applicable at other Antarctic sites. While much of the research has made significant progress in understanding the risks, there is no evidence, and indeed considerable doubt, that these methods could be successfully applied at sites with warmer and windier climates or more remote locations.

Norwegian Antarctic sites

Dutch archaeologist Hacquebord (1992) reported a multidisciplinary study of the environmental impact of an abandoned Norwegian whaling station at Deception Island (operational 1906 to 1931). Photographs and references in the text clearly show that corrosion of metal tanks and building elements are severe and wastes from whale blood and bone have stimulated plant growth. The paper was not intended to examine the preservation concerns although it gives insight into the challenges of developing a strategy for conservation of the site.

Norway established ‘Maudheim’ in Dronning Maud Land as the base for the Norwegian-British-Swedish Antarctic Expedition of 1949-52 but this was covered by eight metres of drifting snow within 10 years (Barr 2000) which limits opportunities for excavation (figure 2.23). Norway Station, established during the IGY was also covered by snow (Susan Barr, e-mail to the author 17 April 2002).
Doyle (1992) discussed the search for Amundsen’s tent left at the South Pole proposed by a glaciologist, Christensen. Norway ICOMOS opposed the proposal citing a high risk of damage due to unqualified personnel and the project did not proceed (Barr 2001 personal communication). Ground penetrating radar was proposed to locate the tent to then be “dug up with chainsaws” (Doyle 1992: paragraph 7) and “an archaeologist will then do the delicate work of digging out the tent and preserving it” (ibid.: paragraph 28). The article highlights the concerns expressed by Warren (1989: 14) about the lack of guidelines on use of appropriate excavation methods and qualified personnel.

*United Kingdom (British Antarctic Territory)*

The British Antarctic Survey Annual Report (1991) stated abandoned bases established as part of the secret 1940s ‘Operation Tabarin’ are now being 'cleaned up' although there are some concerns these may cause much interesting historical material to be inadvertently lost. Shears and Hall (1992) discuss the British approach to management of abandoned bases and field stations, which is mainly concentrated on implementing the Madrid Protocol and states that:

“Their poor state can be attributed to the ingress of ice and water caused partly by lack of maintenance, but also by vandalism” (ibid.: 3.1).
Four British bases from the 1940s (sites 61-64, Table 1.2) were added to the list of Antarctic Treaty designated historic sites in 1995 and buildings at Port Lockroy (figure 2.24) are managed by the UK Antarctic Heritage Trust (UKAHT) (http://www.ukaht.org/index.htm).

Figure 2.24: Bransfield House at Port Lockroy (R Atkinson, undated UKAHT)

Figure 2.25: Map of UK sites (UKAHT website, downloaded 14 March 2008)
US sites

Numerous US whaling ships visited Antarctica during the early to mid-nineteenth century although few traces have been found. The US Amundsen-Scott Base at the South Pole (Table 1.1 site 1) has an unusual geodesic dome building is undoubtedly of some historic interest. However, neither it, nor other historically interesting Jamesway huts from the US McMurdo Base have been professionally assessed and since 1993 there have been proposals for their removal. Detailed archaeological surveys were made of Byrd’s East Base, abandoned in 1941 and the nearby Ronne Expedition base (1947-48). Parfit (1993), Broadbent (1992) and Spude and Spude (1993) show clear evidence of damage caused by the wind (figure 2.26) and deterioration by corrosion. Broadbent (1992: 15) mentions equipment including a spare aircraft engine, tractor; large quantity of food and clothes, garbage dump that were "largely untouched by either vandalism or deterioration… Organic materials were well preserved by the polar environment, and, consequently, the remnants of the seals used as dog food by the British were everywhere... Paper, cloth and wood were also in good condition, but metal had suffered considerably from the maritime climate". Spude and Spude (1993) prepared a comprehensive and detailed management plan for the site identifying major risks from hazardous materials. In 1991-92 a site restoration team collected artefacts, removed hazardous materials and stabilised buildings, the areas around the buildings, and prepared gravel and rock pathways. Interpretative information including a visitor handout was prepared (Broadbent 1992).

Figure 2.26: Wind damage at East Base (Parfit 1993: 111)
2.5 Discussion

2.5.1 Gaps in the literature

*Site survey methodologies*

There is no comprehensive guide to methods suitable for surveying the condition and deterioration problems of polar historic sites, for example to outline standard methods for salt deposition or corrosivity measurement, or use of Ground Penetrating Radar.

*Terminology of deterioration processes*

The lack of standard terminology for some deterioration processes helps perpetuate imprecise descriptors such as ‘freeze-thaw damage’ and makes it difficult to search the literature. Development of a glossary would significantly improve communication.

*Accuracy of information*

Some published information was found to be inaccurate, inconsistent or unsubstantiated, as discussed in Appendix F and further examined in Chapters 4 to 10. It is important to document empirical evidence to determine the real cause of deterioration and identify treatments that will target cause rather than symptoms.

2.5.2 Deterioration information

Reports on 35 relevant polar historic sites collated in Table 2.1 demonstrate they are not ‘in a state of near perfect preservation’ and many problems threaten their survival.

*Damage by temperature and humidity changes*

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12 While such a guide is beyond the scope of this thesis, it would be beneficial in improving conservation practices.
‘Permafrost movement’ is reported at many Arctic sites and at Davis Station, Borchegrevink’s hut and Cape Evans but is more accurately described as ice lens formation. Ice ingress into buildings was reported at Kellett’s Store House, Snow Hill Island, Maudheim, Cape Denison, Port Martin, Wilkes, and at the Ross Dependency sites and is reported to cause crushing and high RH. Artefacts at polar sites have frequently been observed to deteriorate when excavated from ice.

**Metals**

Corrosion was reported at coastal historic sites but limited rate measurements were available.

**Salts**

Salt deposits are rarely reported in the conservation reports of polar historic buildings. Defibring was not initially (1985) widely reported although a photo of Krisch’s grave (figure 2.27) in Franz Josef Land suggests the problem was unrecognised. Blanchette, Held and Farrell (2002) have now published considerable research on this problem.

Figure 2.27: Krisch's grave, Franz Josef Land (Barr 1995: 118)

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13 An initial attempt has been made in the glossary in this thesis.
2. Literature review

Wind damage

Structural damage by wind was reported at many sites in both polar regions. Corrasion was reported at Beechey Island, Kerketen, Axel Heiberg Island Fossil Forest, Wilkes, Cape Denison, Byrd’s East Base and at all the Ross Dependency sites using varied terminology. This problem is not reported for sites in Greenland, Franz Josef Land and UK huts in the Antarctic Peninsula which may reflect incompleteness of records.

Biodeterioration

Food (eg ham) survives in Shackleton’s hut and bodies buried in permafrost are still in good condition after several centuries in Svalbard. However, research in Canada, Svalbard, Franz Josef Land and at all major sites in the Antarctic showed that fungi and bacteria are prevalent problems. Farrell et al (2004) demonstrate that fungi and bacteria can still grow at low temperatures at rates that will certainly damage materials in the long term\textsuperscript{14}.

Human impacts

Severe damage by visitors is reported at most Arctic sites in Canada, Svalbard and at some Antarctic sites, particularly IGY bases such as Wilkes whereas it is less significant than weather damage at most other Antarctic sites. Tourism is increasing in both polar regions.

Deterioration rate measurements

While the literature provides some qualitative information on damage processes, measurement of rates of deterioration and field research evaluating conservation treatments are rare. Only Harrowfield (on corrasion), Grattan \textit{et al} (wind erosion), King \textit{et al} (on corrosion), Peacock (on impact of freezing-thawing cycles on textiles) provide detailed methodologies and rate measurements for their respective studies. These data are limited to one or a few sites although

\\textsuperscript{14} This research is reviewed in detail in Chapter 9 including citations.
there is potential benefit to apply these measurements more extensively to develop new rate measurement methodologies for other deterioration processes in a more comprehensive manner.

Lack of accepted methodologies and rate data limits the ability to prioritise conservation work, and inhibits comparison between different sites, which in turn diminishes opportunities for collaborative research between nations interested in preservation of polar historic sites.

**Comparability of conservation problems in different polar locations**

In addition to the previously discussed climatic and political conditions, Arctic sites are sovereign national territory so artefacts can be, and are, excavated and removed offsite, often because of risks of human disturbance. In Antarctica greater logistics problems and the Antarctic Treaty provisions for *in situ* preservation limit this approach.

**Success of conservation treatments in polar regions**

Jenness (1990) and Harrowfield (1996) reported that some previous excavation methods have caused damage and many treatments have been unsuccessful or highly controversial, particularly ice removal. Removal of ice from inside Antarctic historic buildings has occurred at Nordenskjold’s hut, Borchgrevink’s hut, Mawson’s (Main) Hut, Scott’s Cape Evans Hut and Hut Point yet detailed environmental monitoring that would help understand impacts of ice removal has only been undertaken at Cape Evans and Cape Denison (as reported in this thesis).

**2.6 Summary**

- Conservation problems are widespread and serious, yet the myth of ‘near-perfect preservation’ (Trevelyan 1996) persists.
- While it is often proposed that treatments for Antarctic historic sites should be sought from prior experience at Arctic sites\(^{15}\), the analysis in Table 2.1 shows many Arctic treatments are not appropriate (due to climatic or logistic differences) or are not permissible (under the
Antarctic Treaty) and that in many aspects (eg monitoring of temperature and RH) are already highly developed in Antarctica.

- There is abundant evidence that many previous conservation treatments used in both the Arctic and Antarctica have failed, yet there has been no comprehensive analysis of the reasons to guide improvement of conservation survey methods and conservation treatments. The difficulty of repeated access to sites to assess effectiveness of treatments makes it important to learn from experience at all polar historic sites.

- The most significant gaps in the literature are:
  - Lack of quantitative methods for measuring rates of deterioration in Antarctic conditions, and consequently a lack of deterioration rate data;
  - Insufficient analysis of environmental conditions inside buildings; and
  - Insufficient reporting on effectiveness of conservation treatments, especially with respect to ‘re-treatability’.

15 Comments to the author from tourists at Antarctic historic sites and some participants at Mawson’s Huts Foundation.
Table 2.1: Summary analysis of literature on Arctic and Antarctic historic sites

<table>
<thead>
<tr>
<th>Region</th>
<th>Sites</th>
<th>Excavation and site survey</th>
<th>Materials present</th>
<th>Deterioration issues identified or recorded</th>
<th>Conservation treatments reported</th>
<th>Monitoring of T and RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arctic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alaska</td>
<td>Barter Island, 18th century native site with later 19th century European activity</td>
<td>Experimental techniques using fire on top of frozen ground (Jenness 1990)</td>
<td>Wood, bone, human remains, native clothing</td>
<td>Damage mostly by human intervention (Jenness 1990)</td>
<td>No details, general references in Jenness (1990).</td>
<td>Nil (Alaska Historical Office)</td>
</tr>
<tr>
<td></td>
<td>Utqiavik, native site ca. 1500 near Barrow</td>
<td>Warm water poured on artefacts, no conservation treatments given (anon 1985)</td>
<td>Inupiat site with wood, clothing and hunting equipment (bone etc), no metals.</td>
<td>Generally good condition due to recent excavation from permafrost (anon 1985)</td>
<td>Few details given- photos show organic artefacts (Dekin 1987, Newell 1984); bodies and clothing intact</td>
<td>Nil- site was re-buried (Dekin 1987)</td>
</tr>
<tr>
<td>Canadian High Arctic</td>
<td>Kellett’s Storehouse, 1850s, Dealy Island, Nunavut (fig 1.10) (Franklin era site), Fort Conger (Blanchette, R, Held &amp; Jurgens 2008)</td>
<td>Photogrammetric recording, warm water used to melt ice (Hett &amp; Weaver 1980)</td>
<td>Dealy Island- Stone building containing huge quantity of Royal Navy supplies for over 60 men, including canned foods, fresh apples, clothing, &gt;100 boots, coal, iron stoves and ballast tanks, wooden posts and doors, tarred canvas roof, sledges, glass bottles, whale boat, cairn, graves (Harington 1964, Weaver 1978, Janes 1982, Trafton 1989). Ft Conger- wood, etc.</td>
<td>Dealy Island- Vandalism and illegal excavation and collection, bear damage, meltwater, permafrost activity, corrosion, fungi, waterlogged wood in active layer, no defibring recorded (Hett &amp; Weaver 1980). Ft Conger- fungi (Blanchette et al 2008).</td>
<td>Meltwater diversion, insulated plywood floor installed to retain permafrost, selected artefacts taken to Yellowknife and Ottawa (leather and textiles) for treatment; remainder left under floor in permafrost was successful in reducing deterioration (Janes 1982). Treatment of tin cans from various sites (Fox 1979, Hawley et al 1981, Thorp 1986, Wight 1979). Ft Conger- funds for treatment being sought.</td>
<td>Single thermo hygrograph used in early 1980s, single datalogger used until recently (Bilz 1989) indicates under-floor temperatures around +2.2°C, RH 80% against external conditions +4.1°C, 63% RH (Bilz 2002).</td>
</tr>
</tbody>
</table>

\(^{16}\) In this table ‘No information found’ indicates no information was found via the literature review processes discussed in Chapter 2, noting the difficulties mentioned, and any follow up enquiries via professional contacts listed in the Acknowledgements.
<table>
<thead>
<tr>
<th>Location/ Site/ Date</th>
<th>Details</th>
<th>Problems</th>
<th>Conservation Efforts</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northumberland House and Franklin-era graves (fig 2.6); 1840s-1850s Beechey Island, Nunavut</td>
<td>Warm water used to melt ice, including during excavation of 3 bodies (Kowal, Krahn &amp; Beattie 1989). Stone, wood, human bodies, food cans, glass bottles, barrels (CCI 1976).</td>
<td>Main problem: human interference. Also wind erosion, bears, Corrosion affects Breadalbane wheel (Sutherland 1985). Fungi- see also reports by Blanchette et al 2008.</td>
<td>Epoxy resin replica gravemarkers failed due to wind erosion, new wooden replicas installed late 1980s. Sutherland (1985) underlined the need for pre-excavation consultation with conservators</td>
<td>No information available.</td>
</tr>
<tr>
<td>Keketen Island (ca. 1500-1921) whaling site, Nunavut</td>
<td>No details given. Whaleboat slipway (wood + metal fasteners), trypots, iron tanks, barrels, anchor and chain and other ship remains, graves. (<a href="http://www.historicplaces.ca/en/rep-reg/place-lieu.aspx?id=15682">http://www.historicplaces.ca/en/rep-reg/place-lieu.aspx?id=15682</a>).</td>
<td>Wildlife damage, wind erosion damages wooden grave markers, skidoo collisions with snow-covered artefacts, permafrost movement, biodeterioration in active layer.</td>
<td>No detailed report available although building work and artefact treatment, walkways and interpretation have been done</td>
<td>No buildings suitable for monitoring? No information was found.</td>
</tr>
<tr>
<td>Greenland</td>
<td>Cape Dalton hut</td>
<td>Not stated (Amdrup 1902) Timber building, objects not described</td>
<td>No information available</td>
<td>No information available</td>
</tr>
<tr>
<td>Peary’s North Pole expedition hut, 1908-09</td>
<td>Building relocated to Qanaaq, current status not known Timber building, objects not described (Gilberg 1987)</td>
<td>Not stated</td>
<td>Gilberg 1987 (insufficient detail)</td>
<td>No information available</td>
</tr>
<tr>
<td>Historic document caches in various locations, 19th century</td>
<td>No details given (Dawes 1967). Paper documents usually in metal container, occasional leather components (Dawes 1967).</td>
<td>Some corrosion and damage from moisture, but no major problems with driven snow (Dawes 1967).</td>
<td>Not given (Dawes 1967)</td>
<td>Nil</td>
</tr>
</tbody>
</table>
### Antarctichamna and NE Greenland trapper’s huts (fig 2.7)

See Nanok website discussed in Chapter 2-this provides pictures and general discussion of condition.

- **Mainly timber buildings of traditional Scandinavian style with glass windows, ferrous chimneys and various felt covering plus associated hunting artefacts.**
- **Fungi affects wood in contact with the ground, bear damage; some wind and snow ingress problems. Some human interference.**

**Buildings are maintained by restoration with new materials that are similar to the originals.**

**Not undertaken.**

### Svalbard

**17th to 18th century whaling sites, Smeerenburg, Amsterdamoya (fig 2.9)**

- **Leather, textiles, ceramics (including smoking pipes), iron tools and try pots. Human remains (fig 1.9) and clothing in burials (Reymert 1979, 1988),**
- **Biodeterioration of organic artefacts in active layer. Fungi. No details of metal object treatment but known to be corroded. Permafrost heave, wildlife damage (bears, foxes) cited in many publications.**


**Periodic visits by cultural heritage personnel inspect the site, some rangers used to supervise visitors.**

### 18th -19th century trapping sites including Pomors (Russian), Scandinavians

- Zavyalov (1989) and Chernosvitov (1989) give details but not available in Australia, thought to include use of black polyethylene sheeting to hasten melting of permafrost. Some earlier excavations (1950-60s) cited in Harrowfield 1996: 11 recovered hunting and skinning equipment.
- **Timber buildings, usually log construction, driftwood or planked with exterior covering of batten ed tar paper. Pomor sites usually have characteristic high wooden crosses. Some buildings have slate floors and turf roofs (Barr 1993).**
- **Visitor interference, coastal erosion are most severe problems (Barr 1985, 1998). Decay of timber in contact with soil. Wind damage.**

**Damaged and at risk crosses have been moved into museums (Harrowfield 1996: 13). Damaged lower planks of huts replaced, removal of soil accumulation, re-turfed roof of oldest hut (1827) See Harrowfield 1996: 11-13. Carpenters have carried out some building repairs.**

**Periodic visits by cultural heritage personnel inspect the sites, annual visit by Governor, some rangers used to supervise visitors (Harrowfield 1996: 11).**
<table>
<thead>
<tr>
<th>Location</th>
<th>Late 19th century to early 20th century expedition buildings, eg Andree Balloon site (fig 2.9), Camp Wellman, Virgoahamm (figs 2.4, 2.10)</th>
<th>Surface surveys (Capelotti 1994).</th>
<th>4 huts, two wrecked airships, airship hangar, outbuildings, fuel depots, chemical wastes, ceramic and metal debris, 2 dead expeditioners (Capelotti 1994).</th>
<th>Corrosion (Capelotti 1994), wind damage, corrosion, visitor damage</th>
<th>No information available on conservation treatments.</th>
<th>No information available although National Park rangers appear to visit periodically. No monitoring of T&amp;RH inside buildings.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Russia and Franz Josef Land</td>
<td>Barents Hut, Novaya Zemlya 1596 (figs 1.1, 2.13)</td>
<td>Surface surveys (Hacqueboard 1991) Unauthorised digging (ibid)</td>
<td>C17th hut of wood, metals, ceramics, clothing, books, navigation instruments, swords and weapons. Artefacts removed by Carlsen in 1871, many artefacts now in museums,</td>
<td>Extensive visitor disturbance, building remains are fragmentary, wood decayed, corrosion (Hacquebord 1991)</td>
<td>No information available.</td>
<td>Site access is difficult. No known regular visits.</td>
</tr>
<tr>
<td>Various Russian, Norwegian, Austrian and other sites listed in Franz Josef Land and Severnaya Zemlya Barr 1995 (figs 1.12, 2.30)</td>
<td>Surface surveys (Barr 1991, 1995) but difficult to find information on any excavations or detailed reports.</td>
<td>Varied- including basic shelters used by Nansen and others (driftwood, animal skins), memorials, plaques, etc to large complexes such as weather stations (Barr 1995: 138). Some sites are protected, others evidently vulnerable.</td>
<td>Extensive deterioration evident in Barr 1995 including water damage, corrosion, biodeterioration, human impacts reported, defibring (fig 2.30).</td>
<td>No detailed information available- some material has been repatriated to museums.</td>
<td>No information found.</td>
<td></td>
</tr>
<tr>
<td>Eira House</td>
<td>No information</td>
<td>Timber building, wire stays (Barr 1995)</td>
<td>Nil (Barr 1995)</td>
<td>Stated to not be required (ibid).</td>
<td>No information available</td>
<td></td>
</tr>
<tr>
<td>Antarctic</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>South Orkneys, South</td>
<td>Melchior (Argentina, 1940s)</td>
<td>Nil (anon 1974)</td>
<td>Timber, plywood, metal/insulation composite sheet</td>
<td>No information available</td>
<td>No information available</td>
<td>No information found</td>
</tr>
<tr>
<td>Location</td>
<td>Significance and Description</td>
<td>Conservation Issues</td>
<td>Actions taken</td>
<td>Notes</td>
<td></td>
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<tr>
<td>San Telmo wreck, 1820s, Cape Shirreff on Livingston Is</td>
<td>Underwater survey (Torres and Aguayo 1993). Early 19th century wooden sailing ship and equipment</td>
<td>Not known</td>
<td>Full reports could not be obtained (Torres and Aguayo 1993).</td>
<td>No information found.</td>
<td></td>
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</tr>
<tr>
<td>Sealing sites on Greenwich Is, South Shetlands consisting mainly of low stone walls with some timber floors and associated equipment.</td>
<td>Stehberg et al (2008) provide methodology and references, also Pearson (2007). Stone tools; bone, ceramics, glass bottles, some metals, leather fragments and some tools with metal tips on wood and string shafts</td>
<td>Stehberg et al (2008) and Pearson (2007) provide a summary of conservation issues, including human interference and various erosion processes.</td>
<td>No detailed reports of treatment.</td>
<td>Since these are not conventional enclosed buildings, monitoring is not undertaken.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>US base- Byrd’s East Base, Stonington Island, re-occupation by Ronne expedition with some later British material (fig 2.29...)</td>
<td>No ice excavation from building, some artefacts excavated from ice (Broadbent 1992, Spude and Spude 1993) Prefabricated timber hut, rockwool insulation, scientific equipment, animal carcases, tinned and other food, clothing, transport equipment, dogs, medical supplies, extensive hazardous materials (Parfit 1993).</td>
<td>Corrosion, fungi (Arenz &amp; Blanchette 2009), wind damage to cladding of building, ice accumulation, breakages, vandalism, erosion of timber by particles (Spude &amp; Spude 1993).</td>
<td>Environmental clean up, selective removal of artefacts, ‘stabilised buildings’, pathways constructed for visitors. Recommended evaluation by conservator (Spude and Spude 1993)</td>
<td>No information found.</td>
<td></td>
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<tr>
<td>Region/Station</td>
<td>Notes</td>
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<tr>
<td><strong>Dronning Maud Land (Norwegian sector)</strong></td>
<td>No information found. N/A N/A</td>
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</tr>
<tr>
<td>Maudheim (Norwegian-British-Swedish Antarctic Expedition, 1949-52, fig 2.26)</td>
<td>Not excavated, covered by eight metres of drifting snow within 10 years (Barr 1987: 76) Wooden and composite materials (Susan Barr, email to the author 2002) No information found. N/A N/A</td>
<td></td>
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</tr>
<tr>
<td>Norway Station (IGY)</td>
<td>Covered with snow, not excavated Wooden and composite materials, few details available (email from Susan Barr 2002) No information found. N/A N/A</td>
<td></td>
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<tr>
<td>Mawson Station, ANARE 1954.</td>
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<tr>
<td>Location</td>
<td>Observations &amp; Conditions</td>
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<tr>
<td>Davis Station, ANARE</td>
<td>Established in 1950s, included sole surviving polygonal hut from Heard Island (1940s) used as Paint Store (fig 2.15). Platcha Hut is a field hut approx 20km east of Davis, built in 1961.</td>
<td>Paint Store: wood, plywood, interlocking panels with no nails, painted. 1950s, 60s buildings: including Jamesway huts of cloth, wood and composite materials with metal fittings, others are metal/polymer sandwich construction. Fittings include characteristic furniture, innovative heating systems, communications &amp; scientific equipment, Corrosion, corrasion (fig 6.24), snow drift issues, 'permafrost', wet insulation, proposed for removal and replacement by new buildings. Old Paint Store and Platcha hut were both in good condition in 1992, as discussed in this thesis.</td>
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<tr>
<td>Wilkes, US IGY station</td>
<td>Transferred to Australia, abandoned since 1960s (fig 2.17). Surface survey (Clark &amp; Wishart 1989, 1991), buildings are largely filled with ice. Jamesway buildings comprising cloth, composite plywood, glazing, metal, large quantities of hazardous materials including explosives, oil, chemicals, asbestos, food, medical and scientific equipment (Clark and Wishart 1989, 1991).</td>
<td>Ice accumulation inside buildings and obscures hazardous materials, corrosion, corrasion (possibly confused with defibring), meltwater, vandalism, threats from hazardous materials (Clark &amp; Wishart 1989, 1991). Monitoring of the hazardous materials is ongoing &amp; reported on AAD website. Ambrose and Godfrey (1998) have monitored one building which was sealed with plywood &amp; silastic; others not monitored.</td>
<td></td>
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<tr>
<td>Oasis, Bunger Hills, Russian IGY base.</td>
<td>Not known</td>
<td>No description available of buildings, concrete pillar is designated monument</td>
<td>No information found</td>
<td>No information available</td>
<td>No information found, presumed nil</td>
<td></td>
</tr>
<tr>
<td>Vostok, occupied IGY base.</td>
<td>Not undertaken, older buildings are progressively buried in ice</td>
<td>Steel and timber construction with various scientific equipment and furnishing</td>
<td>No information found</td>
<td>No information available</td>
<td>No information found, presumed nil</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>Description and Details</td>
<td>Conservation Status</td>
<td>Comments</td>
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<td>Ile des Petrels (Dumont d’Urville) French research base 1951 (fig 2.23): Ice excavation not required; buildings not professionally surveyed. Wooden/composite buildings, metal, food, clothing, concrete, glass, composites containing polymer (Vallette 1958). Station buildings still in use (Le Mouël, personal communication).</td>
<td>Some buildings still in use (eg accommodation buildings, geophysical buildings); periodic building maintenance.</td>
<td>Periodic inspection by station personnel. T&amp;R monitoring not undertaken.</td>
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<tr>
<td>Hut Type</td>
<td>Description</td>
<td>Condition and Maintenance Measures</td>
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<tr>
<td>Shackleton’s Nimrod Hut 1908</td>
<td>No major ice accumulation, regular inspection by NZ Antarctic Heritage Trust</td>
<td>Wooden building, seaweed insulation, iron stove, scientific &amp; photographic equipment, furniture, tinned food (indoors, outdoors), leather, fur sleeping bag, smoked ham, papers, glass &amp; ceramics, clothing, sledges, pony equipment and hay, motor car equipment. (see Mason 1999, Blanchette et al 2004 and others listed in Chapter 4)</td>
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</tr>
<tr>
<td>Scott’s Terra Nova Hut 1911</td>
<td>Major ice removal in 1960 (Quartermain 1961); regular inspections by NZ Antarctic Trust. See also Harrowfield 1978, Ritchie 1990, Ritchie &amp; Fyfe 1995. Ongoing surveys and investigations are reported by the NZAHT on their website.</td>
<td>Wooden building, seaweed insulation, iron stove, furniture, scientific &amp; photographic equipment, tinned food (indoors, outdoors), leather, fur sleeping bag, papers, glass &amp; ceramics, clothing, mirror, sledges, kennels, animal carcasses (Quartermain 1963). See also Pearson 1992. Vickers car on seabed (anon 1991), Mason 1999, Blanchette et al 2004 and others listed in Chapter 4)</td>
<td></td>
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</tr>
</tbody>
</table>
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CHAPTER 3 METHODOLOGICAL APPROACH FOR INVESTIGATING DETERIORATION OF HISTORIC SITES IN ANTARCTICA

Figure 3.1: Examples of resources used to guide development of thesis methodologies

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3. Methodological approach

3.1 OBJECTIVES AND SCOPE

This chapter provides an overview of the methodological approach used to identify causes of deterioration, measure rates of deterioration and assess the effectiveness of conservation strategies with details of methods given in Chapters 4 to 10. This chapter also establishes the need for the use of rate measurements and treatment evaluation and considers the ethical issues that must guide conservation strategies.

3.2 CONSTRAINTS

3.2.1 Selection of sites for field studies

The difficulties and costs of travel to Antarctica and the severe climate limited the sites that could be visited. Access to the sites visited was by sea, requiring a minimum of one week’s sailing from Hobart. One trip required eight weeks at sea in order to spend three periods ashore of several days each. The Australian Antarctic Division’s ANARE\textsuperscript{1} operations are mainly focussed on the modern research stations at Mawson, Davis and Casey and rarely visit Australia’s most important historic site at Cape Denison.

The visit to the Ross Sea sites was made on a four week tourist voyage and visits ashore are typically limited to a few hours. One voyage selected by the author (because it included a visit to Cape Denison), was unable to land due to bad weather and no other ship was scheduled to visit the site for another two years. Tourist voyages are expensive, ranging from about US$5,000 in the Antarctic Peninsula to over US$15,000 in the Ross Sea area. Although air travel is available to McMurdo Sound, the author was only able to obtain sea voyages to Antarctica. It was not possible for the author to visit any sites in the warmer, more maritime Antarctic Peninsula region (such as the early twentieth century buildings on Paulet Island and Snow Hill Island and mid twentieth century scientific bases such as East Base) although some photographs and information have kindly been provided by colleagues as noted in the acknowledgements.

\textsuperscript{1} Australian National Antarctic Research Expedition (ANARE).
The 12 locations in Table 3.1 were visited. These cover a range of climates and wind regimes and represent a significant proportion of the major historic sites in Antarctica, including:

- five of the six extant buildings of the ‘Heroic Age’;
- two huts representative of the period immediately before the IGY;
- three sites of the IGY period and two post-IGY huts.

<table>
<thead>
<tr>
<th>Site examined, date of oldest buildings</th>
<th>T&lt;sub&gt;mean&lt;/sub&gt; 2 Jan, °C</th>
<th>T&lt;sub&gt;mean&lt;/sub&gt; 2 Jul, °C</th>
<th>Mean annual average wind speed&lt;sup&gt;3&lt;/sup&gt; (ms&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Wind type&lt;sup&gt;4&lt;/sup&gt;</th>
<th>Date of author’s visit</th>
<th>Duration of author’s visit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mawson Station, 1954</td>
<td>+2.5</td>
<td>-13.6</td>
<td>10.25&lt;sup&gt;5&lt;/sup&gt;</td>
<td>K</td>
<td>14-17 Jan ‘92</td>
<td>2 days</td>
</tr>
<tr>
<td>Rumdoodle Hut, 1972 67°46’S 66°41’E</td>
<td>n/a</td>
<td>n/a</td>
<td>11.1&lt;sup&gt;7&lt;/sup&gt;</td>
<td>K</td>
<td>16 Jan ‘92</td>
<td>2 hours</td>
</tr>
<tr>
<td>Davis Station, 1957</td>
<td>+3.1</td>
<td>-14.3</td>
<td>4.6</td>
<td>NK</td>
<td>10-11 Jan ‘92</td>
<td>1 day</td>
</tr>
<tr>
<td>Platcha Hut, 1961</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>K</td>
<td>8-9 Feb ‘92</td>
<td>2 days</td>
</tr>
<tr>
<td>Dumont D’Urville, 1951</td>
<td>n/a</td>
<td>n/a</td>
<td>8.5</td>
<td>K</td>
<td>11 Jan ‘97</td>
<td>4 hours</td>
</tr>
<tr>
<td>Cape Denison, 1912</td>
<td>+0.8&lt;sup&gt;8&lt;/sup&gt;</td>
<td>-17.7&lt;sup&gt;9&lt;/sup&gt;</td>
<td>19.2</td>
<td>K+</td>
<td>10-12 Dec ‘85</td>
<td>3 days</td>
</tr>
<tr>
<td>Cape Adare (Borchgrevink 1895)</td>
<td>n/a</td>
<td>3.3</td>
<td>(Harrowfield 2006)</td>
<td>OFK</td>
<td>8 Feb ‘93</td>
<td>3 hours</td>
</tr>
<tr>
<td>(Campbell 1912)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Cape Royds</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>NK</td>
<td>12 February 1993</td>
<td>2 hours</td>
</tr>
<tr>
<td>Cape Evans</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>NK</td>
<td>11 February 1993</td>
<td>3 hours</td>
</tr>
<tr>
<td>Scott Base TAE hut</td>
<td>-1.2 (NIW A)</td>
<td>-22.3 (NIWA)</td>
<td>5.0&lt;sup&gt;10&lt;/sup&gt;</td>
<td>NK</td>
<td>11 February 1993</td>
<td>3 hours</td>
</tr>
<tr>
<td>Hut Point</td>
<td>0</td>
<td>-21</td>
<td>6.6</td>
<td>NK</td>
<td>11 February 1993</td>
<td>3 hours</td>
</tr>
<tr>
<td>McMurdo Base&lt;sup&gt;11&lt;/sup&gt; IGY buildings</td>
<td>0</td>
<td>-21</td>
<td>6.6</td>
<td>NK</td>
<td>11 February 1993</td>
<td>February 1993, 3 hours</td>
</tr>
</tbody>
</table>

<sup>2</sup> Mean daily maximum temperature for the month specified
<sup>3</sup> Wind speed data from King, JC 1989. Sites with katabatic wind regimes are highlighted in yellow.
<sup>4</sup> K= katabatic; NK= not katabatic; OFK= periodic orographically-forced katabatic; K+= severe katabatic
<sup>5</sup> Australian Bureau of Meteorology data from 3pm daily readings.
<sup>6</sup> The building is not a historic site but the site is useful for comparison with coastal locations, being approximately 18 km inland.
<sup>8</sup> From Madigan, C 1929, Meteorology- Tabulated and Reduced Records of the Cape Denison Station, Adelie Land, AAE 1911-14 Issued June 1929, New South Wales Government Printer, Sydney. Table VIII, mean maximum for Jan 1913
<sup>9</sup> From Madigan 1929 Table VIII, average of mean maximum for Jan 1912 (+0.5°F) and Jan 1913 (-0.3°F)
<sup>11</sup> All McMurdo data is from International Station Meteorological Climate Summary, Version 4, recorded over 26 years.
3. Methodological approach

3.2.2 Research approval and funding

All research undertaken at Australian Antarctic historic sites require project approval through the Antarctic Science Advisory Committee (ASAC). Similar arrangements apply for each national Antarctic program. Each ASAC application requires a large commitment of time and funding received for this project is normally directed to the provision of berths on ANARE ships travelling to Australian Antarctic stations rather than equipment and materials. Time constraints prevented the author from being able to inspect inside ceilings and wall spaces, and indeed such inspections are very rare and remain a problem for development of conservation methodologies for Antarctic historic sites.

3.3 METHODOLOGICAL APPROACH

3.3.1 Establishing the causes of deterioration of Antarctic buildings and artefacts.

The classic scientific method (hypothesis, testing, data analysis and conclusions) was applied for investigating each of the following major classes of deterioration:

- Climatic processes including freezing and thawing cycles and the role of accumulated ice inside buildings (Chapter 4);
- Salt deposition, particularly effects on wood (Chapter 5);
- Corrosion and other damage to metal elements, such as bolts and nails which are crucial to the structural integrity of buildings (Chapter 6);
- Wind processes causing snowdrifting and erosion of surfaces (Chapter 7);
- Photodeterioration of surfaces (Chapter 8);
- Biodeterioration, primarily fungi but including impacts of wildlife (Chapter 9); and
- Human Impacts (Chapter 10).

Interaction of the deterioration processes were examined in Chapter 11 and conservation management plans for the sites were reviewed to consider how these addressed deterioration problems.
3.3.2 Condition reporting and measurement of the rate of deterioration

A template (Table 3.2) was developed to assist recording the condition of the sites:

- A map was used to create rough grids across the site taking account of topography, buildings and major concentrations of artefacts;
- Condition of buildings and artefacts was recorded using visual examination and photos when walking across the site and samples were taken for analysis where permitted;
- Relevant environmental factors in the vicinity were reported (eg meltwater, ice, wind exposure, etc);
- Buildings and artefacts were photographed using scaled reference colour cards wherever possible;
- Severity of the damage/deterioration was categorised using three ordinal categories (stable, fair, poor), the approximate percentage over the visible surface was recorded (in most cases it was not permitted to lift artefacts)\(^\text{12}\) as well as any characteristics of distribution (eg whether problem occurs on underside, exposed areas, etc); and
- The results of the observations were recorded on the site map.

Table 3.2 Template used for site observations

<table>
<thead>
<tr>
<th>Date:</th>
<th>Location:</th>
</tr>
</thead>
</table>

**Pre-departure information requirements**

<table>
<thead>
<tr>
<th>Data</th>
<th>Source</th>
<th>Details and comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permits and research approvals for collection of samples, quarantine, installation of test materials.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meteorological data, maps and satellite imagery and previous reports</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Historic records or scientific/other publications on the site.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Instrumentation and equipment**

<table>
<thead>
<tr>
<th>Item</th>
<th>Source</th>
<th>Details and comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surveying equipment including photogrammetry and GPS equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cameras, including suitable lens and filters, colour cards</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^{12}\) ‘Stable’ indicates that the material or artefact requires no active intervention or treatment. ‘Fair’ indicates the need for intervention to address active deterioration or damage that is progressing towards a critical point. ‘Poor’ indicates the need for immediate attention with the material or artefact being at a critical stage such as nearing structural failure or requiring major treatment.
3. Methodological approach

and reference scale

Temperature and RH monitoring equipment of robust capability

Sample containers and chemical test kits (pH, chlorides, sulphites, sulphates)

Prefabricated exposure rack for test specimens including corrosion coupons, coating samples, repair materials, etc

Pre-landing tasks

<table>
<thead>
<tr>
<th>Task</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Briefing visitors as part of visitor management requirements.</td>
<td>Report any significant questions/comments arising at the briefing.</td>
</tr>
</tbody>
</table>

Site survey- exterior

<table>
<thead>
<tr>
<th>Factor</th>
<th>Observations and data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather conditions - temperature, RH, wind strength and direction, sunlight conditions, blowing snow, etc</td>
<td>(this can affect interpretation- eg, during rare rain events, salt deposits may be washed away)</td>
</tr>
</tbody>
</table>

Are these microclimates due to topography, etc? Evidence of accumulation or ablation zones? (eg protected valley, exposed ridge, etc) E.g. persistent snowdrifts, or reddish snow algae.

Extent and location of snow cover, meltwater and winds scour around buildings. Evidence of recent severe wind events may mean that defibred or photo-deteriorated timber will be stripped bare. Conditions of ice & snow around the building (eg whether multi-year), etc. Observations of wetting/drying stains on timber including ‘tidemarks’ from meltwater.

Salts

<table>
<thead>
<tr>
<th>Issue</th>
<th>Factor</th>
<th>Location</th>
<th>Severity</th>
<th>Extent 13</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt deposition</td>
<td>Salt spray exposure and inundation at high tide?</td>
<td></td>
<td></td>
<td>Evidence of salts on ground? Evidence of salts on buildings and artefacts Natural sources of salts and minerals from the earth</td>
<td></td>
</tr>
<tr>
<td>Surface salts</td>
<td>Guano and other sources (eg chemical use)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Defibring of wood</td>
<td></td>
<td></td>
<td></td>
<td>Is defibring only found in sheltered locations (ie is there evidence that loose fibres are blown off by wind?)</td>
<td></td>
</tr>
<tr>
<td>Interaction of deterioration factors</td>
<td>Corrosion, biodeterioration wind damage, etc</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Corrosion and damage to metals (including relevant salts observation above)

<table>
<thead>
<tr>
<th>Issue</th>
<th>Factor</th>
<th>Location</th>
<th>Severity</th>
<th>Extent</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion affecting exterior building elements</td>
<td>Exposure Type of metal(s), surface condition, types of artefacts etc</td>
<td></td>
<td></td>
<td></td>
<td>Describe characteristics including: Uniform, filiform, pitting, necking and differential aeration, bronze disease, galvanic corrosion, stress cracking, delamination.</td>
</tr>
</tbody>
</table>

---

13 Extent is percentage of surface affected by the problem
3. Methodological approach

<table>
<thead>
<tr>
<th>Measurements of corrosion factors</th>
<th>Time of Wetness</th>
<th>SOx and NOx</th>
<th>Salt candle Coupon measurements</th>
<th>[Record exact location of measurements, dates of exposure, etc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interaction of deterioration factors</td>
<td>Moisture</td>
<td>Wind</td>
<td>salts</td>
<td>Eg wind exposure, salts, etc; sheltering effects. Is periodic immersion occurring?</td>
</tr>
</tbody>
</table>

### Wind damage

<table>
<thead>
<tr>
<th>Issue</th>
<th>Factor</th>
<th>Location</th>
<th>Severity</th>
<th>Extent</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural damage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Evidence of vibration, lifting of timbers, bending, collapse etc</td>
</tr>
<tr>
<td>Wind damage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Does colour of wood indicate recent corrosion? Evidence of dents and impacts from windborne articles? Does this correspond with air flow around building or structure</td>
</tr>
<tr>
<td>Interaction of deterioration factors</td>
<td>(eg defibring, corrosion, etc)</td>
<td></td>
<td></td>
<td></td>
<td>Wind can obliterate evidence of corrosion, defibring and other surface effects.</td>
</tr>
</tbody>
</table>

### Photodeterioration

<table>
<thead>
<tr>
<th>Issue</th>
<th>Factor</th>
<th>Location</th>
<th>Severity</th>
<th>Extent</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials types exposed to sunlight</td>
<td>Extent of damage according to sun orientation</td>
<td></td>
<td></td>
<td></td>
<td>Eg evidence of bleaching/bleaching of paints, violet-coloured glass, patination of timber, etc</td>
</tr>
<tr>
<td>Types of damage</td>
<td>Darkening/bleaching Embrittlement Surface warming Surface cracking</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measurement of light levels</td>
<td>Global Reflected</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potential for controlling exposure</td>
<td>Ability to install covers, move vulnerable artefacts, etc</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interaction of deterioration factors</td>
<td>Eg corrosion, wetting/drying of timber, biodeterioration</td>
<td></td>
<td></td>
<td></td>
<td>Wetting of timber can wash away brown oxidation, corrosion may remove evidence of salt deposition, sunlight may kill algae and fungi in some areas but allow it to flourish elsewhere.</td>
</tr>
</tbody>
</table>

### Biodeterioration

<table>
<thead>
<tr>
<th>Issue</th>
<th>Factor</th>
<th>Location</th>
<th>Severity</th>
<th>Extent</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wildlife locations and numbers</td>
<td>Species Numbers</td>
<td></td>
<td></td>
<td></td>
<td>Are visitors getting to close to wildlife while observing historic sites? Injuries</td>
</tr>
</tbody>
</table>
### 3. Methodological approach

<table>
<thead>
<tr>
<th>numbers</th>
<th>Behaviour <em>(eg moult, nest)</em></th>
<th>to wildlife from historic materials, etc?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of biodeterioration</strong></td>
<td>Fungi</td>
<td>Describe characteristics such as smell, colour, growth patterns, substrate.</td>
</tr>
<tr>
<td></td>
<td>Bacteria</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Algae</td>
<td></td>
</tr>
<tr>
<td><strong>Samples collected</strong></td>
<td>Substrate</td>
<td>Note exact location, time/date collected, substrate type, notes on microclimate conditions, etc.</td>
</tr>
<tr>
<td></td>
<td>Growing conditions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Air circulation</td>
<td></td>
</tr>
<tr>
<td><strong>Interaction of deterioration factors</strong></td>
<td>Photodeterioration</td>
<td>Meltwater availability, fertilising effect from wildlife, light, UV, drying effects of wind, etc.</td>
</tr>
<tr>
<td></td>
<td>Moisture</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wind</td>
<td></td>
</tr>
</tbody>
</table>

### Human impacts

<table>
<thead>
<tr>
<th>Issue</th>
<th>Factor</th>
<th>Location</th>
<th>Activity</th>
<th>Impacts</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site management</td>
<td>Management of visitor access</td>
<td></td>
<td></td>
<td></td>
<td>Issues arising from site management, Comments by visitors and others Do site managers supervise visitors outside buildings as well as inside?</td>
</tr>
<tr>
<td></td>
<td>Numbers of visitors, crew, official observers, scientists ashore and locations during visit</td>
<td></td>
<td></td>
<td></td>
<td>Include evidence of touching or damage to artefacts, inappropriate behaviour <em>(eg smoking)</em>; walking in 'out of bounds' areas, safety issues <em>(eg risks from historic materials)</em>, etc. Information from visitor logs</td>
</tr>
<tr>
<td>Damage to buildings/artefacts from visitors</td>
<td>Patina worn, vulnerable items affected</td>
<td></td>
<td></td>
<td></td>
<td><em>(eg evidence of disturbance or damage to artefacts)</em></td>
</tr>
</tbody>
</table>

### Interior observations

Date and time: Building or structure: .................................................................

<table>
<thead>
<tr>
<th>Issue</th>
<th>Factor</th>
<th>Location</th>
<th>Severity</th>
<th>Extent</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature &amp; RH</td>
<td>Temperature stratification?</td>
<td>Temperature stratification?</td>
<td>Record locations, observations of any ice formation, evidence of meltwater, salts, meltwater trails, sublimation, hoarfrost, etc. Does meltwater form preferentially on particular surfaces, <em>(eg nails)</em> (evidence of thermal bridging)? Other evidence of thermal bridging?</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T &amp; RH variation (diurnal and annual). Comparison of internal and external conditions. Air-tightness of the building.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meltwater formation</td>
<td>Source?</td>
<td>Is freezing of meltwater potentially beneficial in anchoring the structure?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Damage caused</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

14 This includes consideration of how to balance the desire by visitors for access vs preservation concerns, which should be an integral part of any conservation approach.

15 The visitor questionnaire should be undertaken in conjunction with the observations entered above.
### Methodological approach

<table>
<thead>
<tr>
<th>Ice accumulation</th>
<th>Age of ice accumulated</th>
<th>Sources of drift snow into the building; evidence of durations of the problem (e.g., historic attempts to plug the ingress); Feasibility of preventing ingress. What effect of ice accumulation on T &amp; RH? Structural effects? Visitor issues?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation properties</td>
<td>Current condition of insulation, moisture, etc</td>
<td>Historical information on insulation design and materials. Inspection inside wall spaces. Effect of any thermal bridges.</td>
</tr>
<tr>
<td>Interaction of deterioration factors</td>
<td>Biodeterioration Corrosion</td>
<td>Is the presence of biodeterioration &amp; corrosion consistent with T &amp; RH conditions?</td>
</tr>
</tbody>
</table>

### Salts

<table>
<thead>
<tr>
<th>Issue</th>
<th>Factor</th>
<th>Location</th>
<th>Severity</th>
<th>Extent</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Are salts getting into building? Do these cause damage?</td>
<td>Air ingress rate? Ingress via visitors or transfer of artefacts? Dissolution of salts and transport within building?</td>
<td></td>
<td></td>
<td>Observation of locations of salt deposits (noting potential detection problems if salts have deliquesced, otherwise via chemical tests). Note ‘salt trails’ on walls, efflorescence, defibring, etc.</td>
<td></td>
</tr>
<tr>
<td>Salt deposition</td>
<td>Quantitative measurement</td>
<td></td>
<td></td>
<td>Salt candle measurements or other methods, SO$_2$ and NO$_x$</td>
<td></td>
</tr>
<tr>
<td>Type of salts</td>
<td>Marine salts?</td>
<td></td>
<td></td>
<td>Various chemical analyses.</td>
<td></td>
</tr>
<tr>
<td>Interaction with other deterioration</td>
<td>Wind, human impacts?</td>
<td></td>
<td></td>
<td>Corrosion may also be evident in proximity to salts.</td>
<td></td>
</tr>
</tbody>
</table>

### Corrosion

<table>
<thead>
<tr>
<th>Issue</th>
<th>Factor</th>
<th>Location</th>
<th>Severity</th>
<th>Extent</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type and severity of corrosion occurring</td>
<td>Metals affected Other factors involved in corrosion, e.g., salts, crevice effects, etc.</td>
<td></td>
<td></td>
<td>Describe characteristics including: Uniform, filiform, pitting, necking and differential aeration, bronze disease, galvanic corrosion, stress cracking, delamination. Staining of timber around nails, necking Sulphate reducing bacteria</td>
<td></td>
</tr>
<tr>
<td>Conditions where corrosion occurs</td>
<td>Association with measured T &amp; RH, TOW</td>
<td></td>
<td></td>
<td>Evidence of high moisture or periodic melting? Tin pest? Elevated temperature from thermal bridging? Condition of any items excavated from ice?</td>
<td></td>
</tr>
<tr>
<td>Interaction with other deterioration factors</td>
<td>Salts T &amp; RH</td>
<td></td>
<td></td>
<td>Organic acids from wood, etc.</td>
<td></td>
</tr>
</tbody>
</table>
3. Methodological approach

### Photodeterioration

<table>
<thead>
<tr>
<th>Issue</th>
<th>Factor</th>
<th>Location</th>
<th>Severity</th>
<th>Extent</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials exposed to sunlight via windows</td>
<td>Solar intensity: -Global -Reflected Solar orientation Extent of damage</td>
<td></td>
<td></td>
<td></td>
<td>Note the location, size of any windows and sunlight entry pattern, glazing materials Types of artefacts exposed to sunlight</td>
</tr>
<tr>
<td>Types of damage</td>
<td>Darkening/bleaching Embrittlement Surface cracking</td>
<td></td>
<td></td>
<td></td>
<td>Note any surface warming; note any differential effects where material is partly protected from light.</td>
</tr>
<tr>
<td>Potential for controlling exposure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Curtains, external timber covers, polymer filter films, etc</td>
</tr>
<tr>
<td>Interaction of deterioration factors</td>
<td>Eg corrosion may remove evidence of defibring or photodeterioration</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Biodeterioration

<table>
<thead>
<tr>
<th>Issue</th>
<th>Factor</th>
<th>Location</th>
<th>Severity</th>
<th>Extent</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of biodeterioration</td>
<td>Fungi Bacteria Algae</td>
<td></td>
<td></td>
<td></td>
<td>Note any visible signs and smells in any food remaining, clothing, animal carcasses, etc</td>
</tr>
<tr>
<td>Samples collected</td>
<td>Substrate Growing conditions Air circulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interaction of deterioration factors</td>
<td>Photodeterioration (near windows) Moisture, wind</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Human impacts

<table>
<thead>
<tr>
<th>Issue</th>
<th>Factor</th>
<th>Location</th>
<th>Severity</th>
<th>Extent</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site management</td>
<td>Management and suitability of numbers of visitors inside buildings visit Amenities provided for visitors</td>
<td></td>
<td>Eg what features of the site attract interest &amp; photographs</td>
<td></td>
<td>Include evidence of touching or damage to artefacts, inappropriate behaviour (eg smoking); safety issues (eg risks from historic materials), etc Information from visitor logs Quality/accuracy of information from guides. Are instructions/briefing from voyage personnel/site managers effective? Interpretation requirements</td>
</tr>
<tr>
<td>Damage to buildings/artefacts from visitors</td>
<td>Patina worn, vulnerable items affected</td>
<td></td>
<td></td>
<td>Eg evidence of disturbance or damage to artefacts</td>
<td></td>
</tr>
<tr>
<td>Effect of visitors on T&amp;RH inside buildings</td>
<td>Change in T&amp;RH, time of visitor, duration of effects.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

16 The visitor questionnaire should be undertaken in conjunction with the observations entered above.
3. Methodological approach

Benefits of rate measurements

As well as accurately understanding the causes of deterioration processes it is important to measure the rate at which deterioration is occurring so treatment priorities can be specified in Conservation Management Plans. If damage is occurring at a slow rate it may not be a serious concern but if environmental conditions change, the risks may change. Quantitative deterioration rate measurements also enable comparisons between sites.

Measurements of rates of deterioration rates help to assess the factors causing the deterioration. For example, where a process is known to be dependent on a factor such as humidity, then the extent of deterioration should be able to be quantified against variations in that factor.

3.2.3 Cape Denison as a paradigm of Antarctic historic sites

The author considers one site, Cape Denison, to be a paradigm of the conservation problems of Antarctic historic sites because of the severity and complexity of its problems:

a. Temperatures are low enough for ice to accumulate inside the main hut, and information on ice accumulations and removal was better documented than at the other sites where these problems have occurred.
b. Temperatures are high enough for extensive meltwater and mould occur to occur in summer.
c. It is one of the oldest sites, so deterioration problems have had time to become evident.
d. The wind regime is the most severe (Wendler 1990) of any place in the world.
e. It is remote and uninhabited, which combined with the severe climate makes logistics for conservation operations very complex, necessitating practical solutions (see figure 3.2).
f. Climate data is available from the AAE occupation of the site (Madigan 1929) and from a modern Automatic Weather Station at exactly the same location (Wendler 1990), providing the longest time span of climate data for any Antarctic historic site, and
g. at the time of the author’s visits, the remoteness of the site had minimised disturbance and protected archaeological values.
Thus, Cape Denison has the widest range of deterioration problems, high international historical significance and the greatest logistics constraints, presenting the most complex challenge of all the sites.

Figure 3.2: Bracket for corrosion coupon at Cape Denison, broken by the severe winds, photo by Rupert Summerson 1995.

3.2.4 Approach to deterioration rate measurement

Standard methods for measuring deterioration rates developed by test authorities such as the International Standards Organisation (ISO) and the American Society for Testing and Materials (ASTM) were used wherever possible (e.g. ISO standards for atmospheric corrosion rate). This enabled measurements in Antarctica to be compared with measurements using the same standard at other locations. In some cases, no standard methods were available, or tests required modification to suit Antarctic conditions, especially where temperature specifications cannot be met in Antarctic conditions. These changes were identified where required in the detailed methodology in each chapter.
3.3 DETERMINING PRIORITIES FOR TREATMENT DEVELOPMENT

3.3.1 The need to identify priorities

Many polar enthusiasts have expressed frustration with the conservation requirements of the Burra Charter, arguing that the causes of damage are self-evident and should be treated without further delay. This has been particularly so in the case of Mawson’s Huts which has long been considered at immediate risk of destruction. For example, (Meredith 1990) argued that:

"I believe it's time to invoke Article 10 of the Burra Charter and bring the hut back [to Australia]. This would save the hut and a lot of money too, for sooner or later the continuing cost of looking after the hut in its remote setting (assuming a commitment is ever made to do this) would exceed the cost of repatriating it."

Headland, a polar historian, considered the condition of the site warranted intrusive ‘rescue archaeology’ (personal communication to the author, 1993), which is normally undertaken only when complete destruction is certain and imminent (eg sites about to be washed into the sea).

Madigan (1986: 42) was more forceful in his statement to an Australian government forum:

“I have heard of the proposals for the Hut's disposition, the pros and cons, and the absurd statements attributed to politicians, heritage buffs and the rest, and remain convinced that the only responsible and sensible thing to do is to bring it back to Australia. There is no question about the feasibility of such a proposal, or the relatively small cost of the operations. After all, it was unloaded and erected in three weeks by a team of amateur builders in 1912 - surely it can be disassembled and reloaded by experts in a few weeks in the 1980s. As an item of interest and a permanent monument in Australia to our Antarctic Heritage it would be unsurpassed, and rival such exhibits as the “Fram” in Oslo which attracts international recognition."

Repatriation could also be argued to improve access to the historic buildings, but a significant problem with this approach promoted is that the Madrid Protocol (ratified in 1992, subsequent to the comments by Madigan and Meredith) requires that designated historic sites should remain in
situ. Under the Madrid Protocol, repatriation of major elements such as buildings would require detailed assessment of risks in the repatriation process, and evidence that other treatments, such as *in situ* conservation, are not feasible or practical.\(^{17}\)

Government agencies responsible for managing sites find it difficult to act if there is disagreement between ‘experts’. This occurred in New Zealand’s Ross Dependency when a majority favoured removing ice from the Ross Island huts while a significant minority urged limiting ice removal until its effects could be assessed over a few years (Harrowfield (1990: 60), citing the views of the late Sir Holmes Miller). Subsequent conservation problems arose demonstrating the need to consider the risks of any treatment undertaken as well as the effects of not proceeding. This reinforces the need for an ethical approach to be applied and for conservation priorities to be based upon firm evidence.

### 3.3.2 Ethical considerations

Codes of Ethics and charters developed by major relevant professional organisations (such as ICOMOS) were referenced when considering treatment issues in this thesis. Where no relevant or applicable ethical guidance was available for uniquely Antarctic treatment problems, the issues were identified and discussed in the relevant section of the thesis.

### 3.3.3 Treatment priorities and risk management

Deterioration rate data for Antarctic historic sites are important because:

- Continuous high rates of deterioration indicate that intervention must be considered;
- Rate data can help predict when deterioration will reach a critical level; and
- Deterioration rate data can help predict the behaviour of repair materials (which often need to be similar to the original) and the frequency of maintenance required after treatment.

---

\(^{17}\) Repatriation proponents have not addressed whether all buildings and other elements such as scattered artefacts would also be removed. Modern museum practice also encompasses ‘access’ to historic resources through information technology. In the case of the AAE site, access to images and information on collections of AAE
Various risk management standards have been developed by conservators in different countries, eg Waller (1995)\(^{18}\) in Canada, mostly for management of museum collections and historic houses. These standards typically assign ordinal ranks to frequency (eg low, moderate, high), severity of effects (eg insignificant, major, catastrophic) and predictability of ‘events’ to assist management decisions. The methodology used in this thesis to identify treatment priorities used the major classes of deterioration as the main sources of risk, and inserted these into the standard templates used in Australian and New Zealand Standard AS/NZS 4360 2004 Risk Management (Table 3.3). The highest risks identified are the highest priority for treatment.

AS/NZS 4360\(^ {19}\) was selected because it is one of the easiest to use with a simple template provided and it is familiar to Australian and New Zealand governments who manage a large proportion of the major Antarctic Historic sites. Given the various constraints on this thesis, comprehensive risk assessments were only completed for Cape Denison but were discussed in general terms for the major sites in the examination of each deterioration process in Chapters 4 to 10.

**Table 3.3: Template for risk management**

**Qualitative measures of consequence**

<table>
<thead>
<tr>
<th>Level</th>
<th>Descriptor</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Catastrophic</td>
<td>Destruction of major elements of a site, eg destruction of major buildings or internationally significant monuments</td>
</tr>
<tr>
<td>4</td>
<td>Major</td>
<td>Extensive damage to artefacts and building elements; rapid rate of deterioration sustaining major and urgent conservation treatment</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
<td>Moderate loss of artefacts; high rate of deterioration of materials requiring high cost of treatment</td>
</tr>
<tr>
<td>2</td>
<td>Minor</td>
<td>Minor loss of artefacts; significant rate of deterioration of materials but can be managed by on site treatment at medium cost;</td>
</tr>
<tr>
<td>1</td>
<td>Insignificant</td>
<td>No loss of artefacts or building materials; slow rate of deterioration</td>
</tr>
</tbody>
</table>

**Qualitative measures of likelihood**

<table>
<thead>
<tr>
<th>Level</th>
<th>Descriptor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Almost certain</td>
<td>Is expected to occur in most circumstances</td>
</tr>
</tbody>
</table>


\(^{19}\) The Australian/New Zealand Risk Management Standard (AS/NZS 4360:2004) and the companion handbook Risk Management Guidelines (HB 436:2004) are used by Australian and NZ government agencies to assist in the process of assessing and managing project risks.
3. Methodological approach

### Risk analysis matrix

Note: the highest risks are shaded red with lowest risks in yellow.

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>Insignificant 1</th>
<th>Minor 2</th>
<th>Moderate 3</th>
<th>Major 4</th>
<th>Catastrophic 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 (almost certain)</td>
<td>5</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>4 (likely)</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>3 (moderate)</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>2 (unlikely)</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>1 (rare)</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

### Level of Risk

<table>
<thead>
<tr>
<th>Level of Risk</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;7</td>
<td>Extreme</td>
</tr>
<tr>
<td>6.7</td>
<td>High</td>
</tr>
<tr>
<td>5</td>
<td>Moderate</td>
</tr>
<tr>
<td>&lt;5</td>
<td>Low</td>
</tr>
</tbody>
</table>

### 3.3.4 Monitoring treatment effectiveness

Chapter 2 demonstrated the general lack of evaluation of past in situ building treatments at polar historic sites with a few notable exceptions. Given the severe and unfamiliar conditions occurring at polar sites, and the difficulty of regular access for maintenance at remote locations, it is important that systematic evaluation methods of treatments are developed.

Evaluations require:

- Analyses of risks of site components using AS/NZS 4360 or similar standards;
- Standardised photographic records including repeated surveys from the same location using colour reference cards in detailed photographs;\(^{20}\)
- Repeated, standardised condition surveys to account for any changes over time;
- Monitoring of temperature and RH inside buildings to assess changes due to interventions such as ice removal;
- Advice on critical structural components from a structural engineer; and

\(^{20}\) This accounts for the changes in light quality that are particularly problematic in polar regions.
3. Methodological approach

- Field testing of treatment materials and methods to not only ensure durability but to avert any adverse effects from the treatment, *eg* condensation problems.

Completion of all these investigations was beyond the scope of this thesis although details are provided where available in the following chapters.

3.4 CRITERIA FOR SELECTING TREATMENTS

In accordance with national legislation and professional requirements, a ‘Statement of Significance’ must be prepared for each Antarctic historic site before any treatment decisions are made. This ensures that important elements of the site (*ie* what is to be conserved) are comprehensively identified and documented in a management plan.

3.4.1 Principles: ‘cause no harm’ and ‘re-treatability’

The most important criteria for selection of treatments are to cause no harm and to minimise unforeseen side effects. This is a common principle in other disciplines such as medicine. Horie (1983) described the evolution of the concepts of ‘reversibility’ of conservation treatments, particularly problems arising when polymer treatments fail. Conservators sometimes make decisions to consolidate friable artefacts where it is clear that an object will completely disintegrate if no treatment occurs. In Antarctica, treatments such as over-cladding, or insertion of vapour barriers may themselves be reversible by removal, but the consequences of the failed treatment may not, particularly if damage such as condensation occurs quickly and access to the site too infrequent to detect and rectify the damage in time.

3.4.2 Cost and effectiveness

Cost-benefit analysis of conservation treatment is not as highly developed as in other areas of government administration (*eg* public health) since conservation treatments are not easily standardised, and the rarity and significance of an artefact or building often outweighs cost considerations. Cost considerations are, however, important for Antarctic historic sites since the expenses for transporting people, equipment and materials are particularly high.
3. Methodological approach

Air transport is available to some sites in the Antarctic Peninsula and to McMurdo Base near the Ross Island sites although bulky materials and equipment are often sent ahead by sea. Sites such as Cape Denison, Ile des Petrels, Port Martin and Cape Adare are only accessible by sea, one week from the nearest port, Hobart. Belts of pack ice can persist until late in summer so in some years only large icebreakers can gain access. Charter costs for such large ships may be up to US$75,000 per day.

The severe katabatic winds at Cape Denison and Port Martin can limit operations of ships and helicopters and disrupt conservation work, adding to costs. Some sites are especially difficult, such as Port Martin, which is atop ice cliffs, requiring helicopters in addition to shipping costs (Le Mouël, personal communication to the author, Bourges 1999).

Another cost-benefit consideration is the frequency of maintenance required. If treatment is successful the effective cost of treatment may be lower than a less successful treatment requiring re-treatment, or a treatment that requires frequent maintenance to remain effective. Removing annual ice ingress at a relatively accessible site such as Hut Point may be significantly lower, whereas at Cape Denison it was frequently impossible to land work parties for several years in succession. Due to the number of variables involved in cost estimation, only qualitative cost benefit analysis is provided.

Assessment of treatment effectiveness is potentially vulnerable to subjectivity so the author developed the following criteria for treatment effectiveness (discussed further in Chapter 11):

- Conservation materials must have proven durability in Antarctic conditions (preferably through field testing over at least three years) and use should be avoided where the failure of the material may cause other risks;
- Treatments must consider the ethical requirements of ICOMOS and other relevant codes of practice concerning changes in appearance and effects on historic integrity;
- Treatments must be repeatable and must be effective for the period between which maintenance visits can be carried out.
3. Methodological approach

- Repatriation of artefacts for treatment and return to Antarctica must be considered in the context of the Antarctic Treaty and Madrid Protocol. Where treated artefacts are retained in historic building with high RH the treatment must be effective in those conditions.

3.6 SUMMARY

- Accurate diagnosis of causes of deterioration is paramount in Antarctica due to the severe and unfamiliar environmental conditions and constraints on observation and analysis at the sites.
- Ethical decisions on selection of conservation materials must consider not only durability of the material but its impact on other deterioration processes affecting the building or artefact and be guided by comprehensive risk management.
- Measurement of deterioration rate should use standardised methods to determine priorities for treatment.

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Meredith, P 1990, 'Mawson's Hut: take it or leave it?', Australian Geographic, vol. 18, no. 18, p. 29.


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4. TEMPERATURE, RELATIVE HUMIDITY, ICE AND PHASE CHANGE EFFECTS

Figure 4.1: Meltwater pool at Mawson’s hut (Project Blizzard 1985)

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4.1 AIMS AND INTRODUCTION

The aims of this chapter are to:

- Document the extent and severity of conservation problems due to temperature and RH variations and ice accumulation problems at Antarctic historic sites using a qualitative survey
- Analyse temperature and RH variations in the AAE main hut following ice removal
- Consider how climate change may affect conservation strategies for the AAE main hut.

4.2 LITERATURE AND GAPS IN KNOWLEDGE

“Although abandoned in 1913, the hut and its contents are remarkably well preserved today due to the constant freezing conditions”.


Frequent repetition of this and similar statements reinforce beliefs that conditions inside Antarctic historic buildings are universally cold and dry.

Microclimates in Antarctic historic buildings

Heat and moisture are fundamentally involved in deterioration of wood so understanding effects of variations of these factors within Antarctic historic buildings is important in developing effective conservation strategies.

From empirical data provided in the well-known psychrometric charts it is known that the precise amount of moisture that can occupy a fixed volume of air depends on its temperature, so a closed volume of air at a low temperature produces less water vapour than the same volume at a higher temperature, since there are fewer water molecules with sufficient kinetic energy to escape the water surface. The relative humidity of a mixture of water vapour and air is dependent only on the partial pressure of the water; it is independent of the partial pressure of the air itself, *ie* it does not depend on how many water molecules are present. At 0°C, 4.86586 grams of water can
vaporise in one cubic metre air compared to 17.340 grams at 20°C, so absolute humidity\(^1\) (AH) is low (4.86586 g/m\(^3\)), yet relative humidity\(^2\) (RH) is high (100%).

Ice also produces vapour. The quantity of vapour produced by ice in a closed volume is also published (see [http://www.vaisala.com/humiditycalculator](http://www.vaisala.com/humiditycalculator)) and the quantity depends on its temperature, not the amount of ice present. In addition to freezing and thawing, other phase changes (sublimation, hoarfrost formation) must be considered in polar climates.

Heating an enclosed volume of air causes its relative humidity to fall, which in inhabited buildings is usually countered by artificially humidifying the air for human comfort. This added moisture can condense on cold surfaces and refreeze, often causing long term damage in buildings (Padfield 1998). Most Antarctic historic buildings are unheated, except for some IGY buildings still in use at Mawson Station, Davis Station, Dumont d’Urville, and a few other locations. It is frequently stated that buildings start to fail when they are no longer heated since ice progressively fills the building. Heating systems cannot easily be operated nor maintained in remote locations such as Cape Denison and is therefore not considered as a viable conservation strategy in this thesis.

Measurements of temperature and RH at appropriate locations within a building are routinely used to study microclimate behaviour and analyse deterioration risks for building materials and artefacts and to model the impacts of various conservation strategies (such as removal of ice) on temperature and relative humidity inside buildings.

While much conservation work has been undertaken in Antarctica since 1960, published temperature and RH data was only available from four sites (Cape Denison, Cape Evans, Cape Royds and Hut Point) of which the first two have more detailed data\(^3\). As discussed in Chapter 3, ethical guidelines from various national heritage bodies imply such information should be obtained before major intervention is undertaken.

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\(^1\) AH, the weight of water vapour per weight of air
\(^2\) RH, the percentage of water vapour relative to that at saturation
\(^3\) The key publications are Held (2005) and Ganther *et al* 2002, cited in the list of references.
4. Temperature, RH, ice and phase changes

4.2.1 Impacts of Antarctic climates on deterioration processes

Low temperatures are generally beneficial in reducing deterioration of materials with the exception of embrittlement of some materials\(^4\) and debated effects associated with freezing of water. The rates of most chemical deterioration reactions are temperature dependent, as described in the Arrhenius equation. Higher risk of damage to historic timber is associated with severe or rapid changes in temperature and relative humidity. Conservators have internationally accepted standards for temperatures of 20±2°C with relative humidity 50±5% for optimal preservation of museum collections (Thomson 1986) because of the potential for mould growth above 60% RH and because many organic materials suffer cracking and embrittlement in drier conditions. Greater emphasis is now placed on the period over which any variations of temperature and RH occur. Erhardt & Mecklenberg (1994) stated that “changes caused by environmental fluctuations can be shown to be generally reversible (non-damaging) within a relatively wide (±10 - 15%) range in the moderate RH region”. Padfield (1998) cited significant concerns in applying standard conditions to locations experiencing severe climates. He cited examples in Sweden where freezing on the surfaces of historic materials caused minimal damage whereas maintaining constant temperatures and RH throughout the year caused significant problems including cracking of organic materials.

‘Freeze-thaw damage’ has frequently been reported at historic sites in both polar regions (discussed in Chapter 2.4.1), although the term is not always clearly defined and is used to describe phenomena of differing origins, including permafrost heaving, ice wedging, damage by growth of ice crystals, expansion of water at +4°C and cyclic desiccation when frozen followed by wetting upon thawing. Greater clarity would be achieved by using accepted terminologies

Below the Glass Transition Temperature (\(T_g\)) polymers become hard and brittle, while above \(T_g\) they are flexible and rubber-like. Many common polymers such as poly vinyl chloride (\(T_g\) 50°C) are therefore unsuitable in Antarctica.
4. Temperature, RH, ice and phase changes

defined by Washburn (1979) or the on-line glossary of the [US] National Snow and Ice Data Center⁵.

A distinction again needs to be drawn between large scale effects of freezing and thawing cycles (such as permafrost heave of gravel and soils that can cause buildings to subside), and damage to materials at the sub-millimetre scale, such as in the cells of timber or the pores of rocks. Everett (1961) discussed the types of freezing damage to porous materials rejecting common notions that expansion of water at 4°C or that freezing itself causes damage citing and assessing other conflicting opinions. Most of his research was on rigid porous materials such as stone, rather than stiff porous materials with flexible cell walls such as wood.

Most conservation literature on freezing damage concerns the effects of museum pest treatments involving freezing of dry materials at -20°C for several weeks. An exception is research on wet and frozen textiles from graves in Svalbard that simulated environmental conditions occurring during excavations (Peacock 1999). She found no significant damage occurred to fibres subjected to multiple wet freeze-thaw cycles excepting some reduction in tensile strength and fibre elongation of aged (three centuries) wool fibres.

Comben (1962) showed that wood has greater strength at low temperature and a higher EMC. Buck (1952) studied twelve samples of various wood species, ranging in age from one to 3,700 years, to test the common belief that wood gradually loses its capacity to absorb and desorb moisture. These were taken through a humidity cycle with ample time for response. His experiment demonstrated that dimensional stability is not an attribute of old wood any more than recent wood. Thus high RH and high EMC of timber at low temperatures are not necessarily deleterious.

All of the research above implies that the process of freezing does not damage wood, so this issue was not pursued in detail in the thesis⁶.

⁵ Available at http://nsidc.org/cgi-bin/words/glossary.pl as downloaded on 22 September 2010.
⁶ The author’s attention was drawn to further evidence from spin echo nuclear magnetic resonance studies which show that adsorbed water does not freeze on the cell wall because the impact of hydrogen bonding is nullified (Hsi, E, Hossfeld, R & Bryant, R 1977, ’Nuclear magnetic resonance relaxation study of water absorbed on milled
4.2.2 Ice accumulation and removal from Antarctic historic buildings

The literature review in Chapter 2 demonstrated that removal of ice from Antarctic historic buildings has often been controversial, particularly since it was often undertaken without temperature and RH monitoring. This is routine practice in most historic buildings and is particularly important in extreme and unfamiliar conditions.

Accumulated ice has been removed from the following Antarctic historic buildings:

- Scott’s *Terra Nova* hut at Cape Evans in 1960-61 and in regular ongoing maintenance;
- Scott’s *Discovery* hut at Hut Point in 1960-61 and in regular ongoing maintenance;
- Borchegrevink’s hut at Cape Adare in 1961 and 1990;
- Nordenskjold’s hut at Snow Hill Island in the 1980s and in recent years;
- Mawson’s AAE main hut at Cape Denison in 1977 (Living Hut), 1998 (Workshop) and in several locations in 2000-2003, and ongoing maintenance; and

At the Ross Dependency huts, high RH (70-90%) persists throughout the year (Mason (1999), Held et al 2005) despite extensive removal of ice in the 1960s, subsequent annual ice clearance, a relatively low rate of ice particle ingress and installation in the 1980s of roofing materials to prevent ice ingress.

At Cape Denison, several authors, for example Blunt (1991), considered that ice accumulation caused structural damage and also that ice removal was necessary to control high RH. Blunt (1985, 1991) proposed to remove all ice inside Mawson’s main hut and install to polymer membranes in the roof and walls to prevent further ingress, similar to the approach taken with the Ross Dependency huts.

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northern white cedar', Journal of Colloid and Interface Science, vol. 62, no. 3, pp. 389-95. Thus, if wood is below fibre saturation point, freezing will not cause expansion in the cell wall.
At Wilkes, Ambrose and Godfrey (1998) proposed to reduce RH by increasing ventilation via a venturi system (figure 2.18) to extract moisture using sublimation to remove ice from the sealed building. They described their research as “an attempt to deal with the problem of the annual freeze-thaw cycle and the damage it causes, by intervening to lower the total annual water load whether as ice, meltwater or humidity”. They enclosed a small IGY building with a plywood prefabricated skin over the original structure, sealed with silicone sealant. The outer skin was separated from the original surface by battens to promote air circulation in between the outer and original layers. Issues raised by this research are examined in the discussion section 4.5.2.

Temperature and RH measurements undertaken in the AAE main hut between January 1999 and January 2000 (Daniel & Ashley 2002) were considered “stable because of the buffering ability of the hut”. Daniel and Ashley (ibid) published further assessment of temperature and RH monitoring in the AAE main hut during 1999-2002 after overcladding of the Workshop roof, discussed further in this chapter. Overcladding of the Living hut roof in 2006 was said to have significantly reduced ice ingress\(^7\) and melting although photographs and limited data summaries in 2010 (presented at workshops of the Mawson’s Huts Foundation) indicated some ingress still occurs and hoarfrost was significant.

Godfrey (2002: 35) identified damage to timbers due to expansion of water in timbers under constraint and considered that the fundamental conservation problem affecting the AAE main hut is the melting of snow ingress which re-freezes onto artefacts:

“…there can be no dispute about the problems that are caused when artefacts are encased in solid ice. Excavation is more difficult and artefacts are subsequently at greater risk of damage. This can be prevented by stopping the ingress of snow and by removing that which is already present”…


\(^7\) Data was not yet published.
4. Temperature, RH, ice and phase changes

“The careful removal of accumulated ice and snow from the Workshop of the Main Hut and, particularly, the living section but not the verandahs, has been a principle of site management since conservation expeditions began”.

These concerns have been addressed by retaining ice in the verandahs to try to stabilise interior temperatures combined with overcladding of the roof of the AAE main hut to protect against wind and minimise ice particle ingress.

Thus the following research questions were identified for further investigation:

1. Do ice and meltwater inside buildings cause damage, and if so, how?

2. What are the characteristics of temperature and RH variation in the Terra Nova hut and AAE main hut and how do these variations produce deterioration? Ice is removed regularly as part of the maintenance procedures at sites in the Ross Dependency and major changes had been made in the building periodically since 1960. Data and observations in the Terra Nova hut by other researchers particularly by Mason (1999) and Held et al (2005) provided suitable information to enable a comparison of hygrothermal behaviour with the AAE main hut.

3. How did removal of ice affect temperature and RH conditions inside the AAE main hut? In particular, what are the criteria required to prevent the cycles of melting and re-freezing identified by Godfrey and is this control achievable?

4. How will climate change affect the sites and what are the implications for current conservation strategies?

Scope

Detailed analyses of structural problems related to ice accumulation are outside the scope of this thesis, although the interactions between climatic and structural issues are discussed where relevant. Requirements for modelling of impacts of ice from Mawson’s main hut using temperature and humidity data were identified although the modelling was not carried out due to resource constraints.
4.3 METHODOLOGY

Several different methods were used to address the research questions.

4.3.1 Field Observations, 1985-1997 at 12 Antarctic sites (Research questions 1 and 2)

Field observations were undertaken at 12 sites of varying ages and types (as listed in Table 3.1) to qualitatively assess the extent and severity of problems arising from temperature and relative humidity variations (for questions 1 and 2) using the methodology set out in Table 3.2. It was not possible to examine the most critical locations inside buildings, which are inside wall spaces and under the floors, due both to time constraints and the requirement for permits for such investigations. Building materials and construction characteristics were identified from observation and from the literature. While the observations are qualitative and sometimes occurred too early in summer for optimal observation of meltwater, the aim was to provide an ‘epidemiological’ view of problems arising from temperature, moisture and ice issues at the sites and to identify the causes. More detailed examination of the deterioration problems (fungi, corrosion, etc) are given in subsequent chapters.

4.3.2 Assessment of damage by ice inside buildings (research question 1)

Qualitative observations of the effects of ice were collated and compared with attributed causes (structural, freezing damage, permafrost heave, etc). A review of information in the literature was used to assess the causes of damage attributed to ice, including expansion of water at 4°C, ice crystal formation during phase change and various cyclic freezing and thawing problems.

4.3.3 The nature of hygrothermal behaviour and deterioration impacts (Research questions 2 and 3)

Data from monitoring temperature and RH inside the AAE main hut and the Terra Nova hut were compared with data from the AAE main hut. The AAE main hut at Cape Denison was considered particularly appropriate for this study because:
1. information on the construction methods and materials used for the building were available from detailed previous studies (Blunt 1991, Pearson 1992 and ongoing studies by the Mawson’s Huts Foundation);
2. reports and photographs are available on the previous condition of the building from periodic visits to the site since its construction in 1912 (Blunt 1985; Hayman, Lazer & Hughes 1998);
3. the AAE main hut is the only major Antarctic historic building where the conservation strategy includes retention of ice in part of the building.
4. the site is a paradigm for other Antarctic historic sites (discussed in Chapter 3.2.3); and
5. when systematic monitoring was initiated in 1999 the degree of human intervention with the building fabric was limited to two seasons when ice was removed from the Living hut (in 1977 and 1998) and had been documented photographically.

A summary of the monitoring history for the AAE main hut is now given to provide context for the results.

Initial monitoring in 1985

During the author’s first site visit (10-12 December 1985) only a single thermohygrograph with a clockwork recording drum and hair hygrograph was available. It was placed on Hodgemann’s bunk, approximately 500mm above floor level, since this relatively open area was representative of conditions in the ice free part of the hut.

ACR dataloggers, January 1998

By the time the author was next able to reach the site in January 1997 small, robust and easily calibrated electronic sensors were available due to improvements in technology. Two ACR XT102 dataloggers supplied by the University of Canberra were installed by the Australian Associated Press Mawson’s Hut Foundation. ACR A was placed close to the apex of the Living Hut ceiling, which is most affected by solar radiation and ACR B was placed close to the floor near the centre of the Living Hut, which is representative of conditions in the ice-filled core of

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8 Due to time constraints it was impossible to undertake regular measurements using wet/dry bulb thermometers.
the building. The method of operation of these sensors is widely known and is not described here for space reasons.

*Integrated datalogger monitoring at Cape Denison January 1999- December 2000*

The feasibility of a larger scale datalogger monitoring system was demonstrated by the success in obtaining data from the two ACR loggers. A detailed case was then developed to substantiate the potential benefit of enhanced data collection to relevant funding bodies (Hayman, Hughes and Lazer 1998; Hughes *et al* 1999).

Deterioration processes depend on the interaction of the surface of the material with its surrounding microclimate. Deterioration is thus controlled by local parameters such as surface wetness and surface temperature (for metals), and moisture content and surface/bulk temperature (for timbers). Further details of the methodology and logistical constraints are published in Ganther *et al* 2002, attached as Appendix K and are briefly summarised below. Low temperatures reduce the operating life of the battery required to power the data-logging system so it was therefore necessary to balance the need for data with the need for robust operation of the system. Monitoring could only be carried out in the main hut due to cost constraints but this is justified since this is the largest and most significant building at the site and this can provide a basis for application of modelling for other buildings.

The capacity of the data card restricted the frequency of sensor measurements to one measurement per hour. This is frequent enough to be sensitive to environmental changes although not frequent enough to detect the rapid Föhn\(^9\) effect temperature changes noted by Madigan (1929: 44) illustrated in figure 4.2. The battery capacity and costs of sensors also limited the number of locations that could be monitored, so additional care was needed to include sufficient representative locations throughout the building (see Table 4.1).

Locations for the sensors were chosen on the basis of:

---

\(^9\) Föhn winds occur in the lee of mountains where air is warmed and dried as it descends from higher altitudes. The term katabatic now generally is used to describe cold air flows from higher altitudes.
4. Temperature, RH, ice and phase changes

- being representative of key processes occurring in the building;
- avoidance of direct sunlight, condensation, hoarfrost or melting cycles that could give false data; and
- ability to install or remove the instrument without damaging it or historic fabric of the building.

Figure 4.2: Föhn effect temperature changes measured by the AAE (Madigan 1929)

The Campbell CR10X monitoring system used eight combined Vaisala temperature-RH sensors (see figure 4.3) and 11 surface temperature thermocouple sensors (see figure 4.4). Figure 4.7 shows the location of the sensors. The rationale for sensor locations is given in detail in Ganther et al 2002; the arrangement enabled a range of locations from floor to apex and from outer walls to the core of the building to be monitored. The exterior sensor TRH1 provided data for comparison with interior conditions to assess the buffering effect of the building. This sensor was exposed to extreme conditions so there were well-founded concerns that this vital data could be lost due to wind damage since the AWS at Cape Denison has suffered frequent damage. A Vaisala combined temperature and RH sensor (TRH 6) was placed adjacent to a thermocouple (TC11) on a bunk in the living section to check for any anomalies in trends. Data from the individual sensors was collected by the central logging system and was transferred into graphical formats (Microsoft Excel) for ease of analysis.
Approximately 40 m$^3$ of ice was removed from the building (Ashley 2001: 82) shortly before the monitoring equipment was installed in 1999. It would have been more straightforward to interpret the effects of ice removal if data had been obtained before the ice was removed. The monitoring project was critically dependent on volunteers to install and maintain the monitoring equipment. Steve Martin (State Library of NSW) installed the dataloggers as close as possible to the locations selected by the author, but also needed to make some ad hoc installation decisions as some locations were difficult to access because of ice or the intrusion of ongoing work. Data was downloaded each month from the datalogger system by overwintering volunteers Jim and Yvonne Claypole although severe weather conditions and some other technical problems resulted in some discontinuities in the data\textsuperscript{10}.

Data from the AAE main hut for 2001 to 2006 recently became available which enables a longitudinal analysis of the effects on internal climate of overcladding and ice removal\textsuperscript{11}. The data was first graphed to detect potentially anomalous data, and identify key trends throughout the year, particularly in summer. Data from Vaisala instruments was checked against thermocouples for consistency.

*Analysis of temperature and RH data*

While all data collected was considered in the analysis, the most relevant data are temperature and RH during January, the warmest month when both external and internal temperatures sometimes rise above 0°C and melting occurred, and there is less missing data. Various statistical analyses were tabulated for both the *Terra Nova* hut and AAE main hut to key trends in mean, maxima, minima, ranges of variations and duration of temperatures above 0°C.

\textsuperscript{10} See Table 4.3b

\textsuperscript{11} Sourced from the Australian Antarctic Data Centre (IDN Node AMD/AU) of the Australian Antarctic Division in metadata record "Dataloggers at Mawson's Hut, Cape Denison - microclimate measurements" Daniel, V. and Easther, R. (2003, updated 2010).
4. Temperature, RH, ice and phase changes

Figure 4.3: Vaisala combined temperature and humidity sensor (Steve Martin 1999)

Figure 4.4: Thermocouple (Steve Martin 1999)

Note: the actual thermocouple is less than 1cm and can be inserted in small gaps in wood.
4.3.4 Analysis of the effects of ice removal from the AAE main hut on internal temperature and RH (research question 3)

The data were graphed to identify trends such as lag time and characteristics of temperature differences between exterior and interior temperatures. Histograms of the frequency of temperatures were studied for skewness and kurtosis. Correlations of scatterplots of exterior (independent variable) and interior temperatures (dependent variables) in the AAE main hut were prepared to analyse buffering by the building. Analysis of absolute humidity (AH) behaviour was used to evaluate condensation of vapour in response to temperature changes to determine any mass transfer (net movement of moisture in, out and within the hut).

Differences between external and internal temperatures were compared for the dates in each January for the years 2000-2006 where consistent dates were measured (6 to 18 January) to measure any change in thermal buffering. Since temperature variations are affected by the lag in peak temperatures between the exterior and interior as well as daily and seasonal fluctuations, various statistical data on temperature variations were compiled. The absolute temperature differences between the exterior and interior of the hut before extensive ice removal in 2000 were compared with the variations in the years 2000 to 2006 where data was available.

Interior temperature variations were also compared with ice volume in the hut, although this was limited since there were only three years with detailed estimates of ice quantities inside the Living hut, Workshop and verandahs. From the correlations an assessment was made of the conditions required to prevent cyclic melting and re-freezing within the hut and the feasibility of achieving these conditions was considered in a risk analysis which used the AS 4360 template described in Chapter 3.

4.3.5 Estimation of effects of climate change for the AAE main hut and implications for conservation management (research question 4)

Discussions with several researchers over many years (Simon Hayman, Dan Mackenzie, Wayne Ganther, Ivan Cole) led the author to consider the data requirements for improved modelling of thermal behaviour of the AAE main hut to consider risks associated with temperature variability
and climate change. Due to time constraints, the requirements and benefits of the model are discussed although the actual modelling could not be effected.

Literature sources were consulted to determine likely climate changes for Cape Denison. The effects of temperature change were estimated from applying potential higher temperatures to the correlations derived in 4.3.4 and applying this to the conservation risks identified using AS 4360 as described in Chapter 3.

4.4 RESULTS

4.4.1 Field observations at 12 diverse Antarctic sites

Table 4.1a: Summary of author’s field observations of thermal, moisture and phase change issues

<table>
<thead>
<tr>
<th>Problem</th>
<th>Affected sites</th>
<th>Unaffected sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meltwater outside buildings</td>
<td>Mawson Station Bisoe hut- meltwater flows from upslope and penetrated along</td>
<td>Rumdoodle -this site is at a higher altitude with a cooler climate than</td>
</tr>
<tr>
<td>during summer</td>
<td>bottom of walls, stains indicate frequent past melting; meltwater pools also</td>
<td>Mawson Station, no melting observed and no evidence of previous melting.</td>
</tr>
<tr>
<td></td>
<td>occurred outside the aircraft hangar and several other buildings. Melting</td>
<td>Paint may obscure evidence of any past meltwater flows.</td>
</tr>
<tr>
<td></td>
<td>waters were also in Russian caravan, Met Tech hut and relocated field hut</td>
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</tr>
<tr>
<td></td>
<td>(Alice’s Restaurant).</td>
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<tr>
<td>Mawson Station</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biscoe hut</td>
<td>Rumdoodle -this site is at a higher altitude with a cooler climate than</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mawson Station, no melting observed and no evidence of previous melting.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Paint may obscure evidence of any past meltwater flows.</td>
<td></td>
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<td>Mawson Station</td>
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<tr>
<td>Biscoe hut</td>
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<td>Mawson Station</td>
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<td>Biscoe hut</td>
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<td>Biscoe hut</td>
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<td>Biscoe hut</td>
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<td>Biscoe hut</td>
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<td>Mawson Station</td>
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<tr>
<td>Biscoe hut</td>
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<td>Mawson Station</td>
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<td>Biscoe hut</td>
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<tr>
<td>Biscoe hut</td>
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<td>Mawson Station</td>
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<tr>
<td>Biscoe hut</td>
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<td>Mawson Station</td>
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<td>Biscoe hut</td>
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<td>Mawson Station</td>
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<td>Biscoe hut</td>
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<td>Mawson Station</td>
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<tr>
<td>Biscoe hut</td>
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<td>Mawson Station</td>
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<td>Biscoe hut</td>
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<td>Mawson Station</td>
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<td>Biscoe hut</td>
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<td>Mawson Station</td>
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<td>Biscoe hut</td>
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<td>Mawson Station</td>
<td></td>
<td></td>
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<tr>
<td>Biscoe hut</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4. Temperature, RH, ice and phase changes

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerous observers report snowdrifts from winter till December (e.g., Mason 1999: 19). Vertical stains below nails indicate past meltwater flows down the walls.</td>
<td>Footings. Vertical corrosion stains from nails and plaque (fig 6.22).</td>
</tr>
<tr>
<td><strong>Cape Adare (Borchgrevink)</strong> - pools of meltwater adjacent to piles of guano along most walls (fig 5.11). Some water stains visible on upper walls where there is no corrosion.</td>
<td>TAE hut - flat roof is clear of snow, surrounding area is free of snowdrifts and is well-maintained, which may also remove evidence of past melting.</td>
</tr>
<tr>
<td></td>
<td>McMurdoo - Mess building appears built on a raised base which would exclude water ingress at floor level although rips on exterior fabric may allow ingress via roof, although not evident during the visit (fig 7.2). Water stains evident on exterior.</td>
</tr>
<tr>
<td></td>
<td>Cape Royds - overcladding of roof may prevent problems or obscure evidence, no meltwater ingress evident at floor level. Exterior rust stains and stains from a Cu alloy plaque indicate periodic dripping of water.</td>
</tr>
<tr>
<td>Meltwater inside buildings</td>
<td>Mawson Station Biscoe - meltwater flow from upslope has penetrated along bottom of walls; similarly at Weddell, Electrician’s Workshop - some leakage through roof. Some small areas of roof leakage are evident in Met Tech workshop - raised off ground, as was Russian Caravan and the Mess, so problems are minimal. Electrician’s workshop - wet insulation due to badly corroded panels and via flat roof.</td>
</tr>
<tr>
<td>Affected: 6</td>
<td>Rumdoodle - no evidence of water stains or other signs of ingress via either roof or floor.</td>
</tr>
<tr>
<td>Not affected: 4</td>
<td></td>
</tr>
<tr>
<td>Not examined: 2</td>
<td></td>
</tr>
<tr>
<td><strong>Dumont d’Urville</strong> - not able to be inspected due to use as a dormitory for shiftworkers. <strong>McMurdo</strong> - light conditions were too poor to assess the dark interior.</td>
<td></td>
</tr>
<tr>
<td><strong>Cape Denison</strong> Main hut - Dec 1985 - drips of water evident in ceiling, small amounts of meltwater on floor. 1997 - interior not accessed, but water was seen running inside through gaps in roof cladding of both Living hut and Workshop. Numerous other evidence of meltwater inside the hut 1912, 1930, 1977, 1985, and later years.</td>
<td>TAE hut - metal-cladding appears well-maintained and fairly tightly sealed. Absence of snowdrifts probably assists in preventing meltwater ingress.</td>
</tr>
<tr>
<td><strong>Cape Royds</strong> - evidence of previous meltwater running inside from roof (salt trails, fig 5.5), appears to come from ridgeline. Flow emerges between the lining boards.</td>
<td>Platcha - roof interior is buckled which could suggest some water or ice ingress although no staining was seen. Regular inspection would be a wise precaution.</td>
</tr>
<tr>
<td><strong>Cape Evans</strong> - evidence of hoarfrost and staining on southern wall.</td>
<td><strong>Davis</strong> - wall panels are perforated by corrosion/corrosion so that ice was seem inside wall panels but no evidence of ingress to interior of building. The Donga building is occupied, heated and regularly maintained. Old Paint Store has no</td>
</tr>
</tbody>
</table>
### Evidence of high humidity inside buildings

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hut Point</td>
<td>Interior is very dark but some salt trails were visible inside the roof and minor drips on the floor near the stove.</td>
</tr>
<tr>
<td>Cape Adare</td>
<td>Small amounts of frozen meltwater on floor and one wall.</td>
</tr>
<tr>
<td>Evidence</td>
<td><strong>20</strong> evidence of leaks.</td>
</tr>
<tr>
<td><strong>Dumont d’Urville</strong></td>
<td>(not able to be inspected).</td>
</tr>
<tr>
<td>affected: 6</td>
<td>Not affected: 5</td>
</tr>
<tr>
<td>Not examined: 1</td>
<td></td>
</tr>
<tr>
<td><strong>Rumdoodle</strong></td>
<td>No evidence of corrosion or mould, possibly due to good maintenance.</td>
</tr>
<tr>
<td><strong>Davis</strong></td>
<td>Donga is heated, hence tends to remain dry. Old Paint Store is unheated but there was no evidence of rusting (building is built without nails) and no rusting underneath paint tins.</td>
</tr>
<tr>
<td><strong>Mawson Station</strong></td>
<td>Extensive corrosion inside Aircraft hangar, smell of mould inside Biscoe Hut, Mess and Weddell hut.</td>
</tr>
<tr>
<td><strong>Platcha</strong></td>
<td>Lack of snow drifts against walls and minimal snow ingress probably keeps interior dry. Weather during observation was cold and windy so periodic high humidity cannot be excluded although there was no evidence of rust or mould.</td>
</tr>
<tr>
<td><strong>Cape Denison</strong></td>
<td>Monitoring documented high RH over several years (section 4.4), corrosion and mould also present.</td>
</tr>
<tr>
<td><strong>McMurdo</strong></td>
<td>Heated building reduces humidity.</td>
</tr>
<tr>
<td><strong>Cape Adare</strong></td>
<td>Fungal growth (blue stain, fig 9.8) on some timbers, some artefacts and fittings are corroded (but these may have been relocated from outside).</td>
</tr>
<tr>
<td><strong>TAE hut</strong></td>
<td>Well-maintained building, no apparent leaks or melt staining.</td>
</tr>
<tr>
<td><strong>Cape Evans</strong></td>
<td>Monitoring (Held et al 2005) documented high RH over several years, corrosion and mould also present.</td>
</tr>
<tr>
<td><strong>Cape Royds</strong></td>
<td>Mouldy smells, some artefacts have visible mould or corrosion (though may have been re-located), regular maintenance occurs, high RH documented.</td>
</tr>
<tr>
<td><strong>Hoarfrost</strong></td>
<td>Hoarfrost inside apex of main hut.</td>
</tr>
<tr>
<td><strong>Cape Denison</strong></td>
<td>Not seen by author (but hoarfrost was reported on southern wall by Mason (1999: 20) earlier in summer. In about 2002 a hole was drilled into the north side of the hut to determine whether there was ice inside the wall. The wall was ice-filled at least one metre above floor level and filled the seaweed insulation of Gibson’s quilting (Harrowfield, personal communication on the draft thesis 2009).</td>
</tr>
<tr>
<td><strong>Cracking of external timber</strong></td>
<td>Evident on exterior of all four huts, particularly on darkened timbers of main</td>
</tr>
</tbody>
</table>

Sublimation

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Affected</strong>: 1</td>
<td>Not affected: 3</td>
</tr>
<tr>
<td>Not examined: 8</td>
<td></td>
</tr>
<tr>
<td><strong>Dumont d’Urville</strong></td>
<td>Not inspected inside. Unable to tell at Rumdoodle, Old Paint Store, Platcha, Cape Adare, Cape Royds, Hut Point, TAE Hut.</td>
</tr>
<tr>
<td><strong>Cape Denison</strong></td>
<td>Hoarfrost is an ephemeral condition and is particularly likely to occur in high wind locations. Unlike in continuously heated buildings at Mawson Station, Davis (Dongas), McMurdo.</td>
</tr>
<tr>
<td><strong>Rumdoodle</strong></td>
<td>Exterior timbers are painted.</td>
</tr>
</tbody>
</table>

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12 Held et al 2005  
13 Held et al 2005  
14 Held et al 2005
4. Temperature, RH, ice and phase changes

<table>
<thead>
<tr>
<th>Affected: 5&lt;sup&gt;16&lt;/sup&gt;</th>
<th>hut roof (figure 4.24) rather than freshly eroded timber- discussed in detail in Chapter 8.</th>
<th>so difficult to examine.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not affected: 7</td>
<td>Cape Adare- some cracks evident on external timber (fig 8.20) and on door handle (figure 7.14, possibly due to stress from corrosion of fasteners), but not as evident as Cape Denison. The roof was overclad with Butylclad (butyl rubber sheeting) over the original timbers with wooden batten covering the joins.</td>
<td>Dumont d’Urville- no cracking of bare timber footings is evident, other timber is painted.</td>
</tr>
<tr>
<td>Not examined: 0</td>
<td>Cape Evans- evident on defibred timber on wall (fig 5.14).</td>
<td>TAE hut- metal cladding.</td>
</tr>
<tr>
<td></td>
<td>Alice’s Restaurant, Mawson Station- unpainted 1960s field hut relocated from Taylor Glacier- some longitudinal cracks, also defibred.</td>
<td>Mawson Station- plastic domes have fine stress cracks, but may be due to/exacerbated by UV.</td>
</tr>
<tr>
<td></td>
<td>Cape Royds- some longitudinal cracking evident on walls, especially where corrision timber is darkened (ie not recently eroded).</td>
<td>Cape Evans- distorted backing of mirror, discussed in detail in Ch 6, believed due to differential expansion of metallic backing and glass.</td>
</tr>
<tr>
<td></td>
<td>Hut Point- some longitudinal cracking evident on darkened timber.</td>
<td>No evidence found at Rumdoodle, Platcha, Davis, Cape Denison, Cape Adare, Cape Royds, Hut Point, McMurdo, TAE hut.</td>
</tr>
<tr>
<td>Thermal cracking of other materials</td>
<td>Dumont d’Urville- red paint of Base Marret is faded (fig 7.22), some bubbling of paints on various buildings (but may be due to poor preparation, or poor drying). Fibreglass Arbec buildings are discoloured and opaque, but may be due to/exacerbated by UV.</td>
<td>McMurdo- buildings are not timber</td>
</tr>
<tr>
<td>Affected: 3</td>
<td>Mawson Station- plastic domes have fine stress cracks, but may be due to/exacerbated by UV.</td>
<td></td>
</tr>
<tr>
<td>Not affected: 9</td>
<td>Cape Evans- distorted backing of mirror, discussed in detail in Ch 6, believed due to differential expansion of metallic backing and glass.</td>
<td></td>
</tr>
<tr>
<td>Not examined: 0</td>
<td>No evidence found at Rumdoodle, Platcha, Davis, Cape Denison, Cape Adare, Cape Royds, Hut Point, McMurdo, TAE hut.</td>
<td></td>
</tr>
<tr>
<td>Ice accumulation inside buildings</td>
<td>Cape Denison- ice was entering the building during occupation (1912-13), was evident in 1930, increased in extent by the 1960s, filled the hut in 1977, removed from Living Hut 1977/78, filled the hut again by 1982, partially removed in 1985 and 1997 (both Living Hut), 1998 (Workshop ) and several locations in 2000-2003 but ingress has continued despite over-cladding and various repairs.</td>
<td>Rumdoodle*; Mawson Station* #; Davis* #&lt;sup&gt;15&lt;/sup&gt;; Platcha*; Dumont d’Urville *; Cape Royds, McMurdo * #, TAE hut *.</td>
</tr>
<tr>
<td>Affected: 4</td>
<td>Cape Evans (cleared 1960-61); Hut Point (cleared 1960-61); Borchgrevink’s hut at Cape Adare cleared 1961, 1990. Periodic snow ingress is regularly cleared at Ross Island huts.</td>
<td>Note that buildings with a single asterisk are regularly maintained so ice may not have a chance to accumulate, those marked # are continuously heated, which may help prevent ice accumulation.</td>
</tr>
<tr>
<td>Not affected: 8 (of which 7 are regularly maintained and 3 are heated).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not examined: 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Damage due to freezing processes such as permafrost</strong></td>
<td>Permafrost- there is no evidence of permafrost heaving of the Old Paint Store at Davis, there is no significant buckling of the Ross Island</td>
<td>Sites such as Mawson, Davis, Dumont d’Urville, Cape Denison, Cape Adare are not visibly affected by permafrost</td>
</tr>
</tbody>
</table>

<sup>15</sup> Longitudinal cracks from swelling/shrinkage of timber from moisture changes, not due to structural breakage.

<sup>16</sup> ‘Alice’s Restaurant’ is affected, but cracks may have arisen at previous location. Other buildings at Mawson are painted so cracking cannot be determined.

<sup>17</sup> Davis- intrusion of ice inside Donga panels but not inside building. Old Paint Store- ice accumulation under building
heaving, cracking from expansion at 4°C or ice crystal formation within a material. Affected: probably nil, certainly no significant evidence of damage. Not-affected: 12 buildings. Investigations of the subfloor of Terra Nova hut in 2008 found significant hoarfrost and frozen meltwater but this does not appear to be a permafrost effect (that is, damage from a freezing front causing hydraulic jacking). Ice crystal formation in materials- While hoarfrost formation is common in many of the buildings no visible surface damage was found that could be attributed to ice crystal formation. heaving and any permafrost heaving at Ross Island sites does not appear significant. No evidence of damage by ice crystal formation was reported at any site.

Table 4.1b Summary of thermal, moisture and phase change effects at sites not visited by the author.

<table>
<thead>
<tr>
<th>Issue</th>
<th>Affected sites</th>
<th>Unable to be determined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meltwater outside buildings</td>
<td>East Base (Spude &amp; Spude 1993)</td>
<td>Pt Lockroy</td>
</tr>
<tr>
<td></td>
<td>Wilkes (R Summerson, personal communication)</td>
<td>Pt Martin</td>
</tr>
<tr>
<td></td>
<td>Snow Hill Island (Comerci 1983)</td>
<td></td>
</tr>
<tr>
<td>Meltwater inside buildings</td>
<td>East Base (Spude &amp; Spude 1993)</td>
<td>Pt Martin</td>
</tr>
<tr>
<td></td>
<td>Wilkes (R Summerson, personal communication)</td>
<td>Snow Hill Island</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pt Lockroy</td>
</tr>
<tr>
<td>High humidity</td>
<td>East Base (Broadbent 1992)</td>
<td>Pt Martin</td>
</tr>
<tr>
<td></td>
<td>Wilkes (Clark and Wishart 1991)</td>
<td>Pt Lockroy</td>
</tr>
<tr>
<td></td>
<td>Snow Hill Is (Comerci 1983)</td>
<td></td>
</tr>
<tr>
<td>Corrosion</td>
<td>East Base (Spude &amp; Spude 1993)</td>
<td>Pt Martin</td>
</tr>
<tr>
<td></td>
<td>Snow Hill Is (Comerci 1983)</td>
<td>Pt Lockroy</td>
</tr>
<tr>
<td></td>
<td>Wilkes (Clark and Wishart 1991)</td>
<td></td>
</tr>
<tr>
<td>Periodic wetting/drying</td>
<td>East Base (Spude &amp; Spude 1993)</td>
<td>Pt Martin</td>
</tr>
<tr>
<td></td>
<td>Wilkes (Clark and Wishart 1991)</td>
<td>Pt Lockroy</td>
</tr>
<tr>
<td></td>
<td>Snow Hill Island (Comerci 1983)</td>
<td></td>
</tr>
<tr>
<td>Sublimation</td>
<td>Wilkes (measurement, Ambrose and Godfrey)</td>
<td>Snow Hill Island</td>
</tr>
<tr>
<td></td>
<td></td>
<td>East Base</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pt Martin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pt Lockroy (likelihood due to katabatic winds)</td>
</tr>
<tr>
<td>Cracking of timber</td>
<td>East Base (visible in photos (Spude &amp; Spude 1993)</td>
<td>Pt Lockroy</td>
</tr>
<tr>
<td></td>
<td>Wilkes (visible in photos Clark and Wishart 1991)</td>
<td>Snow Hill Is</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pt Martin</td>
</tr>
<tr>
<td>Thermal cracking of other materials</td>
<td></td>
<td>Pt Lockroy (external timbers appear painted)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pt Martin</td>
</tr>
<tr>
<td>Ice accumulation inside buildings</td>
<td></td>
<td>Snow Hill Island</td>
</tr>
<tr>
<td></td>
<td></td>
<td>East Base</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wilkes</td>
</tr>
</tbody>
</table>

---

18 During summer.
19 Longitudinal cracks from swelling/shrinkage of timber from moisture changes, not due to structural breakage.
The information in these tables is summarised and discussed in 4.5.1.

4.4.2 Temperature and relative humidity data reported at Cape Denison

Project Blizzard monitoring 1984-85

For both sets of observations Hodgeman’s bunk:
- Air temperatures were in the range -5°C ± 2°C, with no distinct daily trend.
- RH varied between 95 to 98%.
- During this period there were, on average, about three people working intermittently inside
  the hut documenting the building using lighting that produced some heat.

ACR loggers 1-28 January 1998

Figure 4.5: Temperature variations measured by ACR A (apex) and ACR B (centre of living hut
less than 30 cm above floor)
4. Temperature, RH, ice and phase changes

Figure 4.6: Relative humidity variations measured by ACR A and ACR B

Integrated datalogger system, 26 January 1999 - 30 December 2000

Due to the large volume of data that was collected the information is summarised in Table 4.3\(^\text{20}\). Surface equilibrium moisture content (SEMC) was calculated from the temperature and RH data using the method of Bramhall (1979) (cited in Appendix K) of a standard piece of timber if it were in the position of the sensor. Surface temperature data from the thermocouples are provided because of potential temperature differences between the air and surface temperatures.

Table 4.3: Summary of temperature and RH data AAE main hut, 26 January 1999 - 30 December 2000 prior to major ice removal (from Ganther \textit{et al} 2002)

Table 4.3a: Air temperatures and RH measurements

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RH max (%)</td>
<td>103</td>
<td>100</td>
<td>96</td>
<td>99</td>
<td>101</td>
<td>96</td>
<td>100</td>
<td>101</td>
</tr>
<tr>
<td>RH average (%)</td>
<td>85</td>
<td>89</td>
<td>85</td>
<td>89</td>
<td>91</td>
<td>88</td>
<td>90</td>
<td>87</td>
</tr>
</tbody>
</table>

\(^{20}\) This is based on Table 1 Ganther \textit{et al} 2002, bound as Appendix K in this thesis.
### Temperature, RH, ice and phase changes

<table>
<thead>
<tr>
<th>RH min (%)</th>
<th>23</th>
<th>56</th>
<th>76</th>
<th>80</th>
<th>84</th>
<th>81</th>
<th>60</th>
<th>56</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp max (°C)</td>
<td>+8.1</td>
<td>-0.3</td>
<td>-0.4</td>
<td>-0.4</td>
<td>-0.3</td>
<td>-0.5</td>
<td>-0.4</td>
<td>+3.3</td>
</tr>
<tr>
<td>Temp average (°C)</td>
<td>-14.0</td>
<td>-14.4</td>
<td>-14.9</td>
<td>-14.8</td>
<td>-13.7</td>
<td>-14.9</td>
<td>-14.4</td>
<td>-13.5</td>
</tr>
<tr>
<td>Temp min (°C)</td>
<td>-32.2</td>
<td>-23.1</td>
<td>-24.3</td>
<td>-22.8</td>
<td>-21.3</td>
<td>-22.2</td>
<td>-22.8</td>
<td>-24.4</td>
</tr>
<tr>
<td>AH max (g/m³)</td>
<td>5.2</td>
<td>4.4</td>
<td>4.0</td>
<td>4.5</td>
<td>4.6</td>
<td>4.2</td>
<td>4.6</td>
<td>5.7</td>
</tr>
<tr>
<td>AH average (g/m³)</td>
<td>1.7</td>
<td>1.7</td>
<td>1.5</td>
<td>1.6</td>
<td>1.8</td>
<td>1.6</td>
<td>1.7</td>
<td>1.8</td>
</tr>
<tr>
<td>AH min (g/m³)</td>
<td>0.3</td>
<td>0.7</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.7</td>
<td>0.7</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Figure 4.7: Location of Vaisala sensors at AAE main hut 1999-2000 (Ganther et al 2002: 3)
4. Temperature, RH, ice and phase changes

Table 4.3b: Surface temperature measurements

<table>
<thead>
<tr>
<th>Location</th>
<th>Temp (°C)</th>
<th>Max.</th>
<th>Ave.</th>
<th>Min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetylene equipment store (TC1)</td>
<td>-0.4</td>
<td>-0.5</td>
<td>-0.4</td>
<td>-22.9</td>
</tr>
<tr>
<td>Wall in Mawson’s room (TC2)</td>
<td>-0.4</td>
<td>-0.4</td>
<td>-0.4</td>
<td>-22.9</td>
</tr>
<tr>
<td>Wooden shelf (TC3)</td>
<td>-0.4</td>
<td>-0.4</td>
<td>-0.4</td>
<td>-22.9</td>
</tr>
<tr>
<td>1m from TC3 (TC4)</td>
<td>+3.2</td>
<td>-13.8</td>
<td>-14.4</td>
<td>-22.9</td>
</tr>
<tr>
<td>Dark room (TC5)</td>
<td>-0.2</td>
<td>-14.4</td>
<td>-13.9</td>
<td>-24.6</td>
</tr>
<tr>
<td>Apex living section (TC6)</td>
<td>+0.3</td>
<td>-13.9</td>
<td>-14.6</td>
<td>-23.4</td>
</tr>
<tr>
<td>In roof cavity at main entrance (TC8)</td>
<td>+0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In roof near TC8 (TC9)</td>
<td>+0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/3m from floor (TC10)</td>
<td>-0.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3c: Data discontinuities due to operational problems:

<table>
<thead>
<tr>
<th>Start of discontinuity</th>
<th>End of discontinuity</th>
<th>Duration of discontinuity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900 hr 24 February</td>
<td>1600 hr 3 May 1999</td>
<td>66 days</td>
</tr>
<tr>
<td>1600 hr 2 June</td>
<td>1600 hr 15 July 1999</td>
<td>41 days</td>
</tr>
<tr>
<td>0900 hr 9 November</td>
<td>2200 hr 4 December 1999</td>
<td>24 days</td>
</tr>
<tr>
<td>2300 30 December 1999</td>
<td>0000 hr 1 January 2000</td>
<td>1 day</td>
</tr>
<tr>
<td>1400 hr 3 January</td>
<td>1200 hr 6 January 2000</td>
<td>2.5 days</td>
</tr>
</tbody>
</table>

Table 4.3d: Number of freeze-thaw cycles

Taking account of the data discontinuities above, the number of instances where temperature exceeded 0°C was examined, presumed to indicate thawing although this is also dependent on the duration of the higher temperatures.

<table>
<thead>
<tr>
<th>Location</th>
<th>dates</th>
<th>Number cycles over 0°C</th>
<th>Duration of temperature&gt;0°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living hut apex</td>
<td>26 January to 24 February 1999 (26 days)</td>
<td>4</td>
<td>&lt; 4 hours</td>
</tr>
<tr>
<td>Other locations (Vaisala sensors)</td>
<td></td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>TC7 (Mawson’s room)</td>
<td>&quot;</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Living hut apex</td>
<td>4 December 1999 to 29 February 2000 (87 days)</td>
<td>28</td>
<td>&lt;4 hours</td>
</tr>
<tr>
<td>Other locations (Vaisala sensors)</td>
<td></td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>TC7 (Mawson’s room)</td>
<td>&quot;</td>
<td>8</td>
<td>Shortest: &lt;3 hours, Longest &gt;52 hours</td>
</tr>
<tr>
<td>Living hut apex</td>
<td>15 November to 30 December 2000 (45 days)</td>
<td>20</td>
<td>&lt;4 hours</td>
</tr>
</tbody>
</table>

Integrated datalogger system, 2000-2006

Data for 2000-2006 was released in 2010 from the Australian Antarctic Data Centre (IDN Node AMD/AU), a part of the Australian Antarctic Division (Commonwealth of Australia)\(^\text{21}\). Extracted

\(^{21}\) These data are described in the metadata record "Dataloggers at Mawson's Hut, Cape Denison - microclimate measurements" Daniel, V. and Easther, R. (2003, updated 2010)
data was compiled in Table 4.4 to compare the temperature and RH variations in relation to major activities such as overcladding and ice removal in the AAE main hut. The difficulties of maintaining the equipment again resulted in some discontinuities in the data which then makes comprehensive statistical analysis very difficult, in addition to the fact that the first available data in 1999 was recorded when the extensive ice removal had already occurred. The key data extracted into the table are those recorded at the exterior, the apex of the living hut and the ‘centroid’\textsuperscript{22}. The data from 2006 onwards is affected by several anomalies with sudden large scale fluctuations in RH (for example in Berry 2010, said to be due to ‘hoarfrost build up’, possibly due to the melting of the hoarfrost). Data for January is more comprehensive that other periods and is important for examining conservation risks as this is generally the warmest month so January data were analysed in greater detail.

Table 4.4: comparisons of temperature and RH data, ice quantities and building interventions, Cape Denison and Cape Evans, since construction.

Detailed volume calculations are provided in Appendix N. All data exclude unknown quantities of ice between external and internal cladding in walls and roofs and exclude subfloor ice.

AAE main hut, Cape Denison

Table 4.4a: Internal capacity of key areas within the AAE main hut

<table>
<thead>
<tr>
<th>Location</th>
<th>verandahs, V</th>
<th>Living Hut, LH</th>
<th>Workshop, WS</th>
<th>Under floor</th>
<th>V+LH+WS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal capacity, m(^3)</td>
<td>121.3</td>
<td>152.2</td>
<td>73.7</td>
<td>Not estimated</td>
<td>347.2</td>
</tr>
</tbody>
</table>

Table 4.4b: Ice volumes changes over time since construction, AAE main hut

<table>
<thead>
<tr>
<th>date</th>
<th>Living hut</th>
<th>Workshop</th>
<th>verandahs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1912</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1931</td>
<td>38</td>
<td>36</td>
<td>120</td>
<td>194</td>
</tr>
<tr>
<td>1978</td>
<td>120</td>
<td>0</td>
<td>120</td>
<td>240</td>
</tr>
</tbody>
</table>

\textsuperscript{22} Sensors were moved for various reasons but the recording point chosen was as close as possible to the geometric centre of the building.
Table 4.4c: AAE main hut building interventions and impact on ice quantities, 1912-2010

<table>
<thead>
<tr>
<th>Date</th>
<th>Building interventions</th>
<th>Estimated ice quantities in hut²³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1912</td>
<td>Building constructed in 1912, not inhabited after 1913.</td>
<td>Presumed nil or minimal, possibly some snow within wall cavities.</td>
</tr>
<tr>
<td>1931</td>
<td>Nil- some snow and ice removed by BANZARE to inspect the building, see figures 4.12, 4.19. The building cladding was substantially intact but ice ingress still occurred.</td>
<td>Verandahs mostly full) Living hut one quarter full (38 m³) Workshop half full (36 m³)</td>
</tr>
<tr>
<td>1977-78</td>
<td>ANARE removed ice from workshop, partial excavation of living section.</td>
<td>Before: full 347 m³ After excavation: 240 m³ (based on Ledingham 1979)</td>
</tr>
</tbody>
</table>

²³ Note: 1 m³ of fresh wind driven Antarctic snow typically weighs 300 kg, old snow weighs 500 kg and firn weighs 600kg (derived from data on the NOAA website at [http://www.srh.noaa.gov/jetstream/append/glossary_d.htm](http://www.srh.noaa.gov/jetstream/append/glossary_d.htm). An average density for snow in the huts, mostly of consistency between old snow and firn with some melted and refrozen ice, is therefore somewhere between, or approximately 550 kg/m³. AAE measured ‘specific gravity of drift-blown snow is 0.511’ (Jacka and Jacka 1988: 62).
<table>
<thead>
<tr>
<th>Date</th>
<th>Building interventions</th>
<th>Estimated ice quantities in hut</th>
</tr>
</thead>
<tbody>
<tr>
<td>1982</td>
<td>Apex of workshop clad with lead sheeting secured with timber battens (fig 7.11, 8.26). Densotape strips used in various locations to prevent ice particle ingress (fig 7.13) but both failed by 1985. Repairs to skylight covers.</td>
<td>Partially full.</td>
</tr>
<tr>
<td>December 1985</td>
<td>Excavation of ice for archaeological research and to install props for platform which was sagging from ice on top. (See figure 4.25, Blunt 1986: 93).</td>
<td>Verandahs mostly full except at SW.</td>
</tr>
<tr>
<td>December 1997</td>
<td>Major removal of ice commenced. Re-cladding over the existing workshop roof with new boards; ‘restoration’ of skylights, skylight covers, ridge capping, valley gutters; structural repairs; and reconstruction/restoration of the central platform structure in the living section of the Main Hut.</td>
<td>Before: full, 347 m³ Subfloor also full. After: 41 m³ of ice removed: Underfloor 25 m³. (Ashley 2001: 82 stated total volume of 326 m³).</td>
</tr>
<tr>
<td>1999 to early 2000</td>
<td>Nil.</td>
<td>The amount of ice remaining is presumed to be the same as 1998, 326 m³. Ice ingress rate not documented.</td>
</tr>
<tr>
<td>December 2002</td>
<td>Large volumes of ice removed (DEWHA 2008: 89) and extensive melting. Godfrey 2002: Plastic sheeting installed in Mawson’s cubicle and on shelving to document ice ingress. 600 mm of ‘archaeological’ floor ice (49 m³). Significant depletion of ice due to high temperatures, especially western wall of Workshop and other areas in the interior of the hut. Concluded (ibid: 8) that overcladding of Workshop and other repairs was successful since no new ice was found on plastic sheeting, although new ice accumulation occurred elsewhere. Subsequently, 725 kg of ice was removed from Mawson’s room (ibid: 25).</td>
<td>Verandahs depleted (~75 m³ lost), 46 m³ remain. From images in Godfrey 2002 it appears ice remaining is ~50% (2.5 m³) of darkroom, 10% Mawson’s cubicle (1.4 m³), 25% rest of Living hut (13.9 m³). Ice on floor: Living area+ workshop=49 m³ Substantial quantities of ice remain under the floor despite extensive melting (ibid : 26). Total= ~112.8 m³.</td>
</tr>
<tr>
<td>2006</td>
<td>Overcladding of Living Hut roof with uncoated boards (figs 7.21, 7.25), large volumes of ice removed in living hut and workshop(DEWHA 2008: 89) Removed 2 m³ ice which had accumulated on plastic sheeting in Mawson’s cubicle since 2002 and 3 m³ from SE corners of living section (DEWHA 2008: 65).</td>
<td>At least 49 m³ of ice remains on floor plus ice ingress of around 5 m³. Total = 54 m³</td>
</tr>
<tr>
<td>2009-10</td>
<td>Continued removal of ice ingress into ‘centroid’ (Berry 2010). Extensive hoarfrost (figs 4.27, 4.31, 4.34) formed on most wall surfaces (ibid: numerous un-numbered figures) although ice ingress had been reduced by installation of plastic barriers in 2007-08.</td>
<td>Ice volume inside hut = 39.8 m³. Based on approx 1/3 of Workshop, 1/10 of Living hut (including archaeological deposit on floor).</td>
</tr>
</tbody>
</table>

Terra Nova hut
Table 4.5: *Terra Nova* hut, Cape Evans, summary of building intervention, ice volumes and temperature and RH data

Total internal volume of *Terra Nova* hut is 378 m$^3$ (see dimension data in Appendix N).

<table>
<thead>
<tr>
<th>Date (data source)</th>
<th>Building interventions</th>
<th>Estimated ice accumulation</th>
<th>Ice, tonnes</th>
<th>T &amp; RH data$^{24}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1911-13</td>
<td>Hut built in January 1911, ceased occupation in January 1913</td>
<td>No ice.</td>
<td>0</td>
<td>Hut was artificially heated during the expedition.</td>
</tr>
<tr>
<td>1915-17</td>
<td>Occupied by Ross Sea Party</td>
<td>Ice progressively infiltrated subfloor and walls after their departure.</td>
<td>n/a</td>
<td>Not measured.</td>
</tr>
<tr>
<td>1947</td>
<td>USS <em>Burton Island</em> visited but did not enter the hut</td>
<td>Hut found to be part-filled with compacted ice (Quartermain 1963: 63), but quantity not given (author’s estimate 95% full with specific gravity 800 kg/m$^3$ =287 tonnes).</td>
<td>287</td>
<td>Not measured.</td>
</tr>
<tr>
<td>1956-57</td>
<td>Endeavour staff re-felted and repaired roof,</td>
<td>Compacted snow in kitchen completely cleared, attempted to clear main room (ibid: 68). Estimate 80% full, with specific gravity 800 kg/m$^3$ = 241 tonnes).</td>
<td>241</td>
<td>Not measured.</td>
</tr>
<tr>
<td>1960-61</td>
<td>Ice removed from internal area of hut (Quartermain 1963: 70) and some from stables; re-covered the roof with railway tarpaulins that were painted over, ‘extracted relics’, shored up shelving.</td>
<td>Two thirds full of ice (ibid: 71), solid ice over floor, six feet of hard ice with compacted snow up to roof level. Estimate 67% full with 204 m$^3$ of ice with specific gravity 950 kg/m$^3$ and 173 m$^3$ at 550 kg/m$^3$ = 193.8 + 95.15 tonnes Total estimated = 288.95 tonnes Underfloor estimate 4m$^3$ (see 2009 comments).</td>
<td>289</td>
<td>Not measured.</td>
</tr>
<tr>
<td>1970s</td>
<td>1976-77 and 1977-78: ice removed from east end of building.</td>
<td>Estimate 40% of total ice volume remains, plus subfloor, ~ 150 m$^3$</td>
<td>150</td>
<td>Not measured.</td>
</tr>
<tr>
<td>1980s</td>
<td>1988-89 and 1989-90:</td>
<td>Ice is continuously</td>
<td>4</td>
<td>Not reported.</td>
</tr>
</tbody>
</table>

$^{24}$ The nearest location where temperature data is available (Scott Base) has an average maximum temperature for January of -1.6°C and an average minimum temperature in August of -41.4°C from records during 1957 to 2007 (available at [http://www.antarctica.ac.uk/met/gjma](http://www.antarctica.ac.uk/met/gjma)).
4. Temperature, RH, ice and phase changes

<table>
<thead>
<tr>
<th>Date (data source)</th>
<th>Building interventions</th>
<th>Estimated ice accumulation</th>
<th>Ice, tonnes</th>
<th>T &amp; RH data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>major effort to remove ice from interior. Snow and ice excavated on an annual basis. (various NZAHT reports) 1989/90 Butylclad (butyl rubber) installed on roof.</td>
<td>removed from interior but assume some ice remains in subfloor, assume this is approximately the same as the volume removed in 2008 (4 tonnes, see below).</td>
<td>4</td>
<td>Conservator Lyn Campbell provided unpublished data from one data logger (RH typically 70-85%) and some hygrometer data (RH 51% to 70%) during January 1991 and similar data for 1992.</td>
</tr>
<tr>
<td>1991-92</td>
<td>Ice continuously removed from interior, significant hoarfrost formation on lower walls.</td>
<td>As for 1980s above.</td>
<td>4</td>
<td>Three loggers, one in the apex. Exterior T: -40 to +0°C Interior T: -40 to +5°C Exterior RH: 60-80% occasionally 50-90% Interior RH: 50-90%, but less frequent variation except during storms, increases in May (Mason 1999).</td>
</tr>
<tr>
<td>1999</td>
<td>Butyl rubber ‘skirt’ installed along base of SE wall in January 1991. Ice was continuously removed from interior, but significant quantities existed in the floor, walls and roof. Ice lens stated to be forming under the floor.</td>
<td>Water was observed to flow under the hut (Mason 1999: 17). At least 4 tonnes in subfloor and smaller quantities in walls and roof (a further 4 tonnes, 8 tonnes total in hut). Hoarfrost on some walls.</td>
<td>8</td>
<td>At ~1.7 m above floor, galley: For Aug 1999 - Aug 2002 T: -35.1° to +9.4°C (ΔT_{annual} = 44.5°C) RH: 59% to 87.3% (ΔRH_{annual} = 28.3%) For 23 Dec 2001 - 20 Jan 2002 T_{av} +3.7°C, RH_{av} 82.7% T_{max} +7.8°C, RH_{max} 93.1% (Held et al 2005).</td>
</tr>
<tr>
<td>2000-2002 (Held et al 2005)</td>
<td>Ice continuously removed from interior, but significant quantities exist in the floor, walls and roof. Ice was previously removed from stables. Concerns expressed about external meltwater entering the hut.</td>
<td>Estimated ice quantity is similar to 1999, ie 8 tonnes.</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>2008-09</td>
<td>Removed ice from subfloor, installed ‘vortex generators’ outside hut to reduce formation of snow drifts.</td>
<td>Estimated ice removed from subfloor: approx 4 tonnes (4000 kg) [as stated by Nigel Watson at 2009 Mawson’s Huts Foundation].</td>
<td>4</td>
<td>Not available.</td>
</tr>
</tbody>
</table>

25 Based on Watson’s estimate given below for 2008-09.
26 Based on approximately 10% of space between outer and inner walls lower walls and 5% of upper walls and roof being filled with infiltrated snow or ice. This is known to be present (evident from meltwater stains) but cannot be easily inspected and varies according to temperature and air flow.
4. Temperature, RH, ice and phase changes

Table 4.6: Temperature trends AAE hut (during the period 6-18 January), years 2000-2006

<table>
<thead>
<tr>
<th>6-18 January of year</th>
<th>Mean exterior</th>
<th>Max.</th>
<th>Min.</th>
<th>Mean apex</th>
<th>Max.</th>
<th>Min.</th>
<th>Mean centroid</th>
<th>Max.</th>
<th>Min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>-0.6651</td>
<td>8.17</td>
<td>-9.24</td>
<td></td>
<td></td>
<td></td>
<td>-2.68617</td>
<td>0.888</td>
<td>-7.57</td>
</tr>
<tr>
<td>2002</td>
<td>2.45722</td>
<td>12.43</td>
<td>-4.575</td>
<td>0.75122</td>
<td>2.597</td>
<td>-2.041</td>
<td>0.258832</td>
<td>1.322</td>
<td>-0.737</td>
</tr>
<tr>
<td>2003</td>
<td>-0.5242</td>
<td>14.21</td>
<td>-7.49</td>
<td>-1.67015</td>
<td>5.237</td>
<td>-5.871</td>
<td>-2.11683</td>
<td>0.927</td>
<td>-5.703</td>
</tr>
<tr>
<td>2004</td>
<td>0.819402</td>
<td>10.92</td>
<td>-9.55</td>
<td>-0.66788</td>
<td>5.228</td>
<td>-7.32</td>
<td>-1.47297</td>
<td>0.423</td>
<td>-6.981</td>
</tr>
<tr>
<td>2006</td>
<td>-0.7984</td>
<td>8.82</td>
<td>-9.53</td>
<td>-2.06853</td>
<td>2.271</td>
<td>-8.69</td>
<td>-2.5286</td>
<td>1.297</td>
<td>-8.22</td>
</tr>
</tbody>
</table>

Note: No apex data collected in 2001, apex sensor was relocated in 2006, NE workshop is nearest comparable sensor.

Figure 4.9: AAE main hut - comparison of average exterior temperatures, 6-18 January

Figure 4.10: Trends of mean external, apex and centroid temperatures 6-18 January, 2000-2006

Note: the mean exterior trend line is the same as shown in Figure 4.8a above.
Figure 4.11: Total duration of temperatures above 0°C during January, 2000-2006

![Graph showing hours of temperatures above 0°C for different locations over the years 2000 to 2006.](image)

Table 4.7: Risk management assessment (following page)
## 4. Temperature, RH, ice and phase changes

<table>
<thead>
<tr>
<th>Risk No.</th>
<th>The Risk - What can happen and how it can happen</th>
<th>Consequence</th>
<th>Description and Adequacy of Existing Controls</th>
<th>Likelihood Rating (a)</th>
<th>Consequence Rating (b)</th>
<th>Overall Risk Level (a+b)</th>
<th>Risk Priority</th>
<th>Treatment controls</th>
<th>Risk rating after treatment/controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High external temperatures (from climate change or natural variation) deplete the quantity of ice in the verandahs and thus reduce the thermal buffering that maintains low temperatures in the centroid.</td>
<td>Interior temperatures rise leading to more meltwater and increased risks of corrosion and biodeterioration. Meltwater re-freezes around artefacts reducing their visibility to visitors and requiring extensive (and expensive) removal treatments that may also risk damage (see details in risk 4). Hoarfrost can form on cold surfaces (eg walls, roof) when RH is high and internal temperatures are higher than surface temperatures.</td>
<td>Overcladding was stated to have improved insulation of centroid. High exterior mean temperatures in January 2002 reduced ice volume in the verandahs to about 40% of capacity. Detailed data on summer temperature variability inside the hut is only available for the past ten years and is not available for the period prior to major ice removal.</td>
<td>5 (Climate scientists generally agree that external temperatures will rise significantly within the next 20 years.</td>
<td>4 (melting of verandah ice occurred in 2002 when temperatures were said to be the highest recorded since 1951 in Terre Adelie). Ice melted in centroid in 2002.</td>
<td>9</td>
<td>1</td>
<td>Install additional insulation in roof and walls?</td>
<td>Requires further investigation. Quantifying the retention of ice in verandahs by hygro-thermal modelling would be useful.</td>
</tr>
<tr>
<td>2</td>
<td>Increased ablation of ice in verandahs from non-thermal causes (such as increased sublimation from winds).</td>
<td>Less thermal protection for the building materials and centroid contents, increased temperatures result. Increased physical damage to verandah timbers.</td>
<td>No existing control addresses this risk as it appears to be uncontrollable, being dependent on the climate although overcladding partially reduces sublimation.</td>
<td>3 If winds increase as expected, sublimation will increase resulting in loss of ice from verandahs.</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>Nil - requires evaluation of treatment options. This could include alternative strategy in 1 above</td>
<td>Not assessed - requires thermal modelling to estimate effectiveness, particularly whether sublimation (risk 2 can be controlled).</td>
</tr>
<tr>
<td>Risk No.</td>
<td>The Risk—What can happen and how it can happen</td>
<td>Consequence</td>
<td>Description and Adequacy of Existing Controls</td>
<td>Likelihood Rating (a)</td>
<td>Consequence Rating (b)</td>
<td>Overall Risk Level (a+b)</td>
<td>Risk Priority</td>
<td>Treatment controls</td>
<td>Risk rating after treatment/controls</td>
</tr>
<tr>
<td>---------</td>
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<td>--------------------------</td>
<td>---------------</td>
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<td>------------------------------------</td>
</tr>
<tr>
<td>3</td>
<td>Temperature data from monitoring sensors may not accurately reflect conditions occurring inside the AAE main hut.</td>
<td>Innaccurate data from sensors leads to an misinterpretation of conditions in the hut.</td>
<td>Hoarfrost is known to form on sensors. Melting is known to occur even when sensor data reports T&lt;0°C.</td>
<td>5</td>
<td>Unknown. Risks from higher temperatures has not been quantified.</td>
<td>Unknown</td>
<td>3</td>
<td>Supplement existing monitoring with leak detectors to directly measure melting at surfaces, then re-assess risks.</td>
<td>Not determined.</td>
</tr>
<tr>
<td>4</td>
<td>Meltwater forms at walls or roof and drips onto artefacts and re-freezes (Godfrey 2002).</td>
<td>a) problems related to wetting (eg corrosion, biodeterioration, etc) b) ice accumulates on shelves, dislodges artefacts or damages shelves c) damage from attempts to remove the ice from the artefacts</td>
<td>Plastic sheeting used to minimise snow on artefacts and shelves. Shelves reinforced using stainless steel brackets (Berry 2010). Some artefacts packed in boxes. Treatments are labour-intensive.</td>
<td>4</td>
<td>2-3</td>
<td>6-7</td>
<td>5</td>
<td>Improve insulation to reduce risks of melting.</td>
<td>While hoarfrost was said to have been reduced by overcladding, it appears to continue to be a problem.</td>
</tr>
</tbody>
</table>

**Likelihood Rating:** 1 rare, 2 unlikely, 3 possible, 4 likely, 5 almost certain.

**Consequence Rating:** 1 insignificant, 2 minor, 3 moderate, 4 major, 5 catastrophic.

**Level of Risk:** <5 low risk – manage by routine procedures, 5 medium risk – specify management responsibility, 6 & 7 high risk – needs senior management attention, >7 extreme risk – detailed action plan required.
4.5 DISCUSSION

4.5.1 Does ice and meltwater inside buildings cause damage, and if so, how? (research question 1).

The observations summarised in Table 4.1 show:

- Meltwater occurred inside buildings at six sites, including even the ‘coldest’ sites on Ross Island;
- Extensive meltwater staining at eight sites indicated significant localised wetting/drying cycles on a regular basis;
- Corrosion is evident outside buildings at all sites within 1 km of the sea and on some artefacts inside buildings;
- There is little evidence of permafrost heaving of buildings or ‘ice-jacking’; and
- Biodeterioration was observed at seven sites and corrosion at ten sites including the colder southern sites.

While ‘freeze-thaw’ damage has been frequently reported (see sections 2.4.1 and 4.2.1) no damage was found by the author at any site that could be attributed to freezing of water rather than melting. Defibred wood, which some have attributed to freezing of water, was found in sheltered positions in among the debris around the AAE main hut.\(^27\)

At many sites, particularly on Ross Island, removal of ice, patching of timbers and installation of barriers to exclude snow ingress had been undertaken with the specific intent to reduce high humidity inside buildings. Ice ingress, however, had continued to occur to some extent at all of the early sites although the primary mode of ingress varied from particle ingress (Cape Denison) to meltwater flow to hoarfrost formation linked to subfloor ice (eg at Cape Evans).

At five major sites that the author was unable to visit (three being in the Antarctic Peninsula), the literature showed:

\(^{27}\) Defibred wood observed at the huts at Ross Island, Cape Adare and Cape Denison was subsequently found to be due to salt damage, not freezing, discussed in Chapter 5.
4. Temperature, RH, ice and phase changes

- Meltwater occurred inside buildings during summer at two sites, but information was unavailable at three sites;
- Corrosion is reported at three sites and no information was available at two sites;
- Ice ingress and accumulation has occurred at four sites and possibly at a fifth;
- High humidity and periodic wetting and drying are known to occur at three of the sites and could not be determined at the others; and
- Defibred timber is reported at Ross Island sites (Blanchette et al. 2002) and at Wilkes.

Arenz and Blanchette (2009) documented biodeterioration problems related to meltwater or high RH at eight Antarctic Peninsula sites and Spude and Spude (1993) reported on East Base showed significant damage from meltwater and high RH although no monitoring data was available.

All of these observations indicate that Antarctic historic sites are not in ‘near-perfect’ condition and significant deterioration occurs that is associated with moisture but no substantiated evidence of damage due to freezing processes. Periodic wetting and moisture transfer is a significant problem at all the historic huts: conditions inside buildings are not always dry, nor are they always below freezing.

To further analyse the first research question, the following aspects were considered:
- What is the evidence that thermal expansion and contraction of building materials causes damage in Antarctic conditions?
- Does phase-change, particularly freezing, cause damage?
- How does ice enter building?
- How does accumulation of ice cause damage?
- How does ice affect temperature and RH inside buildings?
- How can interior temperatures and RH be controlled to avert damage?

*Expansion and contraction damage*

Visual observations at 12 sites recorded in Table 4.1 showed that damage due to thermal expansion and contraction is neither prevalent nor severe despite seasonal variations exceeding
40°C and diurnal variations exceeding 10°C. Analysis of literature relevant to these observations enables further inferences below.

When dissimilar materials are joined, dimensional change due to temperature and/or relative humidity changes may cause failure of the joint unless any stress produced by the change is absorbed by elastic (reversible) or inelastic deformation. The most vulnerable items are adhesive joints in timber, such as in plywood (used for Venesta boxes for sledging equipment). While Venesta boxes at the Ross Island sites appeared substantially intact during the author’s visit in 1993, Blanchette, Held and Farrell (2002: 317) presented evidence of substantial damage, however they ascribed this to defibring not freezing/thawing.

Timber has a small thermal coefficient of expansion but a significant response, albeit relatively slow, to humidity change (Olstad et al 2001). This may be sufficient to prevent expansion damage to nailed metal/timber joints. The rapid temperature fluctuations up to 8°F (4°C) with up to three peaks per hour during Föhn gusts at Cape Denison reported by Madigan (figure 4.2) are far shorter than the response time of timber so they are unlikely to have an adverse effect.

Differences in thermal expansion of conjoined materials can be significant when large diurnal or annual temperature ranges occur. Structural steel frameworks were installed inside seventeenth century Russian wooden churches at Kizhi Pagost after the 1950s (Piskunov in Kelley et al 2000). During winter, the steel shrank so much by comparison with the timber that it failed its purpose of supporting the weakened original timbers (Yuri Piskunov, personal communication Kizhi, Russia 1997).

For unheated Antarctic buildings, higher risk of damage would be expected where the temperature differences are accentuated by differences in surface reflectivity, heat capacity or thermal coefficients of expansion. These are most likely to occur under metal fittings (such as ridge-capping or the lead sheet repairs by the 1977 ANARE on the Workshop roof at Cape Denison and bronze boxes housing the Memorial and Proclamation plaques), and at thermal bridges (such as bolts in timber). Inspection in 1997 of timber under the lead repairs to the Workshop roof that had been torn away by the wind revealed wood with fresh colour stained by
melted snow/ice but no cracks that appear related to temperature changes. The Memorial and Proclamation plaques were stained by corrosion products and had suffered severe defibring\textsuperscript{28} but damage attributable to thermal expansion-contraction damage was not evident.

Failure of silicone adhesive used by ANARE in 1977 is unlikely to be due to temperature changes, since the silicone itself was still flexible and strong when examined in 1985 and 1997. Most silicones are rated for use below -20°C. The silicone was believed to be an acetic acid-curing type (Rod Ledingham personal communication to the author 1985) which forms lead acetate on the metal surface, which could cause it to detach from the metal surface, especially with bending of the lead by wind. Detachment of paint films observed at Dumont d’Urville (figure 2.21) and at Davis (figure 2.13) could not be attributed to thermal stresses, although the relatively deep colour of the paint would absorb heat and could exacerbate other deterioration processes. Paint films of various types are known to become brittle at low temperatures but where the paint is securely attached to the substrate the risks of damage may not be significant, as discussed by Michalski (1996) in the context of freezing in laboratory conditions for museum pest control. Paint on timber exposed to the severe climate at Moor Pyramid (70°18’S 65°08’E) for approximately 12 years did not deteriorate even though about 1.5 mm of surface has been removed by wind action (figure 4.12) and water stains indicate exposure to thawing conditions.

Figure 4.12: Timber exposed at Moor Pyramid (author’s photo 1993)

\textsuperscript{28} Discussed further in Chapter 6 and shown in figures 5.5 and 5.4.
Phase change effects

Phase changes that occur in Antarctic historic buildings are:

- Freezing of water;
- Melting of ice;
- Evaporation (liquid water to vapour);
- Sublimation\(^{29}\) (ice forms vapour directly without the liquid phase, confusingly sometimes called ‘ablation’);
- Hoarfrost\(^{30}\) (vapour directly forms ice without transitioning through the liquid phase); and
- Condensation (vapour to liquid water).

Are freezing processes damaging wood?

As reported in Table 4.1, the author found no evidence of damage due to cyclic freezing and thawing of unconstrained wood even among artefacts in the meltwater pool on the western side of the main hut where freezing and thawing occur often daily during summer. Outdoor artefacts and exterior timbers are typically exposed to about 20-40 freeze-thaw cycles per year (see details in Table 4.3d), typically less than 12 hours duration\(^{31}\). The exceptional conditions during 1-18 January 2002 produced freeze-thaw cycles almost every day throughout the hut interior. Defibring damage of several pieces of timber was observed, but as discussed in Chapter 5, this is due to salt processes not freezing and thawing (see also Appendix F).

Godfrey (2002: 35) cited damage from expansion of freezing water in constrained spaces and reported damage of the Workshop roof as evidence.

“A … problem is the impact of accumulated water that refreezes after being trapped inside building voids... as the snow and ice melts accumulates in the lower regions of..."

\(^{29}\) Archaeologist Anne McConnell observed a space between the walls and the ice inside the hut immediately adjacent to gaps in the walls with no evidence of melting. This observation could be explained by sublimation.

\(^{30}\) See figure 4.14. Hoarfrost generally appears as fine ice crystals deposited on surfaces.

\(^{31}\) These dates include some brief discontinuities in monitoring and avoid longer periods when equipment was not operational. While temperatures may exceed 0°C the amount of actual melting could not be determined. The general pattern was that there was one freeze-melt-freeze cycle per day outside the hut and at the living hut apex and there appear to be fewer elsewhere in the hut.
these spaces and then expands as it refreezes, physical damage to the building fabric is likely. This is a likely cause of the severe damage that has occurred to the structural timbers in the workshop roof and to the tongue and groove boards in the same area. Circumstantial evidence for this process is provided by the extreme damage done to the structural timbers and ceiling boards at plate height on the southern workshop walls. Large masses of solid ice can be seen protruding from these shattered timbers”.

Godfrey did not compare the conditions at the roof with those at the archaeological deposit which extends across the floor and is up to 600 mm deep and where melting cycles also occur yet no comparable damage is evident. Similar melting and refreezing in equally constrained spaces may occur at the building footings although these have not been inspected. For the expansion in volume due to phase change from water to ice (around 10%) to cause shattering of wood would require the stress from volume change to exceed the ability of the wood to deform to accommodate the expansion. While the damage cited is of concern, further examination would be beneficial as there may be several explanations for the damage cited. Preventing melt formation, however, would avert the problem.

Several researchers including Daniels & Kibrya (1998) and Carrlee (2009) have studied risks of freezing damage of composite materials in simulated museum pest treatments of dry materials with no damage or loss of strength due to elastic behaviour of materials. Bodig (1982: 64-66) cites extensive research showing that timber strength increases at lower temperatures and that the permanent effect of ten freezing-thawing cycles on crushing strength of pine is minimal and that small reduction in crushing strength is greater at low MC. The greatest loss in timber strength occurs when free water is present. This suggests damage to wood by freezing is unlikely whereas thawing damage is possible. The extensive review by Carrlee (2009) examined diverse processes implicated in freezing damage, including the role of free and bound water in cell walls. No damage to wet wood was found due to the 0.01% expansion of water at 4°C\(^{32}\), nor due to the 9% decrease in density when freezing occurs at 0°C.

\(^{32}\) This is the temperature at which water reaches its highest density.
‘Freeze-thaw damage’ is regularly raised as a risk for Antarctic historic buildings, so the expense of conclusive testing may be worthwhile. Conclusive evidence regarding whether freezing itself damages wood could be produced by microscopic examination of freezing events in thin sections of wood soaked in water, constrained by bolts or clamps then subjected to freezing at a range of thermal gradients, which controls ice crystal size. A microscope equipped to observe freezing of materials is available at the National Research Institute for Cultural Properties, Tokyo (Takeshi Ishizaki, personal communication, 2000).

*Ice ingress*

Three modes of moisture ingress\(^{33}\) cause ice accumulation in all pre-IGY buildings (Table 4.1). Ice ingress, and the damage it allegedly causes, is perhaps the most complex management issue for the AAE hut so this is examined in detail. Removal and exclusion of ice from the three Ross Island huts has evidently been more successful than from the AAE huts. At Ross Island sites, ice removal can be undertaken as part of annual maintenance due to better logistics, and ice ingress appears to be less problematic due to much lower wind speeds and their more air-tight structures.

The 2007-12 Cape Denison site management plan (DEWHA 2008: 61) states that overcladding of the living hut in December 2006 [was] “considered the only option to secure the interior … from future snow/ice ingress and preserve the significant fabric”…. “This work was done to reduce snow and melt water ingress, protect and retain the remaining cover battens and maintain the structural integrity of the roof plane.”

*Ice accumulation vs ablation*

In Antarctica natural microclimates of net moisture accumulation (‘accumulation zones’) arise due to snow drifting and high humidity. Microclimates of net moisture loss (‘ablation zones’) arise due to high wind speeds and low humidity. Well-known examples of broadscale ablation zones are the Vestfold Hills near Davis (400 km\(^2\)) and the Dry Valleys (4,800 km\(^2\)) in the Ross Dependency. Accumulation and ablation zones also exist at the smaller scale (<10 km\(^2\)): most

\(^{33}\) These are wind-driven ice particles, meltwater flows and vapour permeation.
buildings at Wilkes have been progressively buried under snowdrifts, evidence of an accumulation zone.

It is important to consider whether a site is usually an accumulation or ablation zone since if a historic building is in a natural accumulation zone then removal of ice, and keeping it out, may be very difficult. Ratios of accumulation and ablation can vary at one location from year to year. Snow drifts form in the lee of barriers such as hills and buildings. In locations with strong winds where most precipitation is in the form of blowing snow, any hollow in the ground will fill with snow and ice. The persistence of the snowdrift will depend on relative rates of deposition and ablation. Many historic sites, such as Cape Denison, Port Martin and Wilkes appear to have been unwittingly built in accumulation zones where expeditions had sought protection from the winds, not anticipating snow drift problems. Theoretical understanding of ice accumulation and ablation processes improved after the IGY, and modern polar building practice now identifies appropriate locations and designs (Strub 1996, Incoll 1991).

*The history of ice ingress issues*

Contemporaneous expedition records show that ice and moisture ingress occurred at many historic huts soon after construction, including Nordenskjold’s Snow Hill Island hut, Byrd’s East Base, some British *Operation Tabarin* huts and Wilkes (see Table 4.1). Scott allegedly blamed Shackleton for leaving the window of the Hut Point building open, allowing snow ingress (anon 1983). Cherry Garrard (at Cape Evans) commented on the ceiling joists sagging under the weight of ice and that water dripped through when the hut warmed up (*ibid*). Caretakers at the Ross Island huts in the 1960s mention the almost annual task of removal of the snow build up although every conceivable crack has been filled or sealed (*ibid*).

Windborne ice ingress has been a particular problem for the AAE main hut due to the exceptional winds[^34], its location in a hollow, the volume of blowing snow, and gaps in the structure. However, the Magnetograph House has generally been free of these problems due to the 30

[^34]: Cape Denison is the windiest place on earth at sea level with an annual average wind speed of 80kmh and gusts over 300kmh (Wendler 1990: 266).
tonnes of rock the AAE placed around the structure that have minimised damage to the structure, its more open location that minimises drift accumulation and the greater care taken during construction (described in AAE Scientific Reports Mawson 1929 Series B Vol 1 Terrestrial Magnetism) including three layers of tar paper and two layers of lining boards. Even tightly constructed modern buildings at Cape Denison experience ice ingress, such as the ‘Apple Hut’ used for accommodation in the 1980s which filled with snow in one year (author’s observation, 1985).

Mawson found that ice particles are especially small (0.1-0.4 mm diameter) in Antarctica, as fine as dust (Jacka and Jacka 1988: 61). The hut timbers travelled as deck cargo on an overloaded sailing ship that was frequently wet by waves during the voyage. The timbers dried after the hut was hastily erected, possibly the initial reason for gaps in the tongue and groove cladding. Snow was reported between the boards of the cladding by most researchers visiting the site since 1985 (eg Blunt 1985, (Hughes, JD 1986)). The tongue of the tongue and groove cladding has been damaged by vibration and wind flow, further increasing the risk of snow penetration (figure 4.22).

Figure 4.13: AAE workshop during BANZARE, snow ingress (Chester 1986: 61)
Mawson’s diaries (Jacka and Jacka 1988) state that:

"Bickerton and Hodgeman sealed up the windward window yesterday. Today they put in extra struts on windward side of the roof. The verandah filled with drift coming in at sides of trap door… Hut leaking and I spend much time in securing materials against damage by wet." (ibid: 83)

6.6.12 "It snowed and blizzarded heavily last night… the store is full- the snow is most insidious."

8.6.12 "The [store] roof should have been double, the only way to make a tight roof unless metal-sheathed." (ibid: 89)

The Living Hut, cleared of ice in 1977 (Ledingham 1979), had re-filled by 1981 (Williams & Keys 1982). Ledingham and his team instituted Mawson’s proposed solution to ice ingress by covering the Workshop roof (which had the largest gaps and thinner cladding) with lead sheeting sealed with silicone caulking. This had also failed by 1984 since the lead had been perforated by vibration against raised nail heads and the caulking detached from the metal. The lead sheeting was badly ‘torn’ by 1997 (figure 8.26).

Snow drift around the Cape Denison buildings accumulates mainly during winter when strong katabatic winds blow from the polar plateau. During the AAE occupation (1912 and 1913) snow
drift covered the apex of the Living Hut (figure 4.15). The huts were not visited again in winter until the 1990s when Gadget Hut was occupied. Comprehensive video records by Jim and Yvonne Claypole during 1998 show that, in winter, snow drifts rarely covered the top of the southern wall of the hut. Photographs presented at the 2008 Mawson’s Hut Foundation workshop (similar to figure 4.16) indicated that snow drift present in early December 2007 covered the tops of the southern wall, implying that snow drifts may be quite variable from year to year.

Figure 4.15: Cape Denison, early winter (Mawson 1915 vol 1: 130)
The available AWS wind records from Cape Denison and other nearby sites indicate no significant reduction in winds since 1912-13 (Wendler 1990: 266). The katabatic winds carrying the drift snow to Cape Denison are funnelled by the topography of the polar plateau and the wind ‘catchment area’ covers 10% of the Antarctic continent (Parish & Wendler 1991). Assuming that wind speeds on the polar plateau have not changed then the apparent reduction in drift at Cape Denison in some years may be due to reduced precipitation or increased sublimation on the polar plateau with less snow available for transport to the coast.

If a firmly packed snow bank forms in winter and extends above the walls and persists until summer it may reduce ice particle ingress by filling gaps in the roof and walls during the time of greatest risk during winter blizzards. If no substantial snowbank forms snow can find its way through any gap in the building. In summer however, an extensive snowbank may increase the volume of meltwater that can enter the hut in warm years. Thus there are advantages and disadvantages in the presence of the external snow bank, depending on external temperatures. If melting of the snowbank could be prevented then it’s presence would be wholly beneficial by increasing thermal buffering of interior temperatures and minimising ice loss from the verandahs.
4. Temperature, RH, ice and phase changes

Figure 4.17: AAE main hut interior, excavation in progress, 1985 (Project Blizzard)

Repairs to the skylights in 1998, (Ashley 1997) and overcladding of the roof (on the workshop in 1998 and the Living hut in 2006) attempted to prevent ice particle ingress however by summer 2007-08 windborne particles again penetrated and accumulated on shelves and other near-horizontal surfaces, said to risk their collapse\(^\text{35}\). The author estimated from photographs there was approximately 20 kg on the living hut shelves alone. Some reduction appeared to coincide with diminished snowdrift rates reported during the mid-1990s to 2007, suggesting it may be too early to determine whether the recent repairs are sufficient to solve the ice ingress problems. If ice ingress prevention strategies (such as overcladding) are to be effective they must work even when snowdrift rates are high.

\(^{35}\) This is not surprising as small ice particles have been observed to penetrate even the stitching holes in tents during strong winds (Rupert Summerson, personal communication 1997). Concern was expressed by some participants at the 2008 Mawson’s Hut Foundation workshop that ice ingress will also raise RH but as previously discussed as little as 1.3 kg of ice could produce 100% RH at 0°C. It is unlikely that sufficient particle exclusion could be achieved to keep RH low even if all ice and could be removed.
As at 2010 no overcladding has been carried out on some vertical parts of the southern verandah wall, nor the northern walls. MHF architect Adrian Welke (Welke 2009) stated that the overcladding would only stop ingress if continued right down to the ground. However, this would not prevent water ingress, nor would it address the cycling melting and hoarfrost problem within the hut. At the SW corner Welke noted the importance of maintaining ice in the verandah to reduce windborne ice ingress, his favoured approach being patching or overcladding of the outer walls of the Living Hut and Workshop within the verandah space. He noted that gaps can be seen through the Workshop wall, and at the corners of wall to floor junction, concluding more radical intervention is needed.

**How does ice accumulation cause damage?**

Blunt (1991) considered the weight of accumulated ice to be the cause of structural damage to the AAE main hut and to other Antarctic historic buildings. Various visitors have raised concerns of
‘ice-jacking’, plastic flow and freeze-thaw damage to timber. Plastic flow occurs in glaciers only where ice depth is greater than 11 metres (Prof Bill Budd, personal communication, Hobart 1992), whereas ice is less than five metres deep inside the hut.

Ice accumulation at Wilkes is also reported to produce ‘ice jacking’ and ‘freeze-thaw’ damage. Although the author has not visited Wilkes, photographs appear to show repeated melting and refreezing (eg figure 4.19) and the huts are half-filled with ‘névé’ ice. No visible structural failures, nor major wall or roof distortions are evident. Further investigation and accurate measurements of the building over several years would be required to definitively resolve these concerns. However, the lack of structural distortions suggests any ice-jacking is not significant although the structures have equal depths of ice both outside and inside the structures that may constrain any nett movement.

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36 Ice-jacking is stated to occur when upward forces occur at the end of a freeze-thaw cycle and ice contracts 9% by volume forming a space that can be infiltrated by liquid water underneath an area of ice. This water causes a hydraulic jacking effect when it freezes. Water is essential for the process to occur, permanently frozen ice cannot cause ice-jacking.

37 Névé is snow that is bonding and compacting through partial melting and the weight of snow accumulating on top, usual density exceeds 550 kg/m$^3$. See also glossary.
Ice has accumulated under the Old Paint Store (figures 2.13, 4.20) at Davis, which was built on frozen gravel and was reported by several expeditioners to be suffering from permafrost movement. The ice lens under the building did not appear to completely melt from year to year and was still frozen during the author’s visit in February 1992 when melting could normally be expected. There is no apparent tilting or deformation of the structure and the diagnosis of permafrost damage is therefore doubtful.
Mason (1999:20-21) reviewed ice heave issues at Cape Evans citing engineering studies that describe the mechanism of damage, noting that the presence of water is essential for such damage to occur. The Cape Evans hut is built on loose scoria that is frozen “several inches” below the surface. Mason described how continued growth of the ice lens under the hut could occur but concluded there was no distortion of the hut (ibid: 21) although recommending assessment by specialists.

Ice accumulation within buildings has certainly caused some problems. Blunt (1991) identified damage to the collar ties of the AAE main hut (figure 4.21) in 1984 and concluded this was due to the weight of ice that had accumulated on the platform in the living hut. Project Blizzard excavated ice to install steel building props to support the platform and removed ice from the platform to reduce the load (see figure 4.17). At that time there was approximately two cubic metres of névé on the platform (approximate density 550 kg/m³) (National Snow and Ice Data...
Centre, http://nsidc.org/glaciers/glossary/). The platform was not designed to carry such loads but if there had been ice underneath the platform it could otherwise support the load. Similarly, the weight of re-frozen meltwater accumulating on shelves has bowed the shelves and brackets.

Figure 4.21: AAE hut, broken collar tie (author’s photo 1985)

Measurements of the AAE main hut by architect (Marshall 1987) found no distortion of the overall building structure by the ice. Ashley (1997), also an architect, found no measurable distortion of the shape of the building and reported limited damage to only two structural members inside the building. Removal of further ice from the building during 2002-03 and subsequent years has revealed no further damage, so structural damage from ice ingress thus far is limited.
4.5.2 What is the nature of the hygrothermal behaviour in *Terra Nova* hut and AAE main hut and what deterioration is produced by these variations? (research question 2)

Characteristics of the two huts are provided and the temperature and RH variations are summarised and compared to assist the analysis of deterioration risks which follows.

**Table 4.8: Summary of major building characteristics, temperature and RH data, and deterioration risks, AAE main hut and *Terra Nova* hut**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>AAE main hut</th>
<th>Terra Nova hut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude, °S</td>
<td>67</td>
<td>77</td>
</tr>
<tr>
<td>Climate (exterior)</td>
<td>Extreme wind</td>
<td>Moderate wind</td>
</tr>
<tr>
<td></td>
<td>Warmer annual temperature range (-30 to 0°C)</td>
<td>Colder annual temperature range (typically -40 to 0°C, Mason 1999: 39)</td>
</tr>
<tr>
<td>Total hut volume, m³</td>
<td>347 including verandahs</td>
<td>378</td>
</tr>
<tr>
<td>Insulation, U value (Pearson 1992)</td>
<td>433.63</td>
<td>497.43 (least efficient)</td>
</tr>
<tr>
<td>Current management strategy for ice ingress</td>
<td>From 1997, ice has been retained in the verandahs to provide thermal inertia but ice from the centre of the hut was removed to allow visitor entry. Overcladding of the roof and part of walls protects it from wind, excludes ice particles and improves insulation. Water proof, vapour-permeable membrane was installed under the overcladding.</td>
<td>From 1960s, ice has been removed from the interior of the hut, overcladding with butyl rubber membrane provides historically sympathetic appearance, annual maintenance removes any ice ingress or hoarfrost. The artefacts are a key attraction for visitors. Ice removed from under floor in 2008-09.</td>
</tr>
<tr>
<td>Ice quantity in hut</td>
<td>Approx 121 m³ in verandahs (~60 tonnes) with ~49 m³ in the archaeological deposit and unknown subfloor quantity. Some continuing ice particle ingress and variable condensation/sublimation.</td>
<td>Ice regularly removed from interior since 1960s, 4 tonnes removed from under floor in 2008-09, minor condensation and sublimation problems.</td>
</tr>
<tr>
<td>Critical ice volume</td>
<td>0.491 kg</td>
<td>2.365 kg</td>
</tr>
<tr>
<td>Temperatures during January, centre of hut</td>
<td>T&lt;sub&gt;max&lt;/sub&gt; T&lt;sub&gt;average&lt;/sub&gt; (°C)</td>
<td>2000-2002, 1.7m above floor in galley -35 to +9.4 °C Late December 2001 to 20 January 2002, average temperature +3.7 °C, T&lt;sub&gt;max&lt;/sub&gt; +7.8 °C (Held et al 2005)</td>
</tr>
<tr>
<td>2000:</td>
<td>-5.3</td>
<td>-6.6</td>
</tr>
<tr>
<td>2001:</td>
<td>+0.9</td>
<td>-2.7</td>
</tr>
<tr>
<td>2002:</td>
<td>+1.3</td>
<td>+0.3</td>
</tr>
<tr>
<td>2003:</td>
<td>+0.9</td>
<td>-2.1</td>
</tr>
<tr>
<td>2004:</td>
<td>+0.4</td>
<td>-1.5</td>
</tr>
<tr>
<td>2005:</td>
<td>-0.2</td>
<td>-3.1</td>
</tr>
<tr>
<td>2006:</td>
<td>+1.3</td>
<td>-2.5</td>
</tr>
<tr>
<td>1999-2000:</td>
<td>apex 56-100% Centroid 80-99</td>
<td></td>
</tr>
<tr>
<td>January 2002: centroid average 96%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>January 2006: centroid consistently &gt; 90%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009-2010:</td>
<td>apex 92-100% shelf 93-100%</td>
<td></td>
</tr>
<tr>
<td><em>Higher RH, but less variable</em></td>
<td><em>Lower RH, but large variations</em></td>
<td></td>
</tr>
</tbody>
</table>
4. Temperature, RH, ice and phase changes

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>AAE main hut</th>
<th>Terra Nova hut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth hours (T&gt;0°C, RH&gt;80%)</td>
<td>Exterior: 21</td>
<td>Interior data only</td>
</tr>
<tr>
<td></td>
<td>Apex: 96</td>
<td>257 hours in 2000 and</td>
</tr>
<tr>
<td></td>
<td>Centroid: 0</td>
<td>120 hours in 2001 in darkroom ceiling (Held et al 2005)</td>
</tr>
<tr>
<td>Temperature gain by hut in summer</td>
<td>Centroid rarely over 0°C.</td>
<td>Mason 1999</td>
</tr>
<tr>
<td></td>
<td>In January 2002: mean centroid temperature was warmer than mean exterior</td>
<td>For a typical summer day max at apex ~+5°C, max at exterior 0°C, Thus apex often ~ 5° warmer than exterior.</td>
</tr>
<tr>
<td>Summary</td>
<td>Despite difficulties in comparability of the measurements (in terms of location within the building, lack of external temperatures for Cape Evans, etc) internal temperatures in the Terra Nova hut are surprising high given the more southerly location and generally colder climate. Terra Nova hut absorbs heat and has less efficient insulation. RH levels are lower but more variable in the Terra Nova hut and growth hours are much longer.</td>
<td></td>
</tr>
</tbody>
</table>

Analysis of AAE Main hut monitoring data

*Project Blizzard monitoring 1985*

RH measurements were consistently high (>95%) inside the hut during summer\(^{38}\). There was extensive ice inside the Living hut and the Workshop appeared to the almost completely filled. Mawson’s room in the Living hut contained a large accumulation of remarkable planar ice crystals up to 5cm across hanging from the roof (Chester 1986: 185). Their large size implied the air was still during crystal growth (Prof Bill Budd, glaciologist, personal communication, Hobart 1992) and that there was limited air ingress into the living hut void as large crystals will not form in moving air with low RH.

*ACR loggers January 1998*

Although there is limited data from this period it is useful for comparisons with later years because the hut contained ~340 m\(^3\) of ice (author’s estimate, see figure 4.8) at the beginning of the period. Approximately 40 m\(^3\) were removed during December 1997\(^{39}\). Distinct daily temperature and RH variations occurred over the four-week period in January 1998 at the apex.

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\(^{38}\) Blunt (1986: 105) undertook monitoring in early 1985 (late summer), sensors located on a shelf in Mawson’s cubicle; Hughes undertook monitoring in December 1985 (early summer), sensor located on Hodgeman’s bunk.

\(^{39}\) The remaining volume estimated by Ashley (2001: 82) was “301 m\(^3\) remain in in the Main Hut: 176 m\(^3\) in the verandahs (58% of total ice in the Main Hut,); 50.5 m\(^3\) in the living section (17% of total ice and 28% in living section space); and 74.5 m\(^3\) in the workshop (28% of total ice and 66% in workshop space)”.
(ACR A) with diurnal variation in the centroid being much smaller and rarely above -5°C. Apex temperatures varied from -10°C to +14°C ±1°C and were generally colder than the centroid (-6°C to -8°C ±1°C). At the apex nine freeze-thaw cycles occurred during the month with nil in the centroid. At the apex there was a 24°C annual range compared to a 14°C annual range for the centroid. RH at the apex is more variable (60 to 100% ±3% RH) than the centroid (95 to 98% RH ±3%) which is consistently high. Meltwater flows were evident on the walls and ceiling inside the hut, particularly at the western wall near Hodgeman’s bunk.
Figure 4.22: Ice removed during the AAP expedition 1997-98 (Ashley 2001: 83)
Integrated datalogger system, January 1999- December 2000

Analysis of results from January 1999 to January 2000 are discussed in detail in Ganther et al (2002), bound as Appendix K. Key data from this paper is summarised below.

Temperatures and RH were stable during winter, as expected since there was no sun. During October 1999, exterior temperatures increased markedly and internal RH increased: September 1999 ranged from -25.44°C to -12.56°C; in October 1999 the temperature range was -22.22°C to -4.59°C. While there is some variation, in both 1999 and 2000 temperatures rose steadily during October. During October the external RH is also very high (85-95%). Similar external patterns are evident for later years, such as 2003 which has fairly complete data.

During January and February for both 1999 and 2000 pronounced daily variations are seen for both internal and external sensors and RH. Internal temperature maxima occur at 19.00 to 20.00, three to four hours behind the outdoor maximum (16.00), due to the time taken to warm up the air inside the building through heat transfer from the structure. The external minima occurred around 06.00, whilst the internal minima occurred around 08.00-09.00.

Between January 1999 and January 2000, the greatest internal extremes of temperatures and RH were measured at the Living Hut apex\textsuperscript{40}. Temperature variations inside the hut near the apex (-24.4 - +3.3°C, average -13.5°C, ΔT = 27.7°C) are smaller than the external variations (-32.2 to +8.1°C, average -14.0°C, ΔT = 40.3°C), so even without significant ice in the core of the building offered some natural insulation. Variations in the Workshop, the most stable location, were an annual temperature range of 21.6°C (from -21.3 to -0.3°C), average -13.7°C, and RH range of 17% (from 101 to 84%), average 91%. The extreme daily temperature range during 26-31 January 1999 at the exterior was +2.8 to -10.4°C (range 13°C) and interior (T2) was -2.78 to -7.46 (range 10.2°C).

\textsuperscript{40} The Living Hut roof was overclad in 2006.
The annual variation outside the main hut (during 26 January 1999 to 6 January 2000, \(\Delta T=40.3^\circ\text{C}\)) is not as extreme as some locations in northern Russia. For example Kizhi, site of World Heritage listed wooden churches, experienced annual temperature variations from the -40s to above +30\(^\circ\text{C}\) although RH fluctuations were similar, approximately 30 to 100\% (Margarita Kisternaya, Kizhi 1997, personal communication). Despite these variations, wooden buildings and artefacts have survived there in reasonable condition for over three centuries. Many fungal and structural problems at Kizhi are of recent onset related to interventions in the building fabric (Kelley et al 2000) discussed further in Chapter 8.

Temperature variations recorded by the logger at the apex (TRH8) showed that some heat is transferred to the building interior via that part of the roof, whereas the ice-filled core of the building remains stable (TRH5). At the apex, temperatures and RH show an inverse relationship, *ie* RH of the air increases as temperature decreases and vice versa, suggesting relatively little air interchange with outside air, although the role of any moisture emitted from warming of moist timber needs to be considered.

Other key information derived from datalogging at Cape Denison during 1999-2000 included:

- Interior RH is lowest when exterior temperature is lowest (and exterior RH is highest) an hour after the exterior temperature maximum and three hours before the inside temperature has peaked;
- If RH variations occurred only as a result of temperature changes (i.e if the air volume is closed) then RH would be highest when temperature is lowest and vice versa;
- Absolute humidity trends inside the hut showed the mass of moisture in the air is higher during the day and less at night, implying evaporation is occurring during the day and condensation occurs at night; and
- Condensation could also occur on the surface of any ice remaining in the hut when it is colder than the air.

The data from 1985, 1998 and 1999-2000 at Cape Denison all show high relative humidity (rarely below 70\%, mostly over 90\%, always high away from the apex) inside the hut during
January. This occurs well before the formation of the meltpool outside the building, usually in early February (figure 4.1).

*Integrated datalogger system, 2000-2006 comparison of January temperatures*

The overcladding of the Living Hut roof in December 2006 was said\(^{41}\) to have made a substantial reduction in internal temperature variation and to have reduced RH, although photos and comments from observers in 2009 still show significant quantities of meltwater occur on the ceiling and walls and that some ice ingress is still occurring. Removal of ice in 1998 produced no measurable reduction in interior RH. This is not unexpected since the quantities of ice remaining are more than sufficient to saturate the air at prevailing temperatures if air interchange with the exterior is low (see Table 4.9). Monitoring reported in 2010 (Berry 2010: not paginated) provides graphs showing RH inside all locations in the AAE main hut was still high, typically 95-100\% at the Living hut apex and RH was reported to have increased from a minimum of 87\% in 2007 to 88\% in 2008 to 94\% in 2009. This most recent report recognises that hoarfrost formation appears to adversely affect the operation of the loggers but does not analyse the implications for accuracy of the monitoring and the significance of the results in assessing the efficacy of the whole conservation strategy for the building.

Temperatures in each winter during 2000-2006 follow similar trends with no differences in exterior and interior conditions, due to the absence of the sun. Temperatures during summer are of greater interest since this is the time when melting may occur, which could increase risks of corrosion and biodeterioration, and when loss of ice in the verandahs could reduce thermal inertia and resulting in loss of ice in verandahs with possible risks for anchoring of the building against the wind.

**Temperature and RH variations measured at Ross Island sites**

Monitoring data from three Ross Island huts over three years (Held *et al* 2005) summarised in Table 4.5 shows RH remained high (70-100 \%) throughout this period, despite regular ice

\(^{41}\) Vinod Daniel, presentation at Mawson’s Hut Foundation workshop, Sydney, 22 April 2008 and DEWHA 2008:89.
removal. While RH is generally higher in the AAE main hut annual ice removal at Cape Evans has not reduced RH to the levels that are recommended to reduce deterioration. RH is high inside all three Ross Island huts with similar variations and trends. No data are available for the apex of the roof of the *Terra Nova* hut that would enable similar locations to be compared with the AAE hut\(^{42}\).

During the monitoring period, temperatures in the centre of the Cape Evans hut (2 metres above the floor) ranged from \(-35.1^\circ\) to \(+9.4^\circ\)C (\(\Delta T= 44.5^\circ\)C) and RH varied from 59% to 87.3% RH (\(\Delta RH= 28.3\%\)). A comparable location in the centre of the AAE main hut (Workshop, T5) varied from \(-21.3^\circ\)C to \(-0.3^\circ\)C and 84-101% RH during the monitoring period from 1999-2000 (see Table 4.3). The large temperature variation in the centre of the Cape Evans hut implies an even larger variation occurs near the walls and roof.

Table 4.5 shows that despite the colder climate at Cape Evans, summer daily temperature maxima inside the *Terra Nova* hut are higher than in the AAE main hut. Held *et al* (2005) showed *Terra Nova* temperature maxima exceed that of the other Ross Island huts. Biological ‘growth times’ are also generally longer at *Terra Nova* (eg 257 and 120 hours in 2000 and 2001 respectively in the darkroom ceiling, although in January 2002 there were exceptional growth hours in the AAE main hut). ‘Growth hours’\(^{43}\) measured at *Terra Nova* hut were much higher than at the *Nimrod*, and *Discovery* huts, attributed by Held *et al* (2005) to entry of meltwater and the presence of ice under the floor, causing high RH. The high RH is not unexpected due to the low air exchange rate of 0.3 air changes/hour (Mason 1999) and the relatively low temperatures.

\(^{42}\) Exterior temperatures were provided in Figure 11 of Held *et al* (2005:51), but no summary exterior data are given. The exterior sensor only functioned intermittently (ibid: 46). The nearest location where temperature data is available (Scott Base, less than 50km away) has an average maximum temperature for January of \(-1.6^\circ\)C and an average minimum temperature in August of \(-41.4^\circ\)C from records during 1957 to 2007 (available at [http://www.antarctica.ac.uk/met/gjma](http://www.antarctica.ac.uk/met/gjma)). This gives an annual average temperature range of 43.0°C.

\(^{43}\) Time when temperature exceeds 0°C and simultaneously RH exceeds 80%.
Microclimate formation and behaviour

‘Microclimates’\footnote{Microclimates are localised variations in temperature and humidity within a larger area.} form in unheated buildings due to the effects of heat transmission, vapour transmission, air flow, materials and the building design. As discussed in the first chapter, unusual microclimates arise in Antarctic buildings because of the low solar angle (which produce rapid shade changes), lengthy summer daylight, variations in surface reflectivity and the cooling effect of the wind. The surface temperature of a dark material is warmer than a light-coloured surface of the same type since it absorbs more solar radiation. The low sun angle and the long hours of summer daylight warm walls more strongly than the roof, depending on the time of year (Strub 1996). Cooling by wind is expected to be significant at Cape Denison. Ice and water properties may be significant since ice is a poor thermal insulator but has high thermal inertia (due to its specific heat and latent heat) and liquid water can reduce thermal insulation of building materials.

The quantity of ice required to produce 100% RH inside the Ross Dependency huts at 0°C and the average summer are shown in the two right hand columns in Table 4.9 below. The quantity is calculated from the internal volume of the hut multiplied by the mass of ice that will produce 100% RH at 0°C (from the psychometric table, available online at \url{http://www.vaisala.com/humiditycalculator/?SectionUri=%2finstruments%2frhcalc} The critical ice mass is the absolute humidity at 100% RH at the temperature indicated, multiplied by the internal volume of the hut.
### Table 4.9: Ice mass inside several Antarctic historic huts and critical ice volumes

<table>
<thead>
<tr>
<th>Hut, location</th>
<th>Max building height, m</th>
<th>Internal volume, m³</th>
<th>$T_{\text{max}}$, summer, °C</th>
<th>$T_{\text{av}},$ summer, °C</th>
<th>Ice mass to produce 100% RH at 0°C with no ventilation, kg</th>
<th>Critical ice mass at $T_{\text{av}}$ (summer), kg</th>
<th>Estimated actual ice mass (in tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nimrod, Cape Royds</td>
<td>4.57</td>
<td>147</td>
<td>+2.5 (Held et al 2005)</td>
<td>-0.1</td>
<td>0.715281</td>
<td>0.710</td>
<td>‘nil’</td>
</tr>
<tr>
<td>Terra Nova, Cape Evans</td>
<td>4.22</td>
<td>378</td>
<td>+7.8 (Held et al 2005)</td>
<td>+3.7</td>
<td>1.839295</td>
<td>2.365</td>
<td>‘nil’</td>
</tr>
<tr>
<td>Discovery, Hut Point</td>
<td>4.27</td>
<td>180</td>
<td>+8.2 (Held et al 2005)</td>
<td>+2.0</td>
<td>0.875855</td>
<td>1.004</td>
<td>‘nil’</td>
</tr>
<tr>
<td>AAE, Cape Denison⁴⁶</td>
<td>LH 4.2</td>
<td>152.2</td>
<td>+3.3 (apex LH) (1999-2000)</td>
<td>-5.8</td>
<td>0.740584</td>
<td>0.491</td>
<td>326 m³ = at least 200 tonnes in summer 1999-2000</td>
</tr>
<tr>
<td></td>
<td>WS 3.6</td>
<td>73.7</td>
<td>-0.3 (workshop) (1999-2000)</td>
<td>-5.2</td>
<td>0.358614</td>
<td>0.248</td>
<td></td>
</tr>
</tbody>
</table>

*Notes: ‘Nil’ indicates there is no visible ice inside the building*

Ice ingress quantities each year for the AAE main hut was about an order of magnitude greater than the amount that will produce 100% RH with no ventilation. The mass of ice already inside the hut due to the archaeological deposit is at least four orders of magnitude greater than the critical ice mass, thus further ice removal by itself will not remedy the high RH temperatures also rise, which may increase deterioration.

**Buffering effects in the AAE main hut**

While the exterior air maxima and minima at Cape Denison differ by over 40°C per year, the annual range of temperature in the centre of the hut was less than 23°C per year in 1999-2000 (Ganther et al 2002: 5), so the building produced significant temperature buffering. Buffering can

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⁴⁵ Ice inside the hut was minimal such as hoarfrost on lower walls and in the subfloor (NZAHT website downloaded 2 March 2010). Subfloor ice was removed from the hut in 2008 (see figure 4.19).

⁴⁶ Total volume of Living Hut + Workshop = 225.9 m³. The temperatures shown were measured in 1999-2000 (Ganther et al 2002).
inhibit deterioration by reducing the extent or frequency of temperature and RH variations that leads to cracking of materials and by reducing the number of thawing cycles that produce wetting and biodeterioration. Thermal buffering can be provided by insulation in the building structure (including overcladding) and thermal inertia is contributed the ice inside the hut, in the verandahs and external snowbanks. Buildings promote RH buffering through moderating temperature changes, reducing evaporation losses and by moisture absorbed in the building’s timbers. Thermal buffering can be offset by thermal bridging\footnote{Thermal bridging is direct contact between the exterior and interior that permits thermal conduction, eg via bolts.}; and moisture buffering can be affected by mass transfer from direct air/water/ice interchange with the exterior via gaps in the building fabric or through diffusion through porous materials.

*Insulation and thermal bridges*

Both exterior and interior temperatures exhibit similar cycles, lagged by approximately three to four hours in 1999-2000 due to the time taken to heat up the structure. Thermal lag time for each January during 2000-2006 was variable but appeared to generally decrease (see Table 4.6) and a comparison of exterior to centroid temperature differences correlated against external temperature also indicated a general decrease in thermal insulation during 2000-2006, discussed further in 4.5.3.

Due to the low sun angle at high latitudes, heat transmitted from the sun is greater at the walls rather than the roof. However, heat loss is greater from the roof due to its thermal emissivity and heat loss from wind. Thus internal maxima in the hut are most affected by thermal conductance through wooden walls and thermal inertia of ice in the verandahs whereas internal minima are most affected by heat loss through layers of timber and the air layer in the ceiling. Heat absorption at the walls would be reduced in years when snow banks are high as they reflect more sunlight.

Construction materials used in all the early huts have been identified (Pearson 1992). Data on hygrothermal behaviour of those materials are available from engineering publications. At Cape Denison the original wall insulation comprises “two courses of tarred paper” (Mawson 1915: 86)
and Blunt (1991: 79) states “straw type insulation was found adjacent to the door to the living room” although the author’s 1985 observation was that this may be wood shavings. Summer melting of ice in the building cavities causes the air pockets in the wood shavings to become wet, reducing its insulating properties. Pearson (1992) qualitatively discusses insulation of all the early Antarctic huts and notes the use of two layers Gibson’s quilting (seaweed between two layers of jute) in the Terra Nova hut, which combined with apparently more air tight construction provides more effective insulation (eight hour lag) than at Cape Denison (three hours). Thermal insulation in the walls and roof of the AAE main hut would be significantly less effective since it is often wet during summer.

From construction diagrams of the AAE hut (Blunt 1991) and from observations of preferential melting around bolt heads (figure 4.28), thermal bridging appears to occur via several bolts connecting timbers in the apex of the Living Hut. There are a many bolts in a small area at the hut apex, which is also the location where temperature and humidity variations are greatest. In addition to its adverse effect on insulation, thermal bridges can produce significant deterioration from localised melting and may exacerbate condensation and hoarfrost cycles which increase conservation risks. Infra red imaging could locate and measure such effects which could aid investigation and rectification of heat transfer problems in the building.

While overcladding of the hut and repairing gaps around windows and doors should reduce air and particle ingress and improve insulation, and was stated to have reduced temperature and RH variations (Vinod Daniel, the Mawson’s Hut Foundation workshop, Sydney, 22 April 2008), condensation and hoarfrost cycles could reduce these benefits.

**Moisture retained by the building fabric**

The total quantity of moisture contained in the building timbers can be estimated from the quantity of timber and the percentage of moisture it contains. There are at least 8.7 tonnes of ‘dry’ timber in the hut (see Appendix N). Moisture content of timbers varies throughout the hut and fluctuates throughout the year. Exterior timbers at ground level are completely saturated by

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48 For example, development of a heat transfer model for the building.
the meltpool in summer while the roof is more exposed to drying by the wind and sun. At a given point in time, interior timbers may have significantly different EMC than the exterior timbers. Moisture content (combined with temperature) significantly influences biodeterioration risks, discussed in Chapter 9. Mason (1999) found EMC greater than 20% in many locations in the Terra Nova hut, presenting increased biodeterioration risk if temperatures rise above fungal growth points. Blunt (1986) measured EMC ranging from around 10% on the AAE hut roof to over 30% in Mawson’s cubicle.

To determine the total moisture flux in the timbers of the hut and its role in mass transfer processes in the building an approximation can be made of the scale and relative importance of different modes of water ingress can be made based on the measurements made by Blunt (1986: 108) at Cape Denison and by Mason (1999: 55-58) at Cape Evans. Before overcladding, most of the timber was above the fibre saturation point (FSP) in summer since the wood is almost totally saturated by meltwater throughout the building. The FSP is around 30% in most timbers, which means that the AAE hut timbers under these conditions holds ~2,610 kg of moisture. In winter, the EMC of timber in dry climates typically varies between 12-15% (equivalent to 1044-1305 kg). Thus the change of moisture over one year in the timber was of the order of 1566 kg. The moisture balance for the building is summarised in Table 4.10.

Although moisture will ‘evaporate’ from the exterior due to drying winds, the quantity of moisture in the wood is two orders of magnitude greater than the 1.3 kg critical ice mass that will produce 100% RH inside the hut at 0°C with low air change rates, ie moisture in the timber could be more influential on RH changes than RH in the air inside the hut. This moisture can take part in internal moisture phase change cycles such as condensation and hoarfrost formation.

The use of a venturi⁴⁹ to increase ablation of ice inside the hut would release moisture from the timber into the air inside the hut and the EMC of the timber would fall. Depending on the speed of drying, it may increase risks of cracking of the timber.

⁴⁹ Proposed by Ambrose and Godfrey (1998) as a means to remove ice and dry out the hut.
4. Temperature, RH, ice and phase changes

Thermal inertia of accumulated ice around and inside the AAE main hut

Ice is a poor thermal insulator but has high heat capacity. The verandahs of the main hut contain approximately 121.3 m³ of ice when full\(^{50}\) whereas the core of the hut contains 225.9 m³ when full (Appendix N), so the thermal sink\(^{51}\) provided by a completely ice-filled hut plus verandahs (347.2 m³) is nearly three times that in the verandahs alone (347.2/121.3 = 2.86). The verandahs are only seven feet high (maximum) and some heat is absorbed through the sloping roof, demonstrated by substantial temperature variations in the roof apex.

Key issues arising therefore are:

- Is the ice in the verandahs sufficient to control temperatures in the core of the hut?
- Can the verandahs be kept full of snow to prevent attrition of the thermal buffer by wind, melting and evaporation?
- Will overcladding provide sufficient insulation to prevent melting, or will this be offset by other risks eg condensation problems?

The benefits of the external snowbanks in stabilising thermal variations in the hut by preventing heat absorption at the walls are difficult to calculate without recourse to sophisticated thermal modelling (since the thermal insulation of the ice depends on its location relative to the heat source) although it is possible to identify the following advantages on a qualitative basis:

- Snowbanks reflect over 90% of heat whereas timber and rock absorb it;
- Direct snow contact with the walls and roof increases the thermal sink; and
- Snowbanks protect the snow in the verandahs from sublimation and erosion thus minimising ice ingress into the hut, however, they can contribute meltwater risks in summer.

Pearson (1992: 274) calculated heat transmittance or U-value of nine early Antarctic historic huts from data on the construction materials and design. The Norwegian-designed huts were the most thermally efficient (eg for Borchegrevink’s hut this was 117.40 watts/hour for each °C difference between the inside and outside). The least efficient hut was Terra Nova (497.43), then the AAE hut (433.63). The Nimrod hut was significantly more efficient (362.99). Other factors such as

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\(^{50}\) Ashley’s calculation for the verandahs is 176 m³ (Godden Logan Mackay 2000: 82).

\(^{51}\) Ice requires a large amount of heat (‘latent heat of fusion’ 333.55 joules/gram) to convert into water.
4. Temperature, RH, ice and phase changes

solar orientation (see Chapter 8) and size (Pearson 1992: 275) are also important in determining
the absorption of solar heat by the building. *Terra Nova* hut is vulnerable to solar heating because
of large areas of walls oriented favourably for heat absorption (figure 7.3) and relatively poor
insulation which may explain the relatively high internal temperatures previously discussed.

The theoretical decrease in U value from overcladding the AAE main hut with 23 mm thick
Baltic pine and an approximate 20 mm air gap is small compared with the estimated original
433.63. This suggests that the theoretical increase in insulation from overcladding is modest but
this will also depend on whether this factor is greater than the heat loss from wind (although there
is less wind in summer) and any effects from wet insulation.

*Air infiltration*

Mason measured air infiltration into the *Terra Nova* hut using the carbon dioxide tracer decay
method (Mason 1999: 65-66) and the ‘Blower Door Depressurisation test (*ibid*: 70-72). The
natural infiltration rate at Cape Evans (0.3 air changes/hour) was interpreted as “fairly air tight”
against ASHRAE52 standards. Mason measured external humidity variations generally between
60-80% RH with occasional changes to 50% or 90% occurring over several weeks53. Mason
concluded temperature and RH variations inside the hut were damped and conditions were
stabilised by the building “in all but stormy conditions”. Winds that caused an infiltration of
snow responsible for an RH surge were only 30 km/hr (*ibid*: 41) whereas the annual average
wind speed at Cape Denison is over 80 km/hr!

Air infiltration rates for the AAE main hut have not been measured although the measurements
are safe and relatively inexpensive to perform. Until recent overcladding, the AAE hut would be
expected to be less air-tight than the Cape Evans hut since the tar paper lining and insulation had
been damaged by strong winds and there are numerous gaps in timbers that allow drift
penetration into the building. However, the large planar ice crystals in Mawson’s cubicle
removed in 1997-99 indicated low air infiltration (possibly due to ice accumulations within the

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52 ASHRAE American Society of Heating, Refrigeration and Airconditioning Engineers
53 External RH at Cape Denison ranged from 23- 103% during 1999 (Table 4.3).
walls and roof) since large ice crystals can only form in still air. Air infiltration measurements could be useful to quantify mass transfer processes and determine whether this has a significant impact on ability to control RH in the hut.

**Differences between surface and air temperatures**

The author observed that the timber cladding of the AAE hut was warm to the touch during the December 1985 visit when daylight was almost 24 hours, even though air temperatures were below 0°C. Metal surfaces were also warm, especially dark surfaces such as corroded remnant ridge-capping. Exterior wood surfaces were also warm to touch during the January 1997 visit despite a moderate breeze.

Deterioration of materials increases at higher rates at higher temperatures\(^\text{54}\), so surface temperatures may be more reliable indicators of potential conservation risks in Antarctica than air temperatures. Unfortunately remote measurement of external surface temperatures on the AAE main hut was not feasible because direct sunlight on the thermocouple could give a false reading and the small sensor would have been too vulnerable to weather damage. At *Terra Nova* Bay\(^\text{55}\), which has a climate at least as cold as Ross Island, surface temperatures\(^\text{56}\) of metal coupons reached up to 20°C and the average difference between surface and air temperatures was 1.4°C (King *et al* 2001). While the trends for temperature data obtained from the monitoring system since 1999 are similar (in terms of temporal variations) for both thermocouple and the Vaisala sensors, the actual temperatures recorded differed significantly, particularly affecting the duration of temperatures above 0°C (see Table 4.3d and figure 4.11). The effect of local effects such as hoarfrost on the accuracy of the sensors is discussed below in conjunction with phase change issues. Godfrey (2002: 14) provides a photo showing a wet wall while ice remains on shelf only centimetres away. This indicates air temperature measured at the apex or near a wall does not necessarily indicate whether meltwater risks are present at the walls.

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\(^{54}\) As described by the Arrhenius equation.

\(^{55}\) See details in Appendix I and discussion in Chapter 6.

\(^{56}\) Surface temperature was measured on the reverse side of the coupon.
Effects of moisture variations in the AAE main hut

Melting of ice can accelerate biodeterioration and corrosion, since liquid water is available for biological processes in the former, and for ion transport in the latter. Meltwater flowed outside and inside the hut especially outside along the eastern and western walls (as observed by many summer visitors including Ledingham 1978, 1979, Blunt 1985, 1986, Hayman, Lazer and Hughes 1998, Ashley 1997⁵⁷, and by Mawson’s Huts Foundation personnel in 2002, 2007 and 2008). Evidence of wetting and drying cycles inside buildings includes staining and leaching of timber on the roof (figure 4.24) and ‘tide marks’ up to 30cm above ground level on the lower western wall (figure 4.23) and numerous other locations.⁵⁸

Figure 4.23: Tidemark stains indicating past levels of meltwater depth along western wall of AAE main hut (author’s photo, 1997).

⁵⁷ Ashley (1997: 20) estimated meltwater levels in 1997 at RL 6.065 metres while floor level is RL 5.940 metres, inferring 0.125 metres depth of water over parts of the Living Hut floor.
⁵⁸ There is thus an EMC gradient along each of the vertically mounted timbers with timber at the upper end of the wall being subjected to drying winds while simultaneously the lower end is soaking in water.
Both biodeterioration and corrosion are evident inside the AAE main hut despite low temperatures measured. During 1999, only the apex experienced air temperatures above 0°C combined with RH above 80% (theoretical conditions that allow deterioration to occur), and then for only 1.6% of the year (see Appendix K). However, during the exceptionally warm January 2002, apex and centroid TOW exceeded 300 hours each during 1-18 January and apex TOW varied from 38 in 2000 to 241 hours in 2004 and centroid TOW varied from 0 to 21 hours.

The presence of corrosion and biodeterioration implies that either these processes are occurring at sub-zero temperatures and lower humidities (discussed further in Chapter 6 and 9), or that wetting incidents are not being captured in recording. The errors in temperature measurement for the Vaisala temperature/RH sensors are ±0.5°C and ±3% (discussed in Ganther et al 2002) at any instant in time. Re-calibration was undertaken annually and there was no evidence of significant cumulative error (‘drift’) in measurement. Corrosion rate measured made on coupons outside the hut were higher than expected from the temperature and RH measured (Ganther et al 2002: 5).

Conditions suitable for biodeterioration and corrosion may have occurred after the AAE and before BANZARE when the hut was only partially filled with ice, with no thermal sink to stabilise temperatures. Meltwater is known to have been present then, discussed below. Later visitor records imply greater filling with ice from the early 1960s, so there are several decades where conditions may have been more conducive to corrosion and biodeterioration, although visitor records (listed in Blunt 1991) do not mention any observations of corrosion or biodeterioration.

A further factor to consider is that the temperature and humidity sensors measure air conditions, not surface conditions and many sensors were frequently covered with hoarfrost which would tend to underestimate melting events.

Ice covering an artefact does not cause damage to an artefact of itself and may be protective, as Harrowfield (1991) found that "artefacts [at Cape Adare] encased in ice were well-preserved. The preservation qualities of constant below zero temperatures on artefacts is exemplified by a zinc-plated canister from the 1899 expedition containing an enamel plate, fry pan and teaspoon"
individually wrapped in brown paper in almost new condition." After display for several years in the hut these artefacts are now corroded. Observations at Cape Evans (Harrowfield 1990) also suggest that other artefacts that exhibited no corrosion when excavated had corroded in a few short years on display inside the cleared hut. The huts had not been visited between abandonment in 1913 and 1957, so temperature and RH conditions during that period are unknown. Comments by Scott in 1912 blaming Shackleton’s expedition for snow ingress in the Discovery hut (anon 1983) suggest that hut may have rapidly filled with snow which would more effectively inhibit deterioration.

_Cracking of wood due to moisture change_

Because of the fibrous nature of wood, increases in EMC cause expansion/contraction at different rates in different directions, a phenomenon called anisotropy.\(^{59}\) Shrinkage in the tangential direction (around the tree trunk) is approximately 1.65 times greater than radial shrinkage from the centre to the outside (Kollman & Coté 1968). Shrinkage along the length of the tree is relatively small. Loss of moisture is highest at the end grain of timber.

Loss of moisture can cause cracking of wood and this is more likely at low EMC (Thuvander _et al_ 2002) particularly when EMC falls below the FSP and the cell walls begin to shrink. Wood dimensions change in proportion to its water content rather than the RH surrounding it (Padfield 1998) but wood absorbs or desorbs moisture where RH changes occur steadily over a period of days rather than hours (Kollman & Coté 1968). Thus, the rapid temperature and RH changes reported as Föhn winds during the AAE (figure 4.2) are too rapid to produce sustained change in EMC of timbers.

Extensive longitudinal cracking affected the exterior timbers of all buildings at Cape Denison. Cracking was particularly evident where timber was darkened by sunlight, rather than freshly eroded (figure 4.24). Similar longitudinal cracks, 1-3mm deep, were also observed at Cape Adare and the Ross Island sites associated with chemical weathering, discussed further in Chapter 7 and 8). The cracks in timber are non-elastic expansion or contraction in the tangential direction which

\(^{59}\) Properties that vary depending on the direction or grain of a material.
has exceeded the internal cohesion of the timber\textsuperscript{60}. No such cracks could be observed inside the AAE main hut (such observations being impossible in the Magnetograph House which is lined with tar paper). This implies that such cracking is related to the action of sunlight and freezing cycles are unlikely to be the cause since freezing cycles also occur inside the apex which was not cracked. The more probable causes of the cracking are diurnal changes in MC which cause superficial dimensional stress and weathering action by UV light and chemical action that removes lignin which reduces cohesion between wood fibres.

Figure 4.24: AAE main hut - staining and cracking on the roof (author’s photo 1997)

\textsuperscript{60} They are most unlikely to be due to flexing or twisting of the timber as this would lead to fracturing and splintering.
4. Temperature, RH, ice and phase changes

**Thawing behaviour**

Ice may not immediately melt when air temperature rises above 0°C, depending on heat transfer via radiation, conduction and convection to overcome latent heat. Ice has higher thermal conductivity than air (ice 2.0 W/m.°K, air 0.025 W/m.°K) but ice in the verandahs provides a significant heat sink although the ice only reaches part way to the roof apex (see figure 4.7). Sunshine on the walls and roof melts snow trapped within the wall cavity (figure 4.14). The author observed significant meltwater flows from the wall cavities into the hut during both Cape Denison visits (1985, 1997). Godfrey (2002: 34-35) noted the presence of ice inside the wall cavities even in exceptional warm conditions in January 2002.

Identification of the date of onset, duration and volume of meltwater pooling helps understand thawing behaviour in the building. Onset date of exterior meltwater formation during the AAE is not known as no relevant observations are recorded in the meteorological reports. Frozen meltwater is visible on the floor of the Living Hut in a photo taken during the BANZARE visit on 5-6 January 1931 (Figure 4.12). This shows relatively little snow inside the Living Hut excepting a pile (approximately one cubic metre) on the floor under the platform in the living hut and a similar volume, which appears to be under a skylight. Fletcher’s account (1984: 264-267) of the BANZARE visit provides a photograph of the Workshop (Figure 4.13). Hurley’s diary entry for 5 January 1931 states that there was extensive hoarfrost, icicles hanging from shelves and a large “snow ball” on the stove with an “unbroken sheet of ice about 18 inches thick” on the floor. The formation of hoarfrost under the platform suggests the platform was colder than the surrounding air, probably due to heat loss from the roof from wind.

Mawson’s brief diary notes for 6 January 1931 states (Jacka and Jacka 1988: 366-367):

“A big thaw took place on second day of our visit to Hut there being 2 still sunny days.

Rush of water from direction of upper wireless mast to Hut in pool.”

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61 Blunt 1991 volume 1: 91 cites Mawson 1915 vol 1:212 noting a marked thaw inside the hut on 21 October, “the frost all along the crack dissolved into water and ran down walls”
The flat glassy surface of the frozen meltwater (figure 4.12) suggests it has flowed across the floor via the walls from the external snow banks (suggested from Mawson’s observation above). The word “pool” suggests meltwater surrounded the hut, as it does now, indicating similar meltwater problems have occurred periodically, if not frequently, since at least 1931.

Figure 4.25: Frozen meltwater on the floor of the AAE main hut during BANZARE, January 1931 (Jacka and Jacka 1988: 338)

There are insufficient records and dateable photographs to evaluate meltwater behaviour during later expeditions (*eg* Ledingham 1978, Williams and Keys 1982). Lazer (personal communication) noted that meltwater formation began pooling in early January 1985 during the first Project Blizzard Expedition (figure 4.26). Overwinterers during 1998 reported the meltwater
pool refreezes intermittently in late February and remains completely frozen from early March (Jim Claypole personal communication, Sydney 1999).

Meltwater on and under the floor may affect the condition of the footings. The hut’s timber footings were reputedly set into holes blasted in the rock using explosives, then frozen in place (Chester 1986: 120). Irrespective of the structural arrangement, it is important that these timbers do not rot. This is unlikely if they remain frozen. Complete immersion of the timbers by meltwater will exclude oxygen and thus reduce biodeterioration. Conversely, periodic exposure to air through draining of the meltwater could increase the risk of biodeterioration, depending on temperatures (Gary Johnson, CSIRO Wood Science and Technology, personal communication 1991). This implies the meltwater pool should not be drained, however timber saturated by meltwater at ground level can distribute moisture along the grain via capillary action (figure 4.26). Moisture in the timbers can evaporate or sublime from the wood surface and contribute to high RH inside the building and hoarfrost formation implicated in the internal moisture cyclic of condensation /hoarfrost/ meltwater.

The author identified the importance of investigating the condition of timber foundations of the building (Hughes 1986) and Welke expressed a similar view at the 2008 MHF workshop. However, while the site management plan (DEWHA 2008: 63) recognises the need for caution regarding removing ice from under the floor and the importance of maintaining preventing melting of this ice it is silent on how meltwater under the floor should be managed (eg drainage).

Figure 4.26: AAE main hut, capillary action from meltwater (Chester 1986: 295)
4. Temperature, RH, ice and phase changes

*Internal cycles of evaporation, sublimation, condensation and hoarfrost*

Figure 4.25, taken during the BANZARE, shows abundant hoarfrost and distinctly prismatic ice crystals approximately 2-5cm long on the underside of the beams and boarding of the platform, implying still air with high RH. These and icicles and frozen meltwater on the floor indicate cyclic phase changes have occurred inside the hut for many decades. The author observed hoarfrost on the ceiling inside the Living Hut (figure 4.27) in December 1985 which melted each day during the early afternoon. Metal fasteners were wet before the surrounding hoarfrost melted (figure 4.28), indicating the metal acts as a thermal bridge. The ceiling acted as a suitable site for condensation at night when the air temperature in the hut lagged behind the exterior temperature and the timber is colder due to its connection to the exterior. When the building warms up during the day the hoarfrost melts and/or evaporates, increasing the moisture in the air.

Figure 4.27: AAE main hut, hoarfrost inside the ceiling (author’s photograph 1985)
Figure 4.28: AAE main hut, meltwater around a bolt in the ceiling (author’s photo 1985)

The meltwater ran down the ceiling, leaving distinct stripes (Figure 4.29) along the length of the timber. The roof was bare of ice suggesting this water must have come from melting of snow trapped inside the wall cavity. This effect was most pronounced on the interior of the apex, which was clear of accumulated ice and thus readily visible. Hoarfrost is now a significant problem, despite extensive ice removal, since when the hoarfrost melts it drips onto artefacts and re-freezes and when frozen it obscures the historic appearance of the hut interior (figure 4.31), discussed further in 4.5.2.

Figure 4.29: AAE main hut ceiling, meltwater running down interior timbers (author’s photo 1985)
Hoarfrost was observed at Cape Evans and Cape Royds (e.g. Mason 1999: 57, Held et al. 2005), but was rarely reported at other sites although this requires both the right conditions and observer knowledge. Figure 2.22 shows icicles inside the Terra Nova darkroom before ice removal in 1960, indicating periodic thawing occurred inside the building.

These Antarctic observations support Padfield’s (1998) conclusion that ice accumulation inside buildings is rarely a problem when frozen, but is a problem when it melts. The conservation strategy should then focus on whether it is possible to prevent hoarfrost formation or how it could be removed without harm. Trechsel and Bomberg (1989) documented numerous problems caused by unexpected condensation and freezing in wall and roof spaces due to installation of vapour barriers. This suggests careful consideration should be given to any proposals advocating membrane installation in Antarctic historic buildings where condensation and hoarfrost formation could occur. However, materials that act as vapour barriers (e.g. Butynol used on the exterior of Ross Dependency huts[^62]) or that reduce vapour transmission have been installed in some huts in some cases without considering this risk. Butynol, being dark, also absorbs heat which may promote condensation cycles and other deterioration. Even vapour-permeable membranes are potentially problematic if they form a favoured location for condensation or hoarfrost formation. The ‘vapour-permeable’ membrane used under the overcladding of the AAE living hut, Proctor Roof Shield[^63] has a permeability of 2409 g/m²/day. It can allow significant vapour transmission between the original cladding and the inner surface of the overcladding.

Mason (1999: 20) stated “it seems unlikely that moisture could pervade the exterior shell in significant quantity” but did not specify what quantity would constitute a problem, nor consider whether moisture risks occur within wall and roof cavities. Condensation risks inside wall cavities are highest in summer when the warm side is the outer wall. Condensation occurs where

[^62]: Butynol, a butyl rubber sheeting selected for its durability in polar conditions, was installed externally over the original timber of the Ross Dependency huts in the 1980s. Blunt (1991, vol 2: 265) quotes a “water permeability” of 139 mg/m/hr at 25 mm Hg pressure, compared to 156 for polyethylene. Condensation appears to form on the underside of the timber then meltwater flows inside the hut leaving a trail of salt crystals (figure 5.5).

[^63]: This product is described on the company website as “a triple layer spun bonded polypropylene breather membrane designed for use as an underlay on pitched roofs and for buildings with high internal temperatures and humidities”.

[^79]
warm air meets a cold surface so membranes are to be used they should be located on the ‘warm side’ of walls and must allow water to drain outside the walls, but this is difficult to achieve.

The scale of moisture exchange and temperature patterns inside the hut are now examined to determine requirements for preventing meltwater, which re-freezes on structures and artefacts, after considering the risks in interpreting the monitoring data.

*Hoarfrost and risks in interpretation of monitoring results*

Presentations at the 2008 Mawson’s Hut Foundation showed that most sensors were completely covered with hoarfrost and a plastic hood was placed on one sensor “to prevent freezing of drips on the sensor”. This could give unrepresentative data indicating conditions are colder and more stable than is actually the case. Figure 4.31 shows a similar situation, although the hoarfrost was less extensive at that time.

Some differences were evident between temperatures measured by thermocouples and the combined temperature/RH sensors. The trends were identical in each case with most, although not all, Vaisala sensors recording lower temperatures. Some differences appear to be calibration problems or disturbance of the sensors (*eg* TC5 and TC7 both had sudden increases at 1300 on 7 January 2000). Figure 4.30 shows although trends were similar, temperature differed between an adjacent Vaisala sensor and thermocouple, and the differences were greater in summer than in winter.
Mason (1999: 28) observed differential cooling of some large metal structures (such as tins and a stove) that he believed acted as a cooling fin inside the Terra Nova hut which led to localised cooling and condensation. It is probable that the sensors act in a similar manner. Hoarfrost can form when RH is high and when the sensors are colder than surrounding air. Hoarfrost was particularly abundant on the larger Vaisala sensors. Smaller ‘Tiny Tag’ sensors also formed hoarfrost but in lesser quantities, but measure RH less precisely. Thermocouples were smaller, in greater contact with surfaces (figure 4.4) and were less prone to hoarfrost formation but were said to have sometimes been covered by frozen meltwater. This does not imply criticism of the sensors but illustrates the measurement challenges in extreme conditions that are quite different.
to the normal measurement application. A potential solution is to deploy the sensors only in summer and include small leak detectors in the monitoring system. Using a range of sensor types, including thermocouples and meltwater indicators, helps crosscheck the monitoring data to assist understanding of mass transfer processes. Given the extensive data obtained in winter in previous years it is the summer conditions that are of most benefit in understanding the conservation risks in the hut. Measurement of surface temperatures during a shorter timespan when personnel are present may make it easier to interpret the data (without the complication caused by hoarfrost) and quantify the mass transfer processes occurring.

Figure 4.31: Hoarfrost covering a sensor (courtesy of David Harrowfield 2008)

Mass transfer processes, AAE main hut

Ice particles are blown through gaps in the hut’s cladding by the notorious winds (figure 4.14), and meltwater flows into the hut in summer, so the hut is not a closed system and ‘mass transfer’ of moisture is occurring into and out of the hut. To understand temperature and RH behaviour in the building the impacts of both internal condensation/melting/evaporation cycles

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64 Mason (1999: 35) found significant cooling of sensors placed in windy locations (chimney) in the hut but did not report any problems with hoarfrost formation. Small Hobo H8 Pro dataloggers were used for monitoring in the Ross Island huts (Held et al (2005:46).

65 This image was provided to Dr Harrowfield by a fellow passenger.

66 ‘Mass transfer’ is the movement of water in vapour, liquid or solid from interior to exterior and vice versa.
and the external factors (ingress of ice particles, meltwater seepage, and vapour transmission through gaps in the building structure and absorption via wood) must be considered to help determine whether ice-ingress can be prevented. Mass transfer studies are often used to resolve fungal problems and ‘sick building’ syndrome in air conditioned buildings in warmer climates. Once the quantity of moisture transfer is known this can be used to model the effects of ice removal, climate change and major interventions in the building fabric, such as overcladding.

The scope of Mason’s (1999) mass transfer study of the Terra Nova hut examined hygrometric changes. He found that high RH inside the hut correlated with periods of humid weather, with little contribution of moisture from visitors, and recommended removal of ice from under the hut that contributes moisture inside the hut via capillary action from groundwater in summer. Held et al (2005: 52) recommended removing frost accumulations inside the hut, or removal of snow drifts on the exterior to prevent the frost forming on the cold southern wall. Another option suggested was to increase air circulation. Recently, the floorboards were lifted to remove tonnes of accumulated ice that were causing distortion under the floor67. The flaky appearance of the ice suggested it was hoarfrost forming from cold, moist air under the floor rather than frozen meltwater, although distortion of the floor by hoarfrost alone seems unlikely. Removal of the ice may reduce moisture in the short term, but unless the cause of the problem is addressed the problem may return. Removing meltwater may not solve the problem if the cause is condensation and there may be a range of possible solutions. All options proposed focussed on controlling moisture. Any action that may potentially result in higher temperatures in the Terra Nova hut (such as removal of the snow bank) could increase conservation risks if the RH control is unsuccessful. Mass balance studies with temperature modelling may elucidate these risks and suggest solutions.

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67 Presented at Mawson’s Hut Foundation workshop, Sydney, April 2009.
Figure 4.32: Ice under the floor of Terra Nova hut, NZAHT website downloaded 2 March 2010.

A summary of the key mass transfer processes in the AAE main hut is given in Table 4.10 to facilitate the discussion following. The table provides estimates of total volume of moisture transfer (for solid, liquid and vapour phases) involved in ingress, egress and internal transfer within the hut.
Table 4.10: Mass transfer processes in AAE hut circa 2007 (ie with ~49 m\(^3\) of archaeological deposit, ice retained in the verandahs)

<table>
<thead>
<tr>
<th>Phase</th>
<th>(\text{H}_2\text{O} \text{ ingress into hut})</th>
<th>(\text{H}_2\text{O} \text{ in hut})</th>
<th>(\text{H}_2\text{O} \text{ egress from hut})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type</td>
<td>Kg of (\text{H}_2\text{O}) ingress in the past year</td>
<td>Controls &amp; constraints</td>
</tr>
<tr>
<td>Solid</td>
<td>Windblown ice particles enters via gaps in timber</td>
<td>~20 Less since 2002</td>
<td>Overcladding of roofs reduces ingress, but may enter via walls where sealing is incomplete</td>
</tr>
<tr>
<td></td>
<td>Particles trapped in wall spaces</td>
<td>~50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hoarfrost</td>
<td>~5-10 kg</td>
<td></td>
</tr>
<tr>
<td>Liquid</td>
<td>Rain (rare)</td>
<td>~50-100. Note ingress is highly variable from year to year</td>
<td>Roof membrane reduces water ingress from roof, but not from walls. Membrane may provide a site for condensation.</td>
</tr>
<tr>
<td></td>
<td>Meltwater seepage through roof</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Meltwater through walls</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Meltwater flows inside the hut, eg drips from icicles</td>
<td>820</td>
<td></td>
</tr>
<tr>
<td>Vapour</td>
<td>Air enters the hut through gaps in walls &amp; roof and by diffusion.</td>
<td>0.2</td>
<td>A permeable membrane may slightly reduce air interchange rate between exterior and interior.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>70-120</td>
<td></td>
</tr>
</tbody>
</table>

*From timber: includes any water retained within the archaeological deposit.
Air and vapour infiltration

Absolute humidity data from 1999 (figure 7 in Appendix K) showed there was a daily cycle of change in the mass of water in the air at all the locations monitored. A change in the mass of water in the air implies there must be a source and sink for this moisture. Exterior peak AH (5.2 g/m³) occurred around 1600 hrs each day and at most interior locations the peak AH (4.5 g/m³) occurred around 1900 hrs. Thus there is more moisture present during the day and less at night, implying that moisture was being evaporated during the day and condensed at night.

For condensation to occur there must be a structure or surface that is colder than the air. Such structures could include the timber roof and walls and the ice inside the hut, which is a thermal sink connected to the ground. The ice deposit on the floor remains cold throughout the year and it can therefore act as a site for condensation. Before January 1998 moisture could also condense on the accumulated ice inside the hut. Since 1998, moisture can still condense on cold surfaces throughout the hut, including the floor and the roof and artefacts which have been excavated but were previously covered by ice.

Before the major ice clearances in 1999 air infiltration via the southern part of the hut appeared to be low as ice blocked gaps in the wood cladding. Removal of ice inside the hut and melting of ice in the wall spaces may have increased gaps through which air, and ice particles, can enter the building. Whenever the external snow bank forms along the southern wall, with ice also sealing the wall cavities and the interior ceiling it provides a barrier to ice particle ingress since the snow particles ‘sinter’ together but this depends on climatic variations. In his diary Mawson mentions the sound of the winds decreased when the snow bank formed over the roof exterior, suggesting this provided a substantial barrier (Jacka and Jacka 1988).

The quantity of moisture precipitated from air infiltration will be greater if there is a large temperature differential between the exterior and interior and if the temperatures are higher, since moisture can form more vapour. In 1999-2000 average AH for most locations inside the hut
during summer\textsuperscript{68} was 1.7 g/m\textsuperscript{3} and the average AH in winter is 0.7 g/m\textsuperscript{3}, so there was a net annual mass change inside the building of approximately 1.0 g/m\textsuperscript{3} $\times$ 222.9 m\textsuperscript{3} (the hut internal volume): 0.223 kg on an annual basis. This quantity, while small, still contributes to high RH inside the building.

\textit{Water ingress}

The volume of meltwater that drips from the ceiling and walls and re-freezes onto shelves and artefacts has not been quantified on a regular basis but varies from year to year and appears to be at least several kilos. The weight of ice on shelves in some locations caused bowing and collapse.

While external air temperatures at Cape Denison are usually only above 0°C for short periods, a significant pool of meltwater appears for about six weeks along the western wall of the main hut and in some years along the eastern wall also. Melting of the snow drifts around the hut influences the depth of meltwater, evident in ‘tidemark’ stains on these walls (figure 4.23). The volume of meltwater varies throughout summer as well as from year to year.

During January 2002 time above 0°C reached over 80\% of time (see figures 4.10, 4.11) and Godfrey (2002) noted exceptional melting. Installation of two meltwater detectors (eg conductivity cells) at floor level inside the hut (see Hughes et al 1999) could confirm whether moisture in key locations is in the liquid or solid state, since this is difficult to determine from temperature measurements alone. This would also help determine whether the ‘archaeological deposit’\textsuperscript{69} of approximately ice 600 mm on the floor remains continuously frozen and could be useful to monitor ice conditions in the verandahs.

Ashley (1997, figures 2 and 3, see figure 4.33) stated that the sealskins along the outer eastern wall are the cause of ingress of meltwater into the hut since they dam water above floor level. However, meltwater from the snow bank at the southern wall and the verandah also flow inside

\textsuperscript{68} See Ganther et al 2002: 4 (Appendix K)
\textsuperscript{69} The ice on the floor is believed to contain undisturbed evidence of the original AAE occupation that was not disturbed in the 1977 ice removal and it therefore should not be removed until resources are available for appropriate archaeological investigation.
the hut and will pool where any obstruction to flow occurs. The total volume of meltwater inside the hut is difficult to calculate but a conservative estimate is at least 820 kg of water (based on one cm over the floor with a hut floor area of ~82 m²). This includes melting occurring inside the hut plus meltwater ingress via the walls and roof.

Figure 4.33: Diagram of water ingress into AAE main hut (Ashley 1997:20)

Mason (1999) and Held et al (2005) identified significant meltwater ingress problems in the Terra Nova hut from snowdrifts outside. These caused moisture ingress by capillary action from meltwater pools along the SE wall. Mason (ibid: 135) did not quantify meltwater ingress but considered capillary transport of moisture from the subfloor ice deposit as a minor source of moisture in the hut but did not discuss absorption and desorption of moisture from the walls.

Because small amounts of water can produce 100% RH at low temperatures, draining of meltwater is unlikely to substantially reduce RH inside the AAE main hut even if the difficulties of operating a pump in a hollow and blockages from freezing could be overcome.

**Have interventions in the building fabric been successful in excluding ice ingress?**

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70 The hut is located in a depression in impervious rock.
The combination of overcladding timber and membrane installed between the overcladding and the original timber cladding of the Workshop has reduced but does not appear to have completely prevented ice particle ingress, although ice particles can also enter via gaps in walls, which have not yet been completed covered. Closed cell foam was used underneath the ridgecapping to prevent ingress where wind penetration is more likely. Without being able to detect points of ingress it will remain difficult to prevent ice particle ingress.

Table 4.10 shows that even if ice particle ingress can be reduced by overcladding, meltwater ingress will result in ice accumulation inside the hut. Ice is difficult to remove, although not necessarily damaging, but its presence is contrary to the stated aim of keeping the centroid clear of ice to allow visitor access. This ice produces vapour which then takes part in the internal moisture cycle of hoarfrost formation and melting, especially when the centroid temperature exceeds the apex temperature and when the temperatures are high enough to increase AH.

Recent MHF photographs (summer 2008-09, figure 4.34) show extensive hoarfrost formation on the interior of the roof, much more than in 1985. When the roof warms the hoarfrost melts and flows into the wall space. Previously meltwater from hoarfrost dripped onto the existing accumulation in the hut, with no evident damage whereas now it drips onto exposed artefacts and refreezes, leading to the problems noted by Godfrey (2002).

Figure 4.34: Hoarfrost in AAE hut (Michelle Berry, December 2009)
Venturi method of ice removal

Most large scale ice removal (Ross Island huts, Cape Denison and Snow Hill Island) used methods such as digging or cutting, depending on the hardness of the ice. The venturi method tested by Ambrose and Godfrey at Wilkes (1998, figure 2.15) was proposed for use on the AAE main hut to ‘dry it out’ by ablation, but raises significant questions. Rupert Summerson (personal communication to the author) observed that the Wilkes location may be a natural ablation zone since it is in an open, windy and elevated location that is blown free of snow. The method was also proposed for the Wilkes IGY buildings but most of the Wilkes site is in a depression, an accumulation zone. Thus the location chosen for the ice removal research is atypical of the locations where the technique was to be applied, which could lead to erroneous conclusions about its feasibility.

Application of the venturi method for the AAE hut raises additional concerns:

- The method relies on completely sealing the hut and would require an impermeable membrane on the outer walls to prevent water ingress although moisture could still enter by capillary action;
- Windborne ice particles, or ‘drift’ occurs tens of metres above the ground (Madigan 1929 figure 11), even a large, high venturi may clog with particles (as occurred with the AAE snow gauge) reducing its efficiency;
- Reduced pressure produced by the venturi may cause problems and testing would be required before implementation, taking resources from other priorities;
- Venturi equipment must be securely anchored or it could dislodge and pose risks to the building in extreme winds;
- Aesthetic and historic values could be significantly affected.

Vortex generators

‘Vortex generators’ were installed by the NZAHT at Cape Evans in 2008 to prevent accumulation of snow against the walls of the Terra Nova hut and thereby reduce moisture problems including biodeterioration. Snow fences and ‘vortex generators’ were then proposed at
the Mawson’s Huts Foundation workshop (2009) to minimise snow drift formation and minimise corrosion at Cape Denison. These can be designed to either promote or prevent accumulation of snow drifts by modifying airflow around a structure. Extensive information is available about height, orientation and construction requirements as these are extensively used in northern hemisphere cold climates (Strub 1996). Vortex generators (figure 4.35) were used to prevent snow drift formation at Pegasus airfield near McMurdo Base (Lang, George & Blaisdell 1998) and were effective in preventing accumulation of loose drifts but were ineffective once drifts consolidated via sintering. No information, however, could be found regarding their usage for historic buildings.

Figure 4.35: Vortex generators (http://www.nhm.ac.uk/nature-online/earth/antarctica/blog/images/generators-close-up-350.jpg downloaded 26 June 2010)

71 Consolidation by partial melting and refreezing.
72 Julian Bickersteth, conservator involved with the NZAHT, stated at the 2010 MHF Workshop that the vortex generators had not proved effective at Cape Evans.
Visitor contributions to temperature and RH variation

Humans add heat and humidity inside buildings so visitor numbers inside Antarctic buildings are often limited for this reason, as well as for appropriate supervision and safety. About 1500 people now visit one or more of the Ross Island sites each year because of their fame and relatively easy accessibility from McMurdo and Scott Base.

Mason (1999) modelled the impact of visitors at Cape Evans using a moisture contribution per person of 0.02 kg (CIBSE 1986) per hour with a permitted occupancy of 12 persons. He also matched past records of temperature and RH in the hut to recorded visits and found 12 visitors produced a gain of 7°C over eight hours with a total gain of 0.5 kg of water by the hut air. Mason found the “moisture gain in the hut [from the visitors] was largely offset by the rise in temperature” they produced (ibid: 48). The moisture gain includes both respiration moisture and snow carried on boots and clothes and he concluded that leaving the door open during visits to increase ventilation will reduce the effects of the temperature and humidity spike measured during visits (ibid: 137-139). By contrast, Held et al (2005: 50-51) provided further measurements which showed no significant RH impacts by visitors. The rise in temperature is short term and unlikely to be significant in increasing melting ice or causing EMC changes in wood.

At Cape Denison visitor numbers at the site are much smaller and more intermittent, with 110 visitors in 2006-07 and 450 visitors in 2007-08 but no visitors in some years (Table 10.5 and DEWHA 2008: 38). The 2007-2012 site management plan (page 164) specifies numbers inside the main hut (four, including the guide) and Magnetograph House (three including the guide). Most tourists appear to spend between five and ten minutes each inside the main hut. Lazer undertook recording when visitors entered the hut in 2002 (all for short periods), but these have not been able to be analysed against the monitoring data. Given that the current air infiltration

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73 The Management Plan for Antarctic Specially Protected Area No 155 (Cape Evans, available at [http://www.ats.aq/documents/recatt/A1c396_e.pdf](http://www.ats.aq/documents/recatt/A1c396_e.pdf)) states the average visitor numbers were 1489 per year between 1998 and 2004 and sets a limit of 2,000 visitors.

74 Anne McConnell, personal communication to the author, Canberra 2008 and in discussion at the 2008 Mawson’s Hut Foundation workshop.
rate at Cape Denison is likely to be higher than at Cape Evans the hygrothermal impact of visitors at Cape Denison is also likely to be small.

4.5.3 How did removal of ice affect temperature and RH conditions inside the AAE main hut? In particular, what are the critical criteria required to prevent cycles of melting and re-freezing identified by Godfrey and is this control achievable? (research question 3)

While acknowledging the lack of “hard evidence”, Godfrey (2002) stated:

“allowing the existing snow and ice to remain in the building, on the balance of probabilities, is far more likely to cause further damage than is likely to be caused by its removal”.

This appears to have been accepted as the rationale given for overcladding and ice removal from inside the hut, excluding the verandah (DEWHA 2008: 88):

“The overcladding of the Main Hut roof should largely prevent snow and meltwater from penetrating the hut …. to prevent further damage to interior structural members and fittings …. caused by the melt-freeze cycles which had been producing ice that encapsulated objects and stressed load bearing features”.

The Cape Denison site management plan (DEWHA 2008: 89) states:

“Monitoring has shown that the internal environment is not substantially altered by the removal of some of the ice. Temperature and RH sensors in place since 1999 have found no significant variation since the removal of large volumes of ice in 2002….. Moreover, the recently over-clad roof seals the Main Hut more effectively, and this may increase the rate of ablation”.

However:

- Even if overcladding had been completely successful in preventing ice particle ingress, meltwater ingress still occurs at floor level.
Melting of hoarfrost at the ceiling appears to result in internal cycles of melting and re-freezing that require significant ongoing labour to present the interior for a small number of visitors.

Excavated artefacts inside the hut are exposed to high RH and potential contact with liquid water which presents higher conservation risks.

During 2002 internal temperatures were above 0°C and the building had longer duration of temperatures above 0°C than the exterior (ie it absorbed and retained heat).

Data for 1999 to 2010 (Table 4.5) and 2007-2009 (in Berry 2010) show that overcladding has not reduced RH to levels that prevent deterioration.

No increase in ablation of ice inside the hut is evident from dated photos on the MHF website, which is not unexpected since overcladding reduces ventilation and there is little opportunity for natural sublimation or evaporation.

Similarly, in the Ross Island huts RH remained high despite overcladding and extensive efforts to remove ice since the 1960s and soft rot fungal growths have occurred (Blanchette et al 2004). Daniel and Ashley (2002) proposed RH should be controlled to a variation of ±15% within the centroid but did not specify acceptable temperature or RH levels. While RH in the centroid is generally within this variation it is very high which increases the risks of biodeterioration of wood and corrosion of metal fasteners and fittings which are now exposed to periodic meltwater. Few corrosion and biodeterioration treatments are effective at high RH, and any treatments must meet stringent Antarctic environmental and safety requirements and conservation requirements. Given the difficulties previously explained in controlling RH, what other conservation strategy is feasible?

Has thermal stability changed since ice removal?

75 See previous comments regarding capillary action contribution to high RH inside the hut (Mason 1999). The quantity of water involved is relatively small, but RH is high because air temperatures are low.

76 The Cape Denison site management plan (DEWHA 2008) does not discuss long term post excavation impacts of high RH on metal fasteners and fittings in hut and artefacts. Shelving brackets in the AAE main hut have been replaced due to corrosion risks (Berry 2010).
4. Temperature, RH, ice and phase changes

Correlation of external temperatures and centroid temperatures during each January are shown in figure 4.8. Compiled from available data for 1999-2006, Table 4.6 shows greater variability of the monthly mean centroid temperatures for each January after 2000 excepting January 2002 which had low variability but unusually high temperatures. Analysis of lag times is more complicated but the average lag time (which was 3 hour in 2000) now appears to be reduced.

3. Monitoring over 8 years may be insufficient to provide adequate confidence that removal of centroid ice will provide sufficient remaining ice to stabilise the internal environment of the hut. The temperatures in January 2002 were said to be the hottest in 50 years, but the risk of such events occurring is likely to increase over the next few decades.

4. Daniel and Ashley (2002) considered that conditions in the centroid are the key criteria and that the variability at the apex was not so important. However, melting at the apex is the cause of meltwater that runs onto artefacts and re-freezes. Conditions at the apex therefore should be kept below freezing to prevent this problem. Direct measurement of liquid formation (and duration) using appropriately robust sensors\(^\text{77}\) would help determine whether the ice in the verandahs is protecting the environment in the centroid and whether any supplementary insulation or other intervention is required.

While the scope of these questions is too broad to be answered by this thesis, the modelling proposed in 4.5.5 may help provide relevant data.

Control of mass transfer is complex. Trying to prevent ice ingress at Cape Denison is equivalent to trying to keep dust out of the building in cyclone conditions\(^\text{78}\). Can water ingress be prevented (from melting of snow in the verandahs which flows from upslope)? Photos taken in 2009 after overcladding of both Living Hut and Workshop and some walls indicate snow and meltwater ingress is continuing (Berry 2010), suggesting current strategies (principally overcladding and ice removal from the centre of the hut) may not be not sufficient.

\(^{77}\) Sensors such as impedance dew point sensors used in air conditioning measure adsorption of water vapour into a porous non-conducting "sandwich" between two conductive layers built on top of a base ceramic substrate.

\(^{78}\) The AAE hut suffered snow ingress even when it was new (Mawson 1915).
While the exterior air maxima and minima at Cape Denison differ by over 40°C per year, the core interior air maximum to minimum variations were less than 23°C per year in 1999-2000 (Ganther et al 2002: 5). Both exterior and interior temperatures exhibit similar cycles, lagged by approximately three to four hours in 1999-2000 due to the time taken to heat up the structure. Analysis of thermal lag time for each January during 2000-2006 showed variability but lag time appeared to generally decrease (see Table 4.5) and a comparison of exterior to centroid temperature differences correlated against external temperature also indicated a general decrease in thermal insulation during 2000-2006.

4.5.4 How will climate change affect the sites and what are the implications for current conservation strategies? (research question 4)

Wendler (1990: 266) calculated an increase of 2°C in Terre Adelie per century based on comparisons of the AAE data with measurements made by the modern Automatic Weather Station (AWS) placed at the exact site of the AAE Anemometer. This implies temperature increases in the long term. Monaghan et al (2006) state that higher temperatures will occur throughout Antarctica and this will increase snow fall. However, Goodwin (personal communication, MHF Workshop Sydney 2008) stated that while surface level warming is evident in the Antarctic Peninsula, cooling is occurring overall in East Antarctica due to intensification of westerly winds. Other competing trends include increased variability in snowfall in different parts of Antarctica. Certainly, by 2050 there is broad agreement the Southern Ocean will be much warmer and that present conditions are not indicative of the future conditions. Thus, conservation planning must consider the effects of probable temperature

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79 Two key studies (Monaghan 2006 and Davis 2005) illustrate competing interpretations of climate trends both based on studies in multiple locations. Monaghan et al concluded:

“Future scenarios from global climate models suggest that Antarctic snowfall should increase in a warming climate, mainly due to the greater moisture-holding capacity of warmer air. Perplexing temperature trends have been reported over Antarctica since continuous monitoring began with the International Geophysical Year (IGY) in 1957-1958. “…our 50-year perspective suggests that Antarctic snowfall has slightly decreased over the past decade, while global mean temperatures have been warmer than at any time during the modern instrumental record….. Seasonally averaged precipitation data suggest that there has been no commensurate increase in winter snowfall since at least 1985. These findings suggest that atmospheric circulation variability, rather than thermodynamic moisture increases, may dominate recent Antarctic snowfall variability”.
increases over about 30 years with significant variability in temperatures and precipitation in the next two decades and increased winds.

While Godfrey attributed the exceptional melting at Cape Denison in summer 2001-2002 to climate change (Godfrey 2002) climate change occurs over a period of decades rather than sudden change over a few seasons. The key long term risks that can be anticipated from climate change are:

- Longer duration of higher temperatures will increase meltwater formation in and around the main hut, raising conservation risks, particularly corrosion, biodeterioration and wetting/drying problems of timber;
- Small increases in duration of temperatures above 0°C could increase melting of ice in the verandahs since summer temperatures are already close to 0°C (see Table 4.6)
- If snowfall increases and temperatures rise, more meltwater would form, increasing water ingress into the hut which then freezes, adding to ice removal problems;
- Variations in snow fall may affect the thermal buffering ability of snow deposits in the verandah, so it may be imprudent to rely on this protection from one year to another;
- Rain could occur instead of snow, leading to direct ingress of water or increased capillary infiltration, forming ice inside the building in winter, negating the insulating effect of overcladding; and
- Any decrease in snow deposits in the verandahs could increase risks of wind damage to adjacent timbers increase ice particle infiltration via the southern wall.

Evidence of natural variability of snow depth around the hut implies the site conservation plan must consider how this will affect the thermal stability of the building.

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These findings are “somewhat inconsistent” with Davis et al, which inferred from satellite altimetry data an increase in snowfall accumulation only for 1992-2003, but both research teams concurred there is significant inter-annual variability in snowfall.

80 See section 4.5.1 and figures 4.23, 4.24, 4.14
4.5.5 Further research requirements

a. Mass balance studies undertaken every few years would be useful to quantify moisture ingress by mode (meltwater, windborne ice particles, air) and determine the role of sublimation and hoarfrost in internal moisture cycles. Most conservation effort has focussed on preventing ice particle ingress but if large quantities of moisture (eg meltwater) enter the hut by other means the current ice exclusion via overcladding may be ineffective.

b. Water leak detectors\(^{81}\) should be installed in wall cavities and at floor level to measure the current frequency and duration of melting events, locate sources and quantities of meltwater ingress and monitor the condition of the archaeological deposit.

c. Investigation of the structural design and condition of the subfloor and footing should be undertaken in summer using Ground Penetrating Radar\(^{82}\) to evaluate melting, without disturbing archaeological deposits.

e. Modelling of the potential risks from climate change is needed to check the validity of assumptions relied on by the site management plan, particularly the ability of ice in the verandahs to stabilise current and future interior temperature and RH variations. This must model current temperature and humidity variations in the building to enable quantification of the impact of solar radiation, snow deposition and wind on the quantity and condition of ice in the verandahs.

*Development of models for hygrothermal behaviour of Antarctic historic huts*

Thermal analysis software is used by mechanical engineers to model thermal control in buildings (eg WinTherm, SINDA/FLUINT, TAS). Computational fluid dynamics (CFD) software enables analysis of wind flow and similar engineering problems and could be used to study air and particle ingress into the building. CFD can also take account of surrounding topography. Some

\(^{81}\) Detailed in Hayman et al 1998.
\(^{82}\) Proposed to ASAC by the author in 1994 using the expertise of Dr Tony Siggins of CSIRO. GPR was used at the site to search for the air tractor.
companies offer a fee for service arrangement to run the software with a client’s data (for example, Thermoanalytics Inc at [http://www.thermoanalytics.com/](http://www.thermoanalytics.com/)).

To model thermal behaviour of Antarctic historic buildings requires the following steps:

- Preparing a geometric model of the building(s) from measured drawings to prepare a ‘surface mesh’.
- Inserting data on building materials, thicknesses, and environmental factors (including temperature data recorded in the building).
- Creating boundary conditions for convection inputs, and or imposed heat rates.
- Running the analysis using a set of defined criteria to measure the coherence of the model to actual thermal behaviour of the building (from temperature monitoring data).
- Modifying the model to simulate environmental factors (eg climate change) or design changes (eg interventions in the building such as ice removal, overcladding, etc).

Key data required for the modelling the AAE main hut and Cape Evans hut are available:

- Temperature data[^83];
- Solar radiation data and cloud data representative of the site (measured at a different but similar site in Antarctica);
- Borehole measurements over a yearly cycle of temperatures at 5m below the surface (to represent loss of heat from the building to the ground)[^84];
- Plan and section drawings of the building and/or photogrammetric records;
- Terrain data for the surroundings of the building (Crispo survey for Project Blizzard, 1985);
- Dimensions and density data for the timber used (Blunt 1991);
- Data on the extent of ice inside the building in both plan and section;
- Density data for the ice inside the AAE hut[^85]; and
- Wind speed and direction from as many points as possible at the site[^86].

[^83]: Over nine years of data is available, although the effects of hoarfrost on accuracy must be considered.
[^84]: Data from places with comparable climates elsewhere in Antarctica can be used.
[^85]: This could also be determined from the ice cores collected by Lazer.
[^86]: Some data for Cape Denison is available from measurements by Project Blizzard, AAE, US Automatic Weather Station which could provide a good indication of variability at the site.
Data that is not available for the AAE main hut includes the amount of meltwater inside and under the building, and the temperature of this water. Three estimated values could be used to model best and worst scenarios. In addition, it would be very useful to have air infiltration measurements for the building. The model could then be run to predict temperatures with and without the ice in the verandahs, and with a 2.0°C temperature increase during summer (representing estimated climate change). The outputs from the thermal model could then be used to model hygrometric behaviour of the building to produce a comprehensive model of both temperature and RH behaviour in a range of scenarios.

4.6 SUMMARY

For all Antarctic historic buildings:
1. Literature reviews and site observations found no evidence that the process of freezing (including volume expansion at 4°C and crystallisation at 0°C) causes damage to wood although melting of ice caused a range of problems and is associated with increased corrosion and biodeterioration.
2. Comprehensive literature studies indicates small buildings filled with ice at temperatures continuously below freezing will not suffer ice-jacking, plastic flow or permafrost heave.
3. Ice inside Antarctic historic buildings has only caused significant damage where the weight of ice is unsupported.
4. At the temperatures typically occurring in summer, even small quantities of ice or water inside Antarctic historic huts will produce high RH so removing ice by itself will not reduce RH. Thus strategies to maintain sub-zero temperature should be considered to reduce deterioration risks.

For the AAE main hut:
5. Cyclic melting of hoarfrost and refreezing of meltwater onto artefacts and shelves in the AAE main hut causes problems when removal of the ice from surfaces is attempted. However, strategies to prevent ice ingress (the source of most meltwater) were not entirely successful and hoarfrost continues to cause cyclic melt-freeze problems.
6. Since excavated, artefacts on display are exposed to high RH and meltwater.
4. Temperature, RH, ice and phase changes

7. While meltwater pools around the footings cause problems in summer, it excludes oxygen and thus reduces biodeterioration risks and may help to physically anchor the hut’s footings when frozen in winter;

8. The unusually warm conditions of January 2002 showed that high external temperatures combined with depletion of around half of the ice in the verandahs can lead to temperatures in the core of the AAE main hut remaining above 0°C for substantial periods.

9. Temperatures in the centroid are dependent on exterior temperatures with temperatures during each January during 2000-2006 indicating a stronger relationship and less lag and greater effect from temperature loss at the roof. Hoarfrost forms when centroid temperature exceeds apex temperature, thus apex temperature should be used as a criterion of performance.

10. Field testing of all conservation materials is required to assess not only its durability in Antarctic conditions, but any increased risk that coatings or membranes may change moisture transfer in the building or increase condensation problems.

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5. DAMAGE BY SALTS

Figure 5.1: Saline lakes near Davis Station (author’s photo 1992)

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5.5 DISCUSSION

5.5.1 Characteristics and severity of salt-related deterioration problems (Research question 1)
Salt observations at sites not visited by the author

5.5.2 Composition and origin of the salts (Research question 2)
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Salt composition of snow at Cape Denison (1985)
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5.5.3 Rates of salt deposition inside and outside buildings and factors influencing salt penetration (Research question 3)

5.5.4 Effects of rain, meltwater and other rinsing (Research question 4)

5.5.5 Defibring of wood (Research question 5)

5.5.6 Relationship of salt deposition rates and deterioration risks (Research question 6)

5.5.7 Effectiveness of conservation treatments for salt-related deterioration problems (Research question 7)

5.5.8 Implications for site management (Research question 8)

5.6 SUMMARY
5.1 AIM AND INTRODUCTION

5.1.1 Objectives, terminology and scope

The aim of this chapter is to:

- describe, and where possible quantify, the effects of salts on timber and other organic materials in Antarctic conditions;
- examine the effectiveness of conservation treatments of salt damage; and
- determine requirements for successful treatments.

The focus is on the interpretation and application of existing salt research by other Antarctic researchers, because of logistics constraints on gathering representative samples from all sites.

5.1.2 THE SIGNIFICANCE OF SALT IN DETERIORATION PROCESSES IN ANTARCTICA

Of the 82 historic sites currently recognised by the Antarctic Treaty only six pre-IGY sites are more than one kilometre from the sea, so potential risks of damage by salts are high. The following widely known properties of salts are relevant to conservation of historic materials in Antarctica:

1. All ionic salts accelerate corrosion by increasing the conductivity of the electrolyte that carries electrons involved in corrosion processes. Corrosion is considered separately in Chapter 6;
2. Many salts are hygroscopic and may deliquesce in humid conditions producing a concentrated solution that may be more damaging than when it is dry;
3. Salts can preserve some biological materials by dehydration (as used in preserving meat products);
4. Other salts (particularly nitrates and phosphates) may promote biodeterioration by ‘fertilising’ growth of bacteria and fungi;
5. Salts can be transported by capillary action (*eg* in rising damp) and if the water is evaporated, transported salts can accumulate and cause damage;

6. Salts dissolved in water will lower the water vapour pressure because the water molecules are effectively diluted by the presence of the salts (Raoult’s law of ideal solutions), which makes condensation possible in certain circumstances (Camuffo 1998: 180);

7. Environmental cycles of temperature or humidity, or periodic heating due to direct solar radiation may induce salt migration, precipitation, growth, hydration and expansion and may trigger disruptive cycles within pores of materials, causing fatigue or breaking the internal material structure (Camuffo 1998:181);

8. Salts lower the freezing point of water, allowing some deterioration processes (*eg* corrosion and biodeterioration) to occur at lower temperatures. This property was used in excavation of some frozen archaeological sites (Harrowfield, DL 1984);

9. Salts precipitate in chemical reactions in sequence according to their solubilities; and

10. Isotonic, eutectic and osmotic behaviour of salts may also be relevant.

### 5.2 LITERATURE AND GAPS IN KNOWLEDGE

As shown in Chapter 2 there is no comprehensive study of salt damage covering all Antarctic historic sites although ongoing research by a NZ-US team (Blanchette, Held & Farrell 2002) on salt damage affecting the Ross Dependency huts that has made significant progress and is referred to extensively in this chapter.

#### 5.2.1 Salt deposition processes

Most research on salts in Antarctica focuses on environmental processes of salt transport. (such as Campbell and Claridge (1987), Gore *et al* (1996) and Marion (1995)) examine whether marine or terrestrial salts predominate at specific locations and provide some data on salt composition, deposition rates and chemical processes in Antarctica (see discussion section of this chapter). (Mason 1999) measured atmospheric salt deposition by the ISO Salt Candle method (9225) in Scott’s Hut at Cape Evans. A few salt deposition rate measurements are available from the Antarctic Peninsula (Morcillo *et al* 2004) but throughout Antarctica there are few measurements
where affected historic sites are located. Data is available on salt aerosols collected at selected Australian Antarctic stations (http://www.bom.gov.au/climate/how/antarctic_catalogue.shtml)

5.2.2 Antarctic precipitation data

It is widely known that precipitation rates in Antarctica are low and that rain is comparatively rare, except in northerly parts of the Antarctic Peninsula. Thus salts are not easily flushed from surfaces once deposited. In addition, hypersaline lakes (figure 5.1) and localised salt deposits (figure 5.2) exist at or near some Antarctic bases and historic sites. Data on common ions in snow collected are reported by several national Antarctic organisations and can be accessed through the Scott Polar Research Institute website.

Figure 5.2: Salt deposits at Mawson Station aircraft hangar, author’s photo 1992

Detail of back wall furthest from sea.
5. Salts

5.2.3 Materials damage by salts

Most of the international materials conservation literature on salt damage has focussed on stone monuments in Mediterranean climates, such as the Sphinx in Egypt and frescoes in Italy where salts mostly cause damage by crystallisation after being carried by capillary action from ground waters (Camuffo 1998). Camuffo discussed the significance of dry deposition of airborne particulates, including salt particles. Salt particles can participate in multiple processes including wind erosion, electrophoresis, and chemical reactions that occur at high relative humidities, when selective leaching may occur.

When the author commenced research in Antarctica there were no detailed observations from Antarctic historic sites with respect to salts and the condition of wood. By chance, the author met researchers who had identified ‘defibring’ of wood in industrial cooling towers, in roofs in coastal Australia and in wooden boats used in seawater (Wilkins & Simpson 1988). Photographs confirmed the Antarctic timbers exhibited exactly the same appearance as those identified in their research. This appears to be the first time defibring was identified in Antarctica and attributed to salt action.

At that time, Wilkins and Simpson had concluded that heat (along with high humidity and sea salts) were essential characteristics of the phenomenon but on considering the evidence from Antarctica heat was considered not essential for defibring to occur but may accelerate deterioration. Subsequent contact (personal communication Anthony Wilkins, 1995) revealed that funding problems had prevented further research on processes and factors involved in defibring.

Various reports attributed timber damage with a similar appearance to ‘freeze-thaw’ action (eg (Blunt 1991: volume 2: 70) and others discussed in Appendix F). This indicated the necessity to clarify the cause of defibring and to assess the extent and seriousness of the damage caused by this phenomenon to Antarctic historic sites. At Cape Denison, the author was only permitted to take very small samples of timber for examination which limited opportunities for research.
Blanchette, Held and Farrell (2002) studied ‘defibration’ affecting historic buildings on Ross Island and analysed salts on affected timber and discussed the mechanism of damage. Their research findings are considered in detail in the discussion section of this chapter for comparison in combination with the author’s research to identify potential conservation strategies to address salt deterioration.

5.3 METHODOLOGY

5.3.1 Research questions

Observations of significant deposition of salts during the author’s initial visit to Cape Denison led to development of the following questions to guide further research:

1. What salt-related deterioration problems occur in Antarctica, and what is their severity?
2. What is the composition and origin (e.g. marine or non-marine) of the salts?
3. What is the rate of salt deposition inside and outside Antarctic historic buildings and what factors influence salt penetration into buildings?
4. How does the lack of rain affect rates of salt damage in Antarctica?
5. Is defibring of wood due to freezing-thawing processes of water or due to salts?
6. Can deterioration risks be predicted from salt deposition measurements?
7. What conservation treatments have been undertaken to address salt-related deterioration problems and how effective were they?
8. What are the implications of all of the above for site management?

5.3.2 Field observations (research question 1)

Observations at the 12 different historic sites are summarised in Table 3.1. While it was not possible to conduct a systematic survey of artefacts on a grid basis at each site, use of photographs facilitated observations and the observation template (Table 3.2) helped ensure consistent collection of data for inter-site comparisons. The observations included notes on:

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1 There are several terminology variations used by different researchers. ‘Defibring’ and ‘defibration’ are equivalent.
• Environmental characteristics where salts were observed (proximity to the sea and exposure to sea winds);
• Meteorological factors (especially humidity) that may affect the visibility of salt deposits;
• Potential sources of salts other than sea salt aerosols (e.g., inundation at high tides, guano, chemical usage, etc.); and
• Other evidence of salt damage including corrosion, damage to timber, etc.

5.3.3 Salt composition (research question 2)

Various analytical techniques were used, including Inductively Coupled Plasma, X Ray analysis and Raman microscopy, to determine salt composition and whether these were of marine origin or not, to examine the processes involved in salt deposition.

_Salts collected from snow samples Cape Denison, 1985_

Snow samples were collected on the ground at 16 locations shown on figure 5.6. Samples were collected using a small plastic spatula and were placed in small snap top polyethylene film containers previously rinsed with small quantities of 10 molar nitric acid then soaked in three changes of distilled water to remove any contaminants before being air-dried, closed and taken to the site inside a ‘zip-lok’ sealed plastic bag.

Time constraints and the highly variable distribution of snow on the site prevented sampling of snow on a grid basis across the headland. However, the sampling locations are representative of the different zones at the site:
• Snow drifts around each significant historic building;
• Locations where artefacts are found close to Boat Harbour; and
• Higher elevation locations such as Memorial Cross.

Areas visibly affected by recent melting were avoided to ensure, as much as possible, that the sample composition was typical of freshly deposited snow on a typical early summer day.
The salt solutions collected were analysed by Dante Crisante of Sydney Technical College using Inductively Coupled Plasma\(^2\). Due to funding constraints, no comprehensive analysis of ions was possible, and it was assumed that the majority of the salt present would be sodium chloride due to proximity to the sea. The author subsequently found this was a significant error. No further analyses of salt composition in snow are known to have been done at the site.

*Solid salts inside Ross Island historic buildings, 1996*

Salt deposits and defibring of timbers (both outdoors and indoors) were particularly evident at the Ross Island historic huts but had not, at that time, been reported at other Antarctic historic sites. Deposits were photographed during the author’s visit in February 1993 but permission for sampling could not be obtained until January 1996.

Sheridan Easdale of the New Zealand Antarctic Heritage Trust collected samples from the three historic huts on Ross Island and provided details of the sampling locations given in Table 5.1. Ms Easdale collected the samples by scraping visible salts from the wood surface using a clean dry surgical steel scalpel. The loose salts were then transferred to labelled glass sample jars with polyethylene lids before being sent to the author for analysis using X ray diffraction, X ray fluorescence and Raman microscopy\(^3\).

The samples were examined using the Siemens D501 Diffractometer at the Australian National University during June 1996. The equipment used a Cu X-ray tube with a graphite monochromator and SIE122D Automation. The interpretation of peaks and intensities was

---

\(^2\) Inductively Coupled Plasma (ICP) analysis is used to detect trace metal ions in environmental samples by generating plasma gas in which atoms are present in an ionized state and emit characteristic wavelength specific light which can then be measured.

Advantages of using an ICP include its low detection and ability to use very small sample volumes (0.5 ml of sample solution). Additional information is available from the following weblink to Virginia Tech: [http://www.cee.vt.edu/ewr/environmental/teach/smprimer/icp/icp.html](http://www.cee.vt.edu/ewr/environmental/teach/smprimer/icp/icp.html)

\(^3\) Descriptions of these methods are widely available. XRD and XRF use bombardment by X-radiation to induce elements to emit characteristic wavelengths that can be measured by a detector. Samples are prepared as finely ground powders. Raman microscopy uses a laser connected to a visual microscope to illuminate a sample (which does not need to be powdered) to produce Raman scattering in a range of characteristic wavelengths which can identify the components.
undertaken using a ‘Traces’ program by Diffraction Technology and search matches used µPDSM. The samples were ground in acetone using standard materials and techniques. Because of the small amount of sample available they were mounted in a quartz crystal low background holder for samples CE3, HP2, CE2 and CR1. Side packed samples were: HP3, CE1, HP1, CR3.

The µPDSM program identifies different crystal forms present with the best matches identified at the top of an output list. The search parameters were set identify all components to one percent. The tests were run twice and the crystal forms identified are listed in order of prevalence. Further information on identification and characteristics of minerals is available at:

http://www.handbookofmineralogy.org

Salts in corrosion products from Mawson Station, Davis Station and Rothera

During research on corrosion, through discussion with co-researchers from CSIRO and the University of Canberra it was recognised that analysis of corrosion products could improve understanding of effects of salts on Antarctic sites. Corrosion products were collected from standard low-alloy copper-bearing steel corrosion coupons exposed at three Antarctic sites (Mawson Station, Davis Station and Rothera)\(^4\). These coupons act as receptors for airborne pollutants such as sulphates and chlorides, and can thus provide information on the local geographical distribution of these anions at the test site over the period of exposure. Selection of analytical methods had to be carefully considered as only small amounts of corrosion product sample were available.

Summarising the choice of analytical methods:

- X-ray Fluorescence (XRF) was chosen because of its ability to analyse very small quantities of crystalline material and because the form of the salts could also be identified;
- Inductively-coupled Plasma mass spectrometry (ICP-MS) for its ability to determine anions; and
- Raman microspectroscopy because of its ability to differentiate different crystals within a mixture.
Data on aerosols captured at Mawson and Davis Stations were available from other studies conducted by CSIRO. It is important to ensure all ionic components in a salt sample are accounted for in the analysis. Anions and cations should be in ionic balance\(^5\).

5.3.4 Measurement of salt deposition rate (Research question 3)

*Salt candle method ISO 9225*

Atmospheric chemists study the size, quantity and composition of aerosols and the concentration of pollutant gases, but rarely measure atmospheric salt deposition rates. However, this is the most important information for conservators since salt deposits on the ground may not be representative of atmospheric conditions and can be affected by extraneous factors. Whilst it would be ideal to directly measure salt and even atmospheric gas deposition (*eg* by measuring salts deposited directly onto a surface), the cost and logistics problems made these methods impossible.

The ISO 9225 Salt Candle method is a widely used measurement method for atmospheric salt deposition, enabling comparison at different sites. The salt candle apparatus (figure 5.3, see also figure 6.12) consists of a bottle containing a solution of glycerol and water into which an upturned test tube is inserted, wrapped with gauze bandaging that captures salts from the atmosphere. Salt is deposited onto the gauze surface which remains wet by a wicking action from the solution in the jar. Salt is drawn down into the solution which is changed at monthly or other suitable intervals and chemically analysed.

At the end of the exposure period, the salts are washed into the bottle, and the salt content of the glycerol solution is analysed to determine the quantity of salt collected over the exposure period.

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\(^4\) This research is discussed also in Chapter 6. The method of preparation and processing of the coupons, and the analysis of the samples, are described in Otieno-Alego *et al* 2002, bound as Appendix H in this thesis.

\(^5\) This proved to be particularly important in Antarctica since cost constraints had initially prevented analysis of all the ions, so it was assumed most salts present would be chlorides because of the close proximity of the sites to the sea, as is common elsewhere. As previously mentioned, in Antarctica this assumption was not valid (see discussion section of this chapter) and once this was identified additional care was taken to examine all ionic components.
5. Salts

(King, Ganther & Cole 1999). Minor modifications were made for Antarctic use by increasing the concentration of glycerol from the usual 20% to 40% to prevent freezing that would prevent capillary transport of the glycerol and reduce entrapment of salts. Minor re-design of the brackets holding the bottle improved security in high winds.

Salt candle measurements were limited to Cape Denison due to the cost constraints. The apparatus was exposed during summer when there was no sea ice. Ideally, ISO 9225 salt candle measurements (ISO 1992) would be undertaken at the same time as corrosivity measurements to enable a direct comparison of results. However, salt candle measurements are very time consuming since the ‘candle’ must be changed each month and the wash water must be titrated which requires a skilled operator. In windy locations there is a high risk of the apparatus being damaged.

Figure 5.3: Diagram of salt candle apparatus for ISO 9225
Rosales and Fernandez (2001) found salt candle measurements too difficult to arrange logistically and instead used snow collected in a pluviometer to measure salt deposition at Antarctic Peninsula sites.

Salt deposition inside a building can also be measured using ISO 9225, but could not be conducted inside the AAE main hut as the Antarctic Science Advisory Committee considered that use of a naked flame would endanger the building. This was unfortunate since there has still been no measurement of salt penetration into the building which could quantify the salt-related risks to building fasteners and artefacts and enable comparison with Mason’s (1999) measurements at Cape Evans that also used the salt candle method.

New methods are available from CSIRO for measurement of ‘SOx and NOx’ (sulphur oxide and nitrogen oxide gases) which are common pollutants of interest in various environmental and engineering research. These methods were either too expensive or could not be obtained at short notice when opportunities were available for testing in Antarctica, but are highly recommended (especially for sulphates) for future studies.

5.3.5 Scanning electron microscope (SEM) examination of defibred wood from Cape Denison (research question 5)

Two samples of defibred timber were collected from Cape Denison in 1985. One piece was approximately 70mm long, 15mm thick and 25mm wide, tapering to 5mm at one end. The other was approximately 30mm x 10mm x 8mm. Both appeared to be of Baltic Pine or similar light coloured softwood, and the shape suggested they were parts of a dislodged batten formerly nailed to the roof, the outer surface of which had also been eroded by wind. These were collected from the ground among other debris approximately 1.5 metres from midpoint of the western wall of workshop of the AAE main hut.

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6 This is not feasible at Cape Denison due to wind damage risks and because the pluviometer would fill with snow drift, which is not representative of salt deposition.
7 Explanation had been provided that clearly showed the method did not involve such risks as the ‘candle’ referred to the appearance of the equipment rather than use of an actual candle.
8 With permission of the Australian Heritage Commission and the Australian Antarctic Division
A fragment from the narrow end of the larger sample which exhibited extensive defibring was cut with a scalpel, although many loose fibres detached under vacuum. Other small fragments of the two samples exhibiting typical defibring were examined at a range of magnifications by SEM\(^9\) at the Australian Antarctic Division.

5.3.6 Relationship of deterioration problems and salt deposition/concentration (research question 6)

Salt deposition, wind and composition data are collated in Table 5.4. These are compared with the deterioration problems occurring at the different sites to consider whether evidence for the purported mechanisms of damage causation are clear and how this can identify what treatments will be effective.

5.3.7 Effectiveness of conservation treatments (research question 7)

The Ross Island sites are the only locations where any significant treatments of salt problems have occurred. Literature sources and the author’s observations in 1993 were used to consider the effectiveness of treatments, collated in Table 5.5.

Effectiveness criteria devised by the author are:

- compliance with ethical and aesthetic requirements,
- frequency of any re-treatment required,
- relative costs; and
- ability to prevent further damage.

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\(^9\) The preparation of samples, operation of equipment and application to materials conservation research are described in many widely available publications (\textit{eg} Goldstein \textit{et al} 2003) and are not described here for space reasons. In brief SEM produces images of a surface by scanning it with a high-energy beam of electrons in a raster scan pattern and can produce very highly magnified images (up to 250,000 times). The electrons interact with the atoms at the surface producing signals that characterises the sample’s surface topography, composition and other properties such as electrical conductivity.
5.3.8 Assessment of implications for site management (research question 8)

The key conclusions from all the methods (observations, analyses of salts, etc) were considered together to identify the need for developing new treatments and to assess the consequences of failure of existing treatments.

5.4 RESULTS

5.4 1 Field observations

Table 5.1: Summary of observations of salt problems

Notes: Darker shaded rows indicate sites with predominantly katabatic winds from the polar plateau. Cape Adare experiences periodic orographically forced katabatic winds but also receives significant marine winds. Regarding weather conditions, ‘conducive’ indicates conditions were favourable visually identifying salts (ie RH was below deliquescence for NaCl). ‘Extensive’ means coverage exceeds more than 75% of the area, ‘common’ means coverage between 25 to 74% of the surface.

<table>
<thead>
<tr>
<th>Site and proximity to nearest point of the sea (summer)</th>
<th>Potential salt sources apart from the sea</th>
<th>Salts visible on ground</th>
<th>Salts visible inside buildings</th>
<th>Weather conditions during observation</th>
<th>Defibring-present, observations</th>
<th>Corrosion observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mawson Station, 100-170 m</td>
<td>Localised past chemical usage near met buildings (NaOH).</td>
<td>Yes-extensive (fig 5.2). No evidence of water stains on wood suggests minimal surface flushing.</td>
<td>Yes, moderate in Aircraft Hangar, not evident in other older buildings which are further from shore and more tightly closed.</td>
<td>Conducive. Temperature ranged from about -5° to +1°C; RH variable including snow/sleet. Gusty winds.</td>
<td>Yes, common but localised, moderate severity. Affected fragments of old timber at refuse dump, Alice’s Restaurant(^\text{10}). paint-free timbers on early buildings. Evident in locations sheltered from precipitation and blowing snow.</td>
<td>Extensive, severe especially at Aircraft Hangar (fig 5.2)</td>
</tr>
</tbody>
</table>

\(^{10}\) Field hut relocated from Taylor Glacier to near Horseshoe Harbour.
<table>
<thead>
<tr>
<th>Site and proximity to nearest point of the sea (summer)</th>
<th>Potential salt sources apart from the sea.</th>
<th>Salts visible on ground</th>
<th>Salts visible inside buildings</th>
<th>Weather conditions during observation</th>
<th>Defibring-present, observations</th>
<th>Corrosion observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rumdoodle Hut, 18 km</td>
<td>Unlikely</td>
<td>No</td>
<td>No</td>
<td>Conducive,-10°C, windy, dry</td>
<td>Not observed</td>
<td>Minimal.</td>
</tr>
<tr>
<td>Davis Station, ~ 50-120 m</td>
<td>Hypersaline lakes nearby. Chemical usage possible in some locations.</td>
<td>Yes, extensive, severe. Salt crystals (halite) visible on sheltered exterior of windows.</td>
<td>Some water leakage but salts are not easily seen as most surfaces are painted. Little evidence of water stains or surface flushing by rain or meltwater.</td>
<td>Not conducive. T= ~-5 to +2°C. RH high including some snow/sleet.</td>
<td>Yes, common localised, moderate severity, in areas protected from winds only.</td>
<td>Extensive, severe, associated with corrosion on old dongas.</td>
</tr>
<tr>
<td>Platcha Hut, ~40 m from fjord edge, 18 km from the sea (fig 1.22)</td>
<td>Near hypersaline lakes.</td>
<td>Yes, extensive, moderate</td>
<td>No- surfaces are painted, some stains evident but no salts visible.</td>
<td>Conducive.--5°C, RH moderate, calm.</td>
<td>Yes, extensive on bare timber, moderate in areas protected from wind which retain moisture.</td>
<td>Extensive but moderate severity</td>
</tr>
<tr>
<td>Dumont d’Urville, Base Marret ~100 m from sea (fig 2.23).</td>
<td>Some guano and past chemical use.</td>
<td>Yes, extensive, moderate</td>
<td>Not inspected.</td>
<td>Conducive.--5°C, high RH, cloudy, moderate winds.</td>
<td>Yes, extensive on bare timber, moderate to locally severe. Affects footings of Base Marret, timber crates near air strip.</td>
<td>Extensive, severe</td>
</tr>
<tr>
<td>Cape Denison, Main hut ~45 m, other buildings ~50m from the sea.</td>
<td>No significant guano. No recent chemical use. Water stains on roof and walls indicate some salt flushing occurs from meltwater and rain (rare).</td>
<td>Yes, extensive, moderate. Stepped rectangular crystals (typical of halides) seen on windows of the Apple Hut in 1985 near AAE main hut.</td>
<td>Not evident. Meltwater was running down the walls (1985, fig 4.15, 4.16).</td>
<td>1985 Not conducive. Extensive snow cover was and high RH so salt crystals unlikely to be visible. 1997 Conducive. sunny, moderate RH.</td>
<td>Yes, localised in protected areas among ‘artefact plume’ north of Main Hut; in boxes containing Memorial Plaque and Proclamation Plaque (1977 – 1985). Variable severity (moderate to locally severe) fig 5.3. Strong winds can remove fibres.</td>
<td>Extensive, locally severe. ‘Bronze disease’ on boxes of Memorial and Proclamation plaques. Nails-irridescent. Tin cans, gutters, ridge-capping and fuel tins severely corroded (fig 2.19).</td>
</tr>
<tr>
<td>Site and proximity to nearest point of the sea (summer)</td>
<td>Potential salt sources apart from the sea.</td>
<td>Salts visible on ground</td>
<td>Salts visible inside buildings</td>
<td>Weather conditions during observation</td>
<td>Defibring-present, observations</td>
<td>Corrosion observations</td>
</tr>
<tr>
<td>------------------------------------------------------</td>
<td>------------------------------------------</td>
<td>-----------------------</td>
<td>-------------------------------</td>
<td>-------------------------------------</td>
<td>---------------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>Cape Adare, building are ~100 m from the sea (figs 1.14, 5.11).</td>
<td>Guano (Adelie rookery surrounds buildings). Scattered (food) salt from damaged barrel. Chlorine bleach used during construction (1895) to reduce guano odour. Insulated with seaweed in Gibson's quilting, (Harrowfield, D 1996).</td>
<td>Yes, extensive, severe, particularly where it is high enough above the ground to avoid corrosion by sand particles.</td>
<td>Visible on some objects inside the Southern Cross hut, but these may have been relocated. Defibring noted by (Harrowfield, D 1990: 64) during visit in 1989.</td>
<td>Not conducive. T= -5C RH high. Occasional sleet reduced the likelihood of observing salts on the ground. Harrowfield (1991) noted that RH is always 70-100% in summer.</td>
<td>Yes- moderate. Extensive on exterior timbers, particularly where high enough above ground to avoid corrosion (fig 5.17). Defibred Baltic pine logs are bleached. Some items inside hut are affected, possibly relocated (fig 5.18). Fibres are easily removed by corrosion.</td>
<td>Extensive, severe. Barrel bands have rusted right through but some vestigal metals have irridescent appearance characteristic of chlorides.</td>
</tr>
<tr>
<td>Cape Royds, Nimrod hut ~120 m from the sea.</td>
<td>Guano from adjacent Adelie penguin rookery (November to February). Sulphur compounds from Mt Erebus [subsequently refuted].</td>
<td>Yes. Salt deposits were highly visible on the ground, especially near the met screen (figure 5.7) and towards the penguin rookery. Stables affected.</td>
<td>Yes, extensive, severe. Salt trails (fig 5.5) notably at the junction of the roof and the walls. Defibring on sledges hanging from ceiling, possibly relocated from outside (fig 5.18).</td>
<td>Conducive. T= ~ -10°C RH was low (&lt;35%) as static electricity was evident on author’s clothing.</td>
<td>Yes. Extensive, severe outside, some artefacts (relocated) inside hut. Ropes and cane/rattan bleached and defibred. Significant damage at ground level inside entry area of hut (? capillary action).</td>
<td>Extensive, severe corrosion of tins outside hut (corroded through), fig 6.20.</td>
</tr>
<tr>
<td>Cape Evans Terra Nova hut is ~100 m from the sea</td>
<td>Some historical chemicals stored inside hut. Corroded batteries are shedding powdery material.</td>
<td>Yes, extensive, severe, salt streaks/films on windows, Timber is bleached, northfacing sides as well as west facing side</td>
<td>Yes. Salt runs inside building from the roof.</td>
<td>Conducive. As at Cape Royds</td>
<td>Yes. Extensive, severe, particularly stables (fig 5.14). Defibring on most exterior timbers ~1m above ground, worst on seaward western side. Objects on the</td>
<td>Extensive, severe Blistering, bronze disease, irridescence on steel (fig 5.16, fig 6.20).</td>
</tr>
</tbody>
</table>
### 5. Salts

<table>
<thead>
<tr>
<th>Site and proximity to nearest point of the sea (summer)</th>
<th>Potential salt sources apart from the sea.</th>
<th>Salts visible on ground</th>
<th>Salts visible inside buildings</th>
<th>Weather conditions during observation</th>
<th>Defibring-present, observations</th>
<th>Corrosion observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hut Point, ~100 m</td>
<td>Possible pollutants from McMurdo shipping operations (see fig 10.9).</td>
<td>Yes, extensive, moderate</td>
<td>Not seen, possibly due to poor light. Salts visible on coal (fig 5.19)</td>
<td>Conducive. As at Cape Royds</td>
<td>Yes, extensive, variable (moderate to locally severe) Defibring on most exterior timber 1 m above ground. Worst on sheltered areas.</td>
<td>Extensive, moderate, iridescent patches on some exposed metals.</td>
</tr>
<tr>
<td>Scott Base, TAE hut ~50 m from sea</td>
<td>Possible past chemical usage, including road clearing salts.</td>
<td>Salt deposits on some windows including laboratory, mess, not visible on ground.</td>
<td>Not evident except on base of wooden sign post.</td>
<td>Conducive. As at Cape Royds</td>
<td>Not many unpainted timbers, so difficult to determine.</td>
<td>Significant, streaks of rust on new painted buildings.</td>
</tr>
<tr>
<td>McMurdo Base, &lt;250 m</td>
<td>Possible past chemical usage including road clearing salts.</td>
<td>Salt deposits on some windows including NSF HQ, but not visible on ground.</td>
<td>Too difficult to see.</td>
<td>Conducive. As at Cape Royds.</td>
<td>Evident on exposed timber at base of signs.</td>
<td>Extensive. Significant iridescent patches on exposed metals.</td>
</tr>
</tbody>
</table>

Thus, all except Rumdoodle (18 km inland), i.e. 11 of 12 sites, had visible salt deposits on the ground or on building surfaces. Defibring was evident at 11 of 12 sites, severe at Cape Evans. Significant corrosion was evident at all sites except Rumdoodle.

**Examination of the Memorial plaque and Proclamation Plaque**

These historic plaques were enclosed in bronze boxes in 1977 to protect them from damage by wind borne ice particles. By 1985 both showed evidence of salt deposition and corrosion. Enclosure in the metal box appears to have increased the severity of daily temperature and RH fluctuations through solar warming. In summer the temperature, while not measured, could be expected to be significantly above 0°C for long periods. The interiors of both boxes were wet.
when opened by Project Blizzard in December 1984. Ice particles containing salts penetrated the seal causing the bronze to corrode (figure 2.19), which stained the wood blue (figure 2.20) and resulted in severe defibring (figures 2.18, 5.3). The plaques were returned to Australia in 1985\textsuperscript{11}.

Figure 5.4: Detail of defibring of Proclamation plaque, Project Blizzard 1984

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{proclamation_plaque_defibring.png}
\caption{Detail of defibring of Proclamation plaque, Project Blizzard 1984}
\end{figure}

\textit{Salt trails inside Cape Evans and Cape Royds huts}

Salts are visible as trails of whitish crystals running down the walls and ceiling from the roof (figure 5.5). The trails all had a thicker layer at the edges, evidence of formation by evaporation of liquid (meltwater), although some salt deposits were also visible on the lower walls of Scott’s hut at Cape Evans suggesting capillary action.

The salt trails were easily visible at Cape Evans and at Cape Royds but not so easily visible at Hut Point due to poor weather conditions and insufficient light inside the hut during the visit. At Cape Royds the surfaces area where salts were visible covered approximately five square metres of the ceiling and upper walls on there were at least several grams on each windowsill. At Cape Evans, the salt deposits appeared to be more diffuse but were evident over at least ten square metres of the walls. In each of these huts it would be possible to gather several hundred grams of salt. Such quantities of salts are rarely seen in habitable buildings in temperate climates even next to the sea.

\textsuperscript{11} It should be noted there were few sources of professional conservation advice at that time.
5. Salts

Figure 5.5: Salt deposits inside Cape Royds hut (author’s photo 1993)

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5.4.2 Salt composition and origin

_Salts in snow samples Cape Denison 1985_

Figure 5.6a: Salt sample locations at Cape Denison, 1985, outdoors
Table 5.2a: Analyses of salts from snow at various locations at Cape Denison, 1985

Table 5.2a: salt analyses, Cape Denison and Cape Evans (concentrations in ppm)

Note: Samples 1, 3, 4, 9, 12, 20 and 21 were not tested for salts.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location</th>
<th>Sn</th>
<th>Zn</th>
<th>Fe</th>
<th>Cr</th>
<th>Cl(^{12})</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Underneath acetylene gas generator, Living hut.</td>
<td>72</td>
<td>35</td>
<td>40</td>
<td>37</td>
<td>315</td>
<td>Ice sample contained small reddish particles. When dried, the solid residue appeared to be rust.</td>
</tr>
<tr>
<td>5</td>
<td>Hut entrance.</td>
<td>24</td>
<td>1.5</td>
<td>30</td>
<td>2.0</td>
<td>35</td>
<td>Freshly deposited ‘blown’ (ie not fallen) snow.</td>
</tr>
<tr>
<td>6</td>
<td>Treacle from opened tin in Living hut.</td>
<td>2600</td>
<td>&lt;0.2</td>
<td>3350</td>
<td>&lt;0.1</td>
<td>750</td>
<td>The high Sn and Fe may result from corrosion of the tin can due to the acidic nature of the treacle.</td>
</tr>
<tr>
<td>7</td>
<td>Snow from ground midway between Magnetograph House and Penguin</td>
<td>2.0</td>
<td>1.0</td>
<td>94</td>
<td>0.3</td>
<td>3980</td>
<td>High chloride is not unexpected so close to the sea.</td>
</tr>
</tbody>
</table>

\(^{12}\) Chloride results have been calculated from the sodium content of the samples, assuming equal ratios of both.
<table>
<thead>
<tr>
<th>No.</th>
<th>Location Description</th>
<th>Concentration (g/l)</th>
<th>Chloride (g/l)</th>
<th>Other Salts (g/l)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Hard ice under E skylight, Living Hut</td>
<td>&lt;2.0 0.2 0.6 &lt;0.1</td>
<td>36</td>
<td>The ice had melted and refrozen but was not stained. Appeared to be frozen meltwater from the roof.</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Water from melt pool northern side Magnetograph House</td>
<td>2.0 &lt;0.2 1.0 &lt;0.1</td>
<td>246</td>
<td>Comparatively higher chloride, possibly due to dissolution of salts washed from nearby rocks and concentrated by drying, possibly also from greater exposure to seaspray.</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Snow surrounding treacle container on book case.</td>
<td>220 0.3 530 0.7</td>
<td>120</td>
<td>Water phase extracted in 10% HNO₃</td>
<td></td>
</tr>
<tr>
<td>13(a)</td>
<td></td>
<td>260 1.0 670 1.6</td>
<td>54</td>
<td>Organic phase in 10% HNO₃</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Snow immediately to the east of cross member, Memorial Cross</td>
<td>&lt;2.0 &lt;0.2 &lt;0.2 &lt;0.1</td>
<td>57</td>
<td>Fresh deposited ‘blown’ snow.</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Stained (brown) snow near acetylene plant.</td>
<td>&lt;2.0 220 1.3 &lt;0.1</td>
<td>820</td>
<td>Organic layer is motor oil (identified by odour). Appears to be partly emulsified, which may account for relatively high concentration.</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Snow with yellow stain near roof of Living Hut.</td>
<td>&lt;2.0 26 160 &lt;0.1</td>
<td>1900</td>
<td>Large black algae grew inside the container. The concentration is unusually high. It is difficult to draw conclusions from this sample since it is not clear how the algae arose.</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Rust flake from entrance to Main Hut</td>
<td>4 0.6 4.5 0.1</td>
<td>70</td>
<td>Dissolved in 10% HNO₃</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>E side of cliff, 100 m from sea near John O’Groats</td>
<td>&lt;2.0 &lt;0.2 1.0 &lt;0.1</td>
<td>15</td>
<td>Fresh deposited ‘blown’ snow.</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Cape Evans, latrine</td>
<td>&lt;2.0 &lt;0.2 &lt;0.2 &lt;0.1</td>
<td>210</td>
<td>Snow sample collected from the ground</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Cape Evans, latrine</td>
<td>&lt;2.0 &lt;0.2 1.3 0.1</td>
<td>255</td>
<td>Snow sample collected from the ground</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Cape Evans, latrine</td>
<td>&lt;2.0 &lt;0.2 1.4 &lt;0.1</td>
<td>230</td>
<td>Snow sample collected from the ground</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Cape Evans, latrine</td>
<td>&lt;2.0 &lt;0.2 1.1 0.1</td>
<td>330</td>
<td>Snow sample collected from the ground</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Main hut, Trench 1, layer 3a</td>
<td>&lt;2.0 21 76 0.2</td>
<td>420</td>
<td>Snow sample</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Main hut, Trench 2, layer 2</td>
<td>&lt;2.0 0.7 3.5 &lt;0.1</td>
<td>26</td>
<td>Snow sample</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Main hut, Trench 4, layer 3</td>
<td>&lt;2.0 2.8 54 &lt;0.1</td>
<td>890</td>
<td>Snow sample</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Main hut, Trench 4, layer 4</td>
<td>&lt;2.0 6.0 2.3 &lt;0.1</td>
<td>85</td>
<td>Snow sample</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Main hut, Trench 4, layer 5</td>
<td>&lt;2.0 1.5 1.5 &lt;0.1</td>
<td>63</td>
<td>Snow sample</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Orange ice, Main Hut</td>
<td>6.3 8.9 34 &lt;0.1</td>
<td>2200</td>
<td>Precise location not stated.</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Stained snow from inside Absolute Hut</td>
<td>3.0 1.0 4.1 &lt;0.1</td>
<td>380</td>
<td>Snow sample</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Snow, open area of ground on Gt Mackellar Islet</td>
<td>&lt;2.0 &lt;0.2 0.3 &lt;0.1</td>
<td>3870</td>
<td>Solid is CaCO₃ (identified by micro test with acid, generated effervescence).</td>
<td></td>
</tr>
</tbody>
</table>
5. Salts

<table>
<thead>
<tr>
<th>Element</th>
<th>Detection limits (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn</td>
<td>2.0</td>
</tr>
<tr>
<td>Zn</td>
<td>0.2</td>
</tr>
<tr>
<td>Fe</td>
<td>0.2</td>
</tr>
<tr>
<td>Cr</td>
<td>0.1</td>
</tr>
<tr>
<td>“Cl”</td>
<td>5</td>
</tr>
</tbody>
</table>

The nominal error for the above results is ±10% or better.

**Cape Denison outdoor samples**

Measurements of fresh snow outside and inside the hut recorded sodium concentration of 15-30 ppm, from which chloride concentration was inferred to be equivalent, 15-30 ppm, presuming the predominant salt is NaCl. High concentrations occur close to the sea (eg sample 7, 3980 ppm). Relatively high concentrations occurred in meltwater pools (eg sample 11, 246 ppm) but samples close to the Memorial Cross were only moderately high, (eg sample 14 = 57 ppm).

Falling snow is rare at Cape Denison, whereas blowing snow is high. Accordingly, evenly freshly deposited snow is likely to be blown snow carried by the katabatic winds from the polar plateau. This infers it will have a lower chloride:sulphate ratio than sea salt due to preferential leaching of chloride, as described by Campbell and Claridge. Based on the lowest “chloride” measurement of the outdoor samples, then the background level of blown snow at Cape Denison is approximately 15 ppm and higher concentrations are due to either direct sea salt deposition, or from minerals in the ground, or from concentration of salts of either marine or terrestrial origin.

Heavy metal concentrations outdoors are generally low even when “chloride” is high (eg samples 11, 14, 19, 33) but some samples close to huts have relatively high levels of Sn and Fe (samples 7, 32).

**AAE main hut indoor samples**

Freshly deposited blown snow (sample 5, 35 ppm) and hard ice composed of meltwater (sample 8, 36ppm) and sample 27 (26ppm) are similar to the lowest outdoor “Cl-“ concentrations.
5. Salts

Samples 2 (315 ppm) and corrosion products (sample 15 = 820 ppm; sample 16 = 1900 ppm; sample 31 = 2200 ppm) have significantly higher Na/Cl concentrations suggesting either inflow of meltwater containing higher salt concentrations (eg from rocks) or concentration processes. High concentrations of “Cl” do not necessarily have high concentrations of heavy metals. While the data is limited, it suggests there may be periodic processes which result in relatively concentrated salts entering and remaining in the building.

Cape Evans samples 22-25.

Due to bad weather samples could only be collected from one location near the latrine and the age of the snow at collection was not determined. Concentrations measured (210-330 ppm) were higher than the 34 ppm measured by Blanchette, Held and Farrell (2002, Table 3) in new snow from the roof, as to be expected.

AAE main hut trench samples 26-20

There were not enough samples from the trenches to draw statistically valid relationships, but all Sn and Cr concentrations are below detection, and higher sodium concentration is associated with higher Fe and Zn concentration although the relationship is not constant. Possible reasons include:

- Low concentrations may indicate a layer of fresh snow, comparatively unmelted.
- Frozen meltwater from the roof and walls may contain higher salt concentrations from deposited aerosols.
- Meltwater flowing over the floor may have entered the hut from surrounding rocks, again a source of salts.

Chloride concentrations measured using ion selective electrode are a direct measurement of chloride and were significantly lower than sodium measurements in Table 1, suggesting that Table 5.2a results also include other sodium salts. The chloride ion measurements in Table 5.2b (all taken inside the hut) suggest a background level of approximately 7 mg/litre Cl-. The varying
levels of chlorides found in the different layers suggest intermittent ingress of more concentrated salts in meltwater that have re-frozen.

Table 5.2b: Samples taken in December 1984 to January 1985 from inside and adjacent to the AAE Main Hut, analysed using a chloride ion-selective electrode.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location</th>
<th>Chloride, mg/litre</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>Inside main hut near stove</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td>Ice, E side of hut</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td>SW wall of hut, layer 2</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td>Snow inside hut near shelves</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>#5</td>
<td>S wall profile, layer 4</td>
<td>169</td>
<td>Higher [Cl-] may be due to evident seepage from adjacent rocky area</td>
</tr>
<tr>
<td>#6</td>
<td>Snow sample inside hut, location not known</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>#7</td>
<td>Snow sample on chair, Mawson’s room</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>#8</td>
<td>Ice, NE corner of living hut</td>
<td>Not analysed</td>
<td></td>
</tr>
<tr>
<td>#9</td>
<td>Snow, E of McLean’s bunk</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>#10</td>
<td>Snow, E of McLean’s bunk</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>#11</td>
<td>Snow, living hut, E of FL’s bunk, N of Webb’s</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>#12</td>
<td>Snow, living hut, layer 14/15</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>#13</td>
<td>Snow, living hut, layer 10</td>
<td>355</td>
<td></td>
</tr>
<tr>
<td>#14</td>
<td>Snow, living hut, layer 14a</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>#15</td>
<td>Snow, living hut, layer 2</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>#16</td>
<td>Snow, living hut, layer 4</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

Solid salts inside Ross Island historic buildings 1996

Figure 5.7: Salt samples from C Royds, C Evans, Hut Pt (author’s photo 1996)
## Table 5.3: Analyses of salts collected inside historic buildings on Ross Island

<table>
<thead>
<tr>
<th>Site</th>
<th>Sample name &amp; (ANU identifier)</th>
<th>Date collected</th>
<th>Location in the hut</th>
<th>Compounds identified (strongest match in bold type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hut Point</td>
<td>HP1 (A10347)</td>
<td>23.1.96</td>
<td>Lean-to.</td>
<td>Thenardite ((\text{Na}_2\text{SO}_4, 37-1465)) Potassium sodium aluminium silicate (sandine (a feldspar), anorthite, albite) possibly from dust. Halite (\text{NaCl}) Sodium calcium aluminium silicate hydrate (a zeolite, from volcanic tuff).</td>
</tr>
<tr>
<td>Hut Point</td>
<td>HP2 (10675)</td>
<td>23.1.96</td>
<td>Upper wall and lower part of ceiling near window, SE corner [of building]</td>
<td>Thenardite Ammonium Magnesium sulphate hydrate ((\text{NH}_4)_2\text{Mg(SO}_4\text{)}_2\cdot6\text{H}_2\text{O}) Boussingaultite ((\text{NH})_2\text{Mg(SO}_4\text{)}_2-6(\text{H}_2\text{O})) Eugsterite ((\text{Na}_2\text{Ca(SO}_4\text{)}_3\cdot2\text{H}_2\text{O}))</td>
</tr>
<tr>
<td>Hut Point</td>
<td>HP3 (10676)</td>
<td>23.1.96</td>
<td>Lowered ceiling, NE corner of hut</td>
<td>Thenardite Eugsterite Arcanite ((\text{K}_2\text{SO}_4)) (11 hits but one miss) Hydrotalcite \text{Mg}_6\text{Al}_2\text{CO}<em>3(\text{OH})</em>{16}.4\text{H}_2\text{O} possible.</td>
</tr>
<tr>
<td>Cape Evans</td>
<td>CE1 (10674)</td>
<td>17.1.96</td>
<td>Underside of shelf, immediately left of window in south wall of hut.</td>
<td>Thenardite Also, mirabilite \text{Na}_2\text{SO}_4\cdot10\text{H}_2\text{O}</td>
</tr>
<tr>
<td>Cape Evans</td>
<td>CE2 (10679)</td>
<td>17.1.96</td>
<td>Damp base of wall in SW corner of hut, under table.</td>
<td>Thenardite Eugsterite ((\text{Mn,Ca})\text{SiO}_3) Bustamite</td>
</tr>
<tr>
<td>Cape Evans</td>
<td>CE3 (10675)</td>
<td>17.1.96</td>
<td>Lower part of wall in first bunk area on N side of hut.</td>
<td>Thenardite Copiapite (Iron oxide sulphate hydrate, but some peaks missing, \text{Fe}^{++}\text{Fe}^{+++}_4(\text{SO}_4)<em>6(\text{OH})</em>{20}(\text{H}_2\text{O}) Eugsterite</td>
</tr>
<tr>
<td>Cape Royds</td>
<td>CR1 (19680)</td>
<td>12.1.96</td>
<td>Underside of long shelf on N wall at E end of hut above cot.</td>
<td>Thenardite Gypsum ((\text{CaSO}_4\cdot2\text{H}_2\text{O}))</td>
</tr>
<tr>
<td>Cape Royds</td>
<td>CR2</td>
<td>12.1.96</td>
<td>Wall immediately above (right) window on N side.</td>
<td>Not examined due to difficulty with sample.</td>
</tr>
<tr>
<td>Cape Royds</td>
<td>CR3 (10677)</td>
<td>12.1.96</td>
<td>Ceiling of Shackleton’s room.</td>
<td>Thenardite Eugsterite Burbankite ((\text{Na,Ca})_3(\text{Sr,Ba,Ce})_3(\text{CO}_3)_5) Sodium calcium strontium sulphate (possible)</td>
</tr>
</tbody>
</table>

**Notes:**
- Thenardite is the strongest match in all samples examined by XRD. Testing with barium chloride confirmed the presence of sulphate as a dense precipitate of barium sulphate was formed.
- All the above results were subsequently confirmed using Raman microscopy.
Salts in corrosion products from various Antarctic sites

The composition of aerosols collected at Mawson and Davis Stations are given in Table 5.4 for three species (SO$_4^{2-}$, Na$^+$ and Cl$^-$) in two size fractions (fine ≤1 µm; coarse ≤8 µm), collected on filter papers. The sulphate can be of either sea salt (SS) or non-sea salt (NSS) origin, distinguished by assuming that the SO$_4^{2-}$:Cl$^-$ mole ratio in sea water was 0.0517, see Appendix H Otieno-Alego et al (2000: 6).

The weight percentage of chloride and sulphur in corrosion products is given in the right hand columns of Table 5.4, specifying the analytical method used and other relevant environmental factors.

5.4.3 Measurement of the rate of salt deposition

Salt deposition measurements at various Antarctic sites are collated in Table 5.4 with the results of other researchers included for comparison.

5.4.4 Data on precipitation (rain and snow) from various sources

Rain and snow precipitation data at various sites are presented in Table 5.4. For some sites the only precipitation data available are days of blowing snow.
5. Salts

Table 5.4: Antarctic precipitation, salt deposition and corrosion product data

Note: deeply shaded rows indicate sites with predominantly katabatic winds from the polar plateau. Cape Adare experiences periodic orographically forced katabatic winds but also receives significant marine winds. NSS= non sea salt, SS= sea salt

<table>
<thead>
<tr>
<th>Site (distance from the sea)</th>
<th>Wind- speed (km/hr), direction, type</th>
<th>Precipitation</th>
<th>Salt deposition Collection method</th>
<th>Salt deposition measurement</th>
<th>Salts retained in corrosion products</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>XRF</td>
<td>ICP-MS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NSS SO₄²⁻ fine</td>
<td>99.7 (µg m⁻³)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NSS SO₄²⁻ coarse</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total NSS SO₄²⁻</td>
<td>110.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SS SO₄²⁻ fine</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SS SO₄²⁻ coarse</td>
<td>9.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total ss SO₄²⁻</td>
<td>17.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total SO₄²⁻</td>
<td>128.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Na⁺ fine</td>
<td>37.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Na⁺ coarse</td>
<td>33.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total Na⁺</td>
<td>71.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cl- fine</td>
<td>46.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cl- coarse</td>
<td>50.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total Cl⁻</td>
<td>97.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(reference: Appendix H Table 1)</td>
<td></td>
</tr>
<tr>
<td>Mawson (100-170 metres)</td>
<td>Annual mean 3pm wind speed 10.25 m/s (36.9 kph) (source: <a href="http://www.bom.gov.au">www.bom.gov.au</a>) Katabatic, SE</td>
<td>Precipitation is not measured due to difficulty of distinguishing blowing snow from falling snow. Mostly blowing snow. Rain is rare 4 days of snowfall per month, higher in winter, 10 days of drift snow in winter, one day in summer (per month). (Streten 1990)</td>
<td>Aerosols collected on filters, fine ≤1 µm; coarse ≤8 µm</td>
<td>NSS SO₄²⁻ fine 99.7 (µg m⁻³)</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NSS SO₄²⁻ coarse 11.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total NSS SO₄²⁻ 110.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SS SO₄²⁻ fine 7.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SS SO₄²⁻ coarse 9.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total ss SO₄²⁻ 17.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total SO₄²⁻ 128.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Na⁺ fine 37.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Na⁺ coarse 33.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total Na⁺ 71.6</td>
<td></td>
</tr>
<tr>
<td>Davis (~120 metres)</td>
<td>Mean annual windspeed is 19 km/h. Windiest month is November, lightest winds in May. Direction is between N and E (&gt;80 % in some months).</td>
<td>Mean annual average days of precipitation = 19.2 Annual average precipitation over 30 yrs = 70.9 mm (<a href="http://www.bom.gov.au">www.bom.gov.au</a>) Strong winds rarely cause blowing snow.</td>
<td>Aerosols collected on filters, fine ≤1 µm; coarse ≤8 µm</td>
<td>NSS SO₄²⁻ fine 84.7 (µg m⁻³)</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NSS SO₄²⁻ coarse 70.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total nss SO₄²⁻ 145.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SS SO₄²⁻ fine 139.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SS SO₄²⁻ coarse 105.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total SS SO₄²⁻ 245.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total SO₄²⁻ 364.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Na⁺ fine 455.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Na⁺ coarse 477.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total Na⁺ 932.9</td>
<td></td>
</tr>
</tbody>
</table>
### 5. Salts

<table>
<thead>
<tr>
<th>Site (distance from the sea)</th>
<th>Wind-speed (km/hr), direction, type</th>
<th>Precipitation</th>
<th>Salt deposition</th>
<th>Salt deposition measurement</th>
<th>Salts retained in corrosion products</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Collection method</td>
<td></td>
<td>Chloride (wt %)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>XRF</td>
</tr>
<tr>
<td>Dumont d’Urville (&lt;500 metres)</td>
<td>SE dominant, Mean annual average =29.6 km/hr (Wendler et al, 1997)</td>
<td>Wagenbach <em>et al.</em> (1998) found higher atmospheric sea salt deposition in summer rather than winter. Annual mean sea-salt concentrations measured was 1400 ng m⁻³ but results at different seasons showed high variability dependent on topography.</td>
<td>Not specified in abstract, appears to be atmospheric capture on filter.</td>
<td>Wagenbach <em>et al.</em> state that mirabilite is precipitated from the atmosphere.</td>
<td>n/a</td>
</tr>
<tr>
<td>Cape Denison (AAE hut is 45 metres from edge of Boat Harbour)</td>
<td>AAE: (Madigan, 1929: 19-24) Mean hourly wind velocity= 44.2 mph (71.13 kmh) over 22 months. Wind direction is SSE for 85% of the time, at 51.3 mph.</td>
<td>Snowfalls heaviest in Apr and May. AAE data: 14.3.1912 to 14.4.1913 = 51.82 ins (1316.23 mm) 15.12.1912 to 15.12.1913 = 60.98 ins (1548.89 mm) Drift: During 14.3.1912 to 14.3.1913 = 6246 feet (1.904 km)</td>
<td>ISO 9225 salt candle, 14 days exposure.</td>
<td>Salt candle results summer exposed 27/12/2000 to 8/01/2001 (Ganther <em>et al.</em> 2002)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Compound</th>
<th>Deposition mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>6.7</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>5.5</td>
</tr>
<tr>
<td>Ca</td>
<td>2.8</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>2.4</td>
</tr>
<tr>
<td>K</td>
<td>1.4</td>
</tr>
<tr>
<td>Mg</td>
<td>1.3</td>
</tr>
<tr>
<td>NO₃⁻</td>
<td>0.4</td>
</tr>
<tr>
<td>PO₄³⁻</td>
<td>0.2</td>
</tr>
<tr>
<td>NH₄⁺</td>
<td>0.2</td>
</tr>
<tr>
<td>NO₂⁻</td>
<td>0.0</td>
</tr>
<tr>
<td>Br</td>
<td>0.0</td>
</tr>
<tr>
<td>Li</td>
<td>0.0</td>
</tr>
<tr>
<td>----------</td>
<td>---------------</td>
</tr>
<tr>
<td>Cape Adare (100-120 metres)</td>
<td>Harrowfield (2006: 298): 5 to 26 m/s (18- 94</td>
</tr>
<tr>
<td>Site (distance from the sea)</td>
<td>Wind-speed (km/hr), direction, type</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td></td>
<td>km/hr) in moderate storms. Mainly orographically-forced katabatic. Bernacchi 1901: winds 41.1% S and SE, 41% calm, 17.9% other directions. Strongest winds SE. Gales 20% of the time.</td>
</tr>
<tr>
<td>Cape Royds (~120 metres)</td>
<td>Not available.</td>
</tr>
<tr>
<td>Cape Evans (~100 metres)</td>
<td>Not available.</td>
</tr>
<tr>
<td>Hut Point/ McMurdo (~100 metres)</td>
<td>At Williams Field (15 km S of McMurdo Base), Mason 1999: 20% calm; Rarely W, 21% E, 27% NE, 11% SE, 14% S. Most common winds are 13% NE at 2-5 m/sec, 5% S at 8-10 m/s.</td>
</tr>
<tr>
<td>Scott Base TAE hut</td>
<td>Max gusts to 185 km/hr, less windy</td>
</tr>
</tbody>
</table>
### 5. Salts

<table>
<thead>
<tr>
<th>Site (distance from the sea)</th>
<th>Wind-speed (km/hr), direction, type</th>
<th>Precipitation</th>
<th>Salt deposition Collection method</th>
<th>Salt deposition measurement</th>
<th>Salts retained in corrosion products</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Chloride (wt %)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>XRF</td>
</tr>
<tr>
<td>(~50 metres)</td>
<td>than McMurdo.</td>
<td></td>
<td></td>
<td></td>
<td>n/a</td>
</tr>
<tr>
<td>Rothera (~100 metres)</td>
<td>Mean wind speed 58.0 knots (107.4 kph) mainly northerly (British Antarctic Survey) Max wind gust = 142.6 km/hr Max mean wind speed = 107.4 km/hr Mean wind speed = 22.2 km/hr</td>
<td>Snow/sleet/rain, occasional rain. Days with snow/sleet 225 per year Days rain= 30 50+ gales/year <a href="http://www.antarctica.ac.uk/met/ids/weather/images/fig12.htm">http://www.antarctica.ac.uk/met/ids/weather/images/fig12.htm</a> Turner <em>et al</em> 1995 Antarctic Science 7(3): 327-337</td>
<td>n/a</td>
<td>n/a</td>
<td>0.75</td>
</tr>
<tr>
<td>Jubany (100 m)</td>
<td>Mean wind speed during Nov 1991 to Feb 1993 was 8.55 m/s (30.78 kmh), gusts exceed 90kmh, strongest winds in winter and spring. E-W wind varying with time of day and season, aligned to axis of Potter Cove. 1830 mm in 4 years (av 456 mm/yr) Rain, sleet and snow all occur. Significant se mist in summer.</td>
<td>Titration of contents of pluviometer SO₂ negligible, Cl- 6-30 mg m⁻² day⁻¹ <a href="http://www.antarctica.ac.uk/met/ids/weather/images/fig12.htm">Rivero <em>et al</em> (1996)</a></td>
<td>n/a</td>
<td>n/a</td>
<td>0.25</td>
</tr>
<tr>
<td>Artigas (&lt;200m)</td>
<td>n/a</td>
<td>Minimum mensual rain = 12.7 mm Max mensual rain= 85.2 mm Av annual rain = 512.8 mm</td>
<td>Not stated, but infers titration of contents of pluviometer Negligible SO₂, Cl- deposition 180.1 mg m⁻² day⁻¹. <a href="http://www.antarctica.ac.uk/met/ids/weather/images/fig12.htm">Rivero <em>et al</em> (1996)</a></td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>
5.4.5 Scanning electron microscopy of defibred wood samples from Cape Denison

Figure 5.8 shows SEM images of typical samples of defibred timber, discussed in section 5.5.5. See also SEM images by Blanchette et al (2002) shown in figure 2.2.

Figure 5.8: SEM images of typical samples of defibred timber.
Typical appearance of defibred wood sample from Cape Denison.

Detail of lower left of image 0001 above.
Typical appearance of defibred wood sample from Cape Denison.

Side view of sample show in 0001 above.

Weathered wood from Cape Denison, not defibred.
5.4.6 Conservation treatment for salt-related problems

Table 5.5 lists types of salt treatments carried out at Antarctic historic sites, assessed from available literature and from the author’s observations, where possible.

Table 5.5: Treatments of salt problems.

<table>
<thead>
<tr>
<th>Location</th>
<th>Treatment</th>
<th>Result</th>
<th>Cost</th>
<th>Effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ross Island sites</td>
<td>Brushing, vacuuming (Maxwell &amp; Viduka 2004)</td>
<td>Local reduction in salts near artefacts. Salts from ceiling and walls may dissolve and be re-distributed.</td>
<td>Labour intensive (~100 hours per hut per season) and thus expensive.</td>
<td>Not highly effective in removing salts from corrosion profile of metals. Does not prevent ongoing damage. Requires annual re-treatment.</td>
</tr>
<tr>
<td>Ross Island, Cape Adare, Cape Denison, Snow Hill Island</td>
<td>Re-location of artefacts offsite Bickersteth, Clayton and Tennant (2008)</td>
<td>Potential loss of visitor amenity but may be satisfactory where multiple examples exist.</td>
<td>Packing, transport and storage are labour intensive.</td>
<td>Can be effective for managing risks where exposure is extreme and no practical alternative exists.</td>
</tr>
<tr>
<td>Ross Island sites</td>
<td>Washing of textiles and other organic artefacts to remove salts, using conventional laboratory treatments (UK Natural History Museum Conservation blog, July 2008 available at <a href="http://www.nhm.ac.uk/nature-online/earth/antarctica/blog/?m=200807">http://www.nhm.ac.uk/nature-online/earth/antarctica/blog/?m=200807</a>)</td>
<td>Generally effective in removing salts when undertaken in laboratory (not field) conditions.</td>
<td>Generally labour intensive and high cost due to logistics expenses.</td>
<td>Effective, but must manage exposure risk if returned to original location. High re-exposure risk increases need for re-treatment.</td>
</tr>
<tr>
<td>Ross Island sites</td>
<td>Replacement of damaged timber cladding with new timber (Blanchette, Held and Farrell 2002)</td>
<td>Recurrence of problem after 8 years; loss of original building fabric.</td>
<td>Modest. Several hours to replace (each) small area of timber.</td>
<td>Loss of original material is undesirable, replacement can be acceptable where appropriate materials and techniques are used. Re-treatment was required in &lt; 10 years.</td>
</tr>
<tr>
<td>Preventive treatments proposed by Blanchette, Held and Farrell 2002 for Ross Island sites but applicable elsewhere</td>
<td>a. reduce snow accumulation on and near the huts; and b. improve drainage to reduce moisture migration up the walls; c. divert water flows from the roof and walls d. reduce sources of moisture including getting visitors to take off outdoor shoes to wear slippers inside; e. remove accumulated salts.</td>
<td>Would reduce moisture ingress and prevent salt migration by capillary action but benefits in reducing blown snow are less apparent.</td>
<td>Moderate: most actions would require some hours each year (a, c, d) or possibly days (b, e).</td>
<td>Probably quite effective with a significant advantage that effectiveness can be measured through RH monitoring that is ongoing.</td>
</tr>
</tbody>
</table>

Note: no specific salt treatments appear to have been undertaken at Cape Denison (based on Berry 2010).
Table 5.6 Risk analysis

<table>
<thead>
<tr>
<th>Risk No.</th>
<th>The Risk - What can happen and how it can happen</th>
<th>Consequence</th>
<th>Description and Adequacy of Existing Controls</th>
<th>Likelihood Rating (a)</th>
<th>Consequence Rating (b)</th>
<th>Overall Risk Level (a+b)</th>
<th>Risk Priority</th>
<th>Treatment controls</th>
<th>Risk rating after treatment/controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Salts deposited and/or absorbed on timber cause defibring.</td>
<td>Loss of surface timber and possible acceleration of loss where corrosion also occurs</td>
<td>No existing controls other than overcladding of original surfaces with timber (Cape Denison) or polymer (Ross Island).</td>
<td>5 (exposed exterior) 2 (interior and overclad timber)</td>
<td>3 (exterior) 2 (interior and overclad timber)</td>
<td>8 4</td>
<td>High Low</td>
<td>Overcladding</td>
<td>As for interior - see Risk 4.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Protective coatings prevent crystallisation damage at surface.</td>
<td>Not assessed - requires field and lab trials to determine effectiveness, but likely to be beneficial.</td>
</tr>
<tr>
<td>2</td>
<td>Salts increase corrosion of metals including fasteners.</td>
<td>a. Corrosion products increase damage to wood and cause staining. b. Difficult to replace where the corrosion binds to timber surfaces. c. Surface treatment of exposed portions with coatings.</td>
<td>a. Replacement of corroded fittings- results in loss of original building fabric. b. Risks of physical damage during removal. Defibring damage to wood is currently impossible to treat effectively.</td>
<td>5</td>
<td>4-3</td>
<td>9-8</td>
<td>High</td>
<td>Nil- requires research to develop treatment options.</td>
<td>Not determined.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Re-placement option</td>
<td>Not determined- this should be an option of last resort.</td>
</tr>
<tr>
<td>3</td>
<td>Salts deposit in locations that are difficult to monitor such as inside roof and wall cavities, under floors, etc.</td>
<td>Salts continue to accumulate unseen and potential damage is not assessed.</td>
<td>Nil- no assessment reports available.</td>
<td>4-5</td>
<td>1-4</td>
<td>5-9</td>
<td>Low to high- needs assessment.</td>
<td>Inspection and testing is feasible and inexpensive. Use sensors for monitoring.</td>
<td>Not determined.</td>
</tr>
<tr>
<td>4</td>
<td>Salts deliquesce and migrate to other locations eg via capillary action, etc.</td>
<td>Salts appear as meltwater, risks are not identified, salts move and cause problems in other locations.</td>
<td>Salts brushed/vacuumed off after deposition. Few strategies to prevent deposition and absorption.</td>
<td>4-5</td>
<td>2-4</td>
<td>6-9</td>
<td>High</td>
<td>Monitoring to determine risks treatment strategies.</td>
<td>Not determined.</td>
</tr>
</tbody>
</table>

**Likelihood Rating:** 1 rare, 2 unlikely, 3 possible, 4 likely, 5 almost certain.

**Consequence Rating:** 1 insignificant, 2 minor, 3 moderate, 4 major, 5 catastrophic.

**Level of Risk:** <5 low risk – manage by routine procedures, 5 medium risk – specify management responsibility, 6 & 7 high risk – needs senior management attention, >7 extreme risk – detailed action plan required.
5.5 DISCUSSION

5.5.1 Characteristics and severity of salt-related deterioration problems (Research question 1)

The visual observations summarised in Table 5.2 revealed:

- Salt deposits were visible on the ground outdoors at all of the 12 sites, which are generally less than 200m from the sea edge except Rumdoodle (18 km inland);
- Salt deposits were visible inside buildings at all of the three early Ross Island sites and at Cape Adare;
- Evidence of significant corrosion and defibring was found at all sites except Rumdoodle, although at Cape Denison and Cape Adare defibring was localised to areas protected from wind areas implying defibring may have been more extensive but removed by corrosion;
- As expected, the most extreme deterioration risks apply to artefacts where periodic inundation occurs: e.g. parts of Cape Adare; low lying areas northeast of Boat Harbour at Cape Denison; and the *Aurora* anchor at Cape Evans was partly inundated by seawater during storms (Harrowfield personal communication to the author 1997); and
- Conservation treatments related to salts were undertaken at the four Ross Island sites.

At Cape Royds salts cover the ground to such an extent that the ground appears white in places and could be mistaken for snow except that it is solid, crystalline and tastes salty (Figure 5.9). Observations could underestimate the extent of salt deposits on the ground since the salt crystals are only visible when humidity is below the critical RH.\(^{13}\) Above that RH the salts deliquesce to form a liquid.

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\(^{13}\) Critical relative humidity is defined as the relative humidity of the surrounding atmosphere (at a certain temperature) at which the material begins to absorb moisture from the atmosphere and below which it will not absorb atmospheric moisture. For pure sodium chloride this is 80%. The critical relative humidity of most salts decreases with increasing temperature. Mixtures of salts usually have lower critical humidities than either of the constituents.
Prior to the author’s visit in 1993 no references were found concerning the existence of salt deposits inside the Ross Dependency huts. It is possible that the salts may not have been noticed since their appearance is ephemeral. High relative humidity inside the huts during summer causes deliquescence, making them difficult to distinguish from meltwater.

The most significant limitations of the site observations for detecting salt problems were the inability to examine the spaces inside ceilings and walls. These are needed to understand the processes and impacts of air and water leakage and condensation and to determine if treatments such as overcladding are effective.

Salt observations at sites not visited by the author

Site surveys by Broadbent (1992), Comerci (1983) (1994), Cochran and Collinge (1994) and others at Antarctic Peninsula sites do not specifically comment on the prevalence or severity of defibring and the reports on corrosion are sporadic and only qualitative. However, other evidence, discussed below, suggests significant potential salt risks at these sites.
5.5.2 Composition and origin of the salts (Research question 2)

Salt deposition processes

Salts can be:
- Precipitated in falling snow, which contains sea salts in coastal areas; or
- Carried in drifting snow, which may include non sea salts carried from the troposphere eventually deposited on the polar plateau; or
- Deposited on the ground or inside buildings, and be concentrated by evaporation.

Hingston and Gailitis (1976: 319) stated that the main factors affecting the amount and nature of salts in precipitation are climate, elevation of the land surface and occurrence of saline drainage systems and soils. Chloride precipitation depends partly on wind direction and strength (correlated with latitude), rainfall (partly determined by topography) and distance from the coast (ibid: 328). In coastal locations in mid-latitudes, salts found in rainwater are consistent with the ratio found in seawater. The characteristic ratio of interest to environmental scientists is that of chloride: sulphate. Some locations widely distributed around the world have sulphate in excess of the expected ratio, particularly in desert regions, derived from volcanic, industrial and environmental sources (Hingston and Galaitis (1976: 319). Of these, the most important in Antarctica are sulphur compounds from disintegrating algae and plankton (the Southern Ocean being a particularly rich source) and terrestrial aerosols from soils.

Claridge and Campbell (1996) consider that “the origin of the nitrogen, sulphur and iodine salts in Antarctic snow is ultimately biological”, citing and refuting contrary views of other authors. These salts “are transported to the polar regions by the atmosphere that circulates to maintain the permanent anticyclone over the Antarctic continent. During transport, these compounds are oxidised to nitrates, sulphates and iodates (figure 5.10). Most of these compounds are removed by atmospheric precipitation but … chlorides are removed preferentially” (ibid: 267-268). This appears consistent with the author’s finding of elevated levels of sulphate in samples from the Ross Island sites.
Blanchard and Woodcock (1980) described the predominant role of breaking waves and whitecaps in producing the SS aerosols globally. Both the production of whitecaps and the subsequent transport of sea spray depend on the wind speed. SS concentration increases exponentially with wind speed. For winds $<5\text{ms}^{-1}$, a variable threshold of sea spray is found, either due to higher variability of the wind field over the sea or production of spray in the previous days. For wind speed $<10\text{ms}^{-1}$ the SS concentration increases with the first power of the wind speed; above this speed the concentration increases again and reaches the third power at $20\text{ms}^{-1}$ and more than the fourth power as the winds reach hurricane speed. At Cape Denison, the annual average wind speed measured by the AAE was 69 kilometres per hour, or $19.2\text{ms}^{-1}$ (Madigan 1929), inferring salt concentration should correspond to the third power of the wind speed\textsuperscript{14}. However, the direction of the wind is also significant and at Mawson, Rumdoodle, Platcha, Dumont d’Urville, Cape Denison and to some extent Cape Adare, the dominant katabatic wind is from the polar plateau. These dominant katabatic winds promote deposition of NSS

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\textsuperscript{14} Interestingly, corrosion rates also correspond to the third power of wind speed, so it is possible that deposition rates and corrosion rates could be close (within one order of magnitude).
whereas the weaker sea breezes\textsuperscript{15} promote deposition of sea salts. Thus there is an expectation that at the ‘katabatic’ sites (shaded in table 5.4) NSS should predominate over SS deposition and indeed there is a common assumption (Ashley 2001: 115) that all salt deposition is low at Cape Denison.

An additional factor of importance in Antarctica is the presence or absence of sea ice. Sea ice persists for a longer period at the Ross Island sites (over five months per year) and winds are not so strong as to cause breakup and scattering (see Chapter 7).

**Effect of salts on freezing point**

The components of seawater are very similar throughout the earth’s oceans (Department of Environment Handbook 1994).\textsuperscript{16} Depression of freezing point of salt solutions is a widely known phenomenon with obvious implications in coastal Antarctica since summer air temperatures are generally within a few degrees of freezing point.

Brass (1999) discussed depression of freezing point and its effect on Arctic corrosion rates providing phase diagrams that give rare quantitative data on the effects of salts and their interactions at different temperatures. He showed that concentration of salts can lead to corrosion reactions occurring at temperatures below -50°C. Any increase in salt deposition rates could therefore synergise other deterioration processes by making liquid water available for longer periods.

**Other sources and impacts of salts**

Guano from penguins, and other wildlife to a lesser extent, contains significant quantities of nitrates, phosphates, calcium and ammonia compounds and fertilises growth of fungi, bacteria and algae. The only significantly affected historic site is Cape Adare where over two million

\begin{footnotesize}
\footnotesize
\textsuperscript{15} Breezes from the north blow 3.4 % of the time with average velocity at greatest frequency of 10.0 mph or 4.47 m/s. (Madigan 1929: 131).
\textsuperscript{16} The components are (w/w/) Na 1.07%; Mg 0.132%; Ca 0.042%; K 0.038%; Cl 1.932%; sulphate 0.270%; carbonate 0.007%; bromide 0.006% (see http://cdiac.ornl.gov/ftp/cdiac74/chapter5.pdf)
\end{footnotesize}
penguins breed each summer (figure 5.11) and guano has accumulated around the huts’ walls. Shackleton’s hut is immediately adjacent (but not surrounded by) the southernmost Adelie penguin rookery.

Figure 5.11: Guano accumulation at Cape Adare (author’s photo 1993)

Chemicals used for scientific or operational reasons are another potential source of salts. Large quantities of sodium hydroxide were stored at Wilkes to produce hydrogen for meteorological balloons (Clark & Wishart 1989) and crystalline deposits were evident near the meteorological balloon building at Mawson Station, possibly sodium hydroxide\textsuperscript{17}. Disposal of chemicals for photographic processing and other purposes is known to have occurred at many other sites (personal communication Janet Dalziel, Greenpeace, 1992) before the Madrid Protocol led to tighter controls. While these pollutants are expected to be localised, their presence at historic sites cannot be discounted.

*Salt composition of snow at Cape Denison (1985)*

The concentration of Na\textsuperscript{+} ions outdoors was highest near the Magnetograph House (3980ppm), lowest near John O’Groats (15ppm) and was also relatively low at the Memorial Cross (57ppm). The variability of salt concentration is difficult to interpret since it depends on both deposition
and the potential mixing with meltwater and contact with rock minerals. Nevertheless, the sodium concentrations present are similar to the range at Ross Dependency sites (Blanchette, Held and Farrell 2002).

Concentrations in excavated layers inside the AAE Main hut are variable and there are insufficient samples to determine the extent of variation within each layer and to relate this to the factors that might be responsible. For example, elevated Na+ may be associated with melting/freezing locations rather than snow blown from the polar plateau, or possibly from dissolved salts concentrated by drying from ventilation. Further information could be obtained from analysis of ice cores extracted from the hut by Lazer in 2002 and this would be worthwhile in understanding both melting/freezing episodes as well as salt behaviour.

*Analyses of salts inside Ross Island buildings*

The most significant finding from these analyses was the elevated concentration of sulphate at each location in the three huts. Such deposits of salts are rare inside buildings in other climates even in deserts. Halite was only found in small amounts (in HP1), which was most unexpected due to the proximity of the sea, so the analyses were repeated\(^{18}\) using Raman microscopy which found the same results in addition to identifying some minor components (gypsum). The significance of these results is discussed further in section 5.5.5.

*Aerosol data at Mawson, Davis*

There are marked differences in the SS sulphate ratio measured in aerosols: Mawson (14%) is much lower than at Davis (67%) since the strong katabatic winds at Mawson reduce the marine influence. Mawson also has sodium (8% of Davis) and chloride (4% of Davis).

The NSS fraction of the sulphates measured in the samples of corrosion product originates from bacteria and marine phytoplankton that form dimethylsulphoxide, which can be oxidised by

\(^{17}\) High pH was measured with a test strip.

\(^{18}\) Raman microscopy became available which enabled very small samples to be examined without the need for grinding the crystals.
hydroxyl radicals to SO₂, or methane sulphonate. Aerosol data is useful for heritage conservation in Antarctica since it can improve understanding of salt processes and conservation problems arising.

Analyses of salts in corrosion products from Mawson, Davis and Rothera

Micro-Raman analyses (discussed in Appendix H) demonstrated that the corrosion products consisted mainly of goethite (α-FeOOH) and lepidocrocite (γ-FeOOH), with interdispersed traces of maghemite (γ-Fe₂O₃) and feroxyhite (δ-FeOOH). Sulphate ‘nests’ were randomly found in pits present on the rust layer.

Elevated levels of sulphate have thus been confirmed in all the following sources:
- Aerosols collected at Mawson and Davis
- Salt solids collected inside Ross Island buildings
- Corrosion products from Mawson and Davis and Rothera

Analyses of sulphate, Na⁺ and Cl⁻ ions in corrosion coupons exposed at Antarctic sites presented in Appendix H show their concentrations are significantly higher (nearly three times, for each species) than a marine site in Newcastle, NSW. By comparison, Subantarctic islands have much lower levels of these species due to leaching by high rainfall. Chlorides are deposited but the rate of leaching is not sufficient to remove it all from the metal surface, so it is incorporated within the corrosion product. Sulphates are generally less water soluble than chlorides, so their rate is retention is high and the sulphur contents for the Antarctic sites approach that of industrial sites.

Two bronze boxes covering the Memorial and Proclamation plaques at Cape Denison were thought (in 1985) to have suffered ‘bronze disease’, caused by chlorides (Hughes 1986). It was not possible to test the salts present but the presence of sulphates from samples collected elsewhere at the site suggests sulphates may be present so the corrosion occurring may not be strictly ‘bronze disease’ but the result of several different corrosion processes.
5.5.3 Rates of salt deposition inside and outside buildings and factors influencing salt penetration (Research question 3)

Campbell and Claridge (1987) found chloride concentrations in Antarctic snow and ice samples decreased with distance from the coast (ibid: 240). Mirabilite (Na₂SO₄.10H₂O) was found as large masses on old sea ice, especially near the Koettlitz Glacier in McMurdo Sound. The removal of chloride noted in studies in Dronning Maud Land (ibid: 241) “was attributed either to a non marine source of sodium or to selective removal of chloride in coastal regions”…. “Most salts are initially derived from the sea in the form of aerosols and, in coastal regions, salts may be present in solution in sufficiently high concentrations for the precipitation of either halite or mirabilite, depending on the temperature.” (ibid: 255).

They concluded that “the bulk of the aerosolic material was sulphate, believed to have been transported to the interior of the continent through the upper troposphere or the lower stratosphere” (ibid: 242). Salt deposition concentrations were found to be higher in summer than in winter (ibid: 241), for example, at Moledezhnaya, expected to be due to the formation of sea ice in winter. However, this is contradicted by more recent research (Curran et al 2006) that found higher deposition in winter due to wind deposition from ‘frost flowers’ on the surface of sea ice.

At Jubany, Rosales and Fernandez (2001) measured outdoor salt deposition using Mohr titration of water collected in the pluviometers and found levels ranging from six to 30 mg m⁻² day⁻¹. This high rate of deposition indicates salts may adversely affect historic buildings in the relatively warmer climate of the Antarctic Peninsula, although the modes and extent of salt infiltration may differ since winds are weaker and more rain occurs.

A large area of salt crystals (not analysed by the author and no known published analysis) exists approximately 100 metres seaward of Shackleton’s Nimrod hut at Cape Royds (figure 5.12). This appears to have formed from evaporation of salty meltwater that has drained off surrounding rocks, combined with penguin guano. These salts could easily be redeposited by wind on the hut.
Mason (1999) carried out four ISO 9225 salt candle measurements: two located outside Scott’s Hut at Cape Evans and two located inside the building for a period of 37 days each. The seaward exterior sample had the highest deposition rate (16.6 g m\(^{-2}\) yr\(^{-1}\)) followed by the sheltered exterior sample. Of the two interior samples, the sample closest to the door had the greater deposition rate.

The classification of airborne salinity based on the salt candle method places all of the Cape Evans samples in the S1 category of ISO 9225, which is one category above insignificant background levels. Mason noted that the distance of the sea ice edge from the hut at the time of the test (about 4km away during early summer) may be a significant factor in the low classification, but Curran et al (2006) suggest winter deposition may be higher.

Mason (1999: 77-78) presumed the salts deposited were predominantly sodium chloride. This may significantly underestimation total salts since the mercurimetric titration reaction used will

\[\text{This method analyses halides only. Pluviometer measurement underestimates deposition since it does not include aerosols.}\]
react with other halides, but not sulphates. Given the evidence of sulphates found inside the huts, and that there are limited means of leaching of chlorides in the interior environment, then the interior salt deposition rate may be higher. Mason (1999: 64) also measured the chloride content of the fibrous insulation (4.2% by weight) which suggested chloride is retained inside the wall spaces and may leach during intermittent moisture flow from meltwater penetration or condensation events.

Setting aside the identity of the salts, sodium chloride deposition rates measured inside the hut by Mason (5.5 and 4.4 g m\(^{-2}\)yr\(^{-1}\)) are approximately one third of the outdoor exposure rates (16.6 and 12.5 g m\(^{-2}\)yr\(^{-1}\)). This is a higher proportion than is commonly found in buildings in temperate conditions, which are commonly around 1/80 of external deposition rates (Cole & Ganther 1999).

The proportion of salt deposition inside the AAE main hut, although not measured, is likely to be a higher proportion of the external deposition due to the stronger winds and greater permeability of the building fabric, as evidenced by the continued ability of snow particles to enter the hut even after extensive overcladding\(^{20}\). As previously mentioned, difficulties with funding, logistics and research approval made it impossible to carry out sufficient salt candle measurements to adequately investigate salt risks. If interior salt deposition at Cape Denison is approximately one third of the deposition of the exterior rate then approximately 0.77 kg of total salts per year will be deposited inside the hut\(^{21}\). An approximate salt budget is given in figure 5.13.

Measurements of ions from the salt candle exposed at Cape Denison in summer 2000-01 with no sea ice present show lower outdoor deposition rates than at Cape Evans during summer (see Table 5.4). Comparison is again dependent on better data on the relationship of sea ice and atmospheric salt deposition but these results seem to indicate salt deterioration risks are lower than for Ross Island sites.

The vortex effect recorded by the AAE at Cape Denison was discussed previously in section 4.5.3. The vortex observation implies that salt-laden air circulates over the headland (figure 5.13) although any increase in salt deposition may depend on how sea ice affects deposition rates.

\(^{20}\) See recent report by archaeologist Anne McConnell for Mawson’s Hut Foundation.
Recent satellite and ocean measurements\(^{22}\) suggest that the katabatic winds form a *polynya* (a persistent formation of open water amongst sea ice) off Cape Denison and another is known to exist off northern Ross Island (Wendler, G, D Gilmore & Curtis 1998). The total chloride:sulphate deposition weight ratio at Cape Denison measured by the ISO salt candle was 2.29, compared to 0.76 at Mawson and 6.05 at Davis (using weight/volume of aerosols). While the quantities measured cannot be directly compared (as different methods were used), the chloride:sulphate ratios are comparable and these suggest there is more sea salt deposition at Cape Denison than at Mawson, although both have katabatic wind regimes. Ideally, to conclusively evaluate salt deposition affecting Antarctic historic sites, ISO salt candle measurements (with full ion analysis) should be repeated at Mawson, Davis, Cape Denison and a Ross Island site along with SO\(_x\) and NO\(_x\) measurements and a corrosion coupon exposures plus representative measurements of salt content of timber and concentrations in meltwater and internal ice (at Cape Denison). This would enable improved analysis of the salt budget to evaluate salt risks.

Figure 5.13: Vortex effect over Cape Denison (Madigan 1929: figure 11)

Table 5.7 qualitatively summarises salt processes at Cape Denison. These include: aerosol deposition onto exterior surfaces, meltwater ingress through the roof and walls, capillary action from ground contact and from salty water from melting of snow drifts along walls and under the

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\(^{21}\) Based on total salt deposition of 20.9 mg/m\(^2\)/day for approx 300 m\(^2\) exterior surface of the hut.

\(^{22}\) See Wendler, Gilmore and Curtis 1998 listed in references.
floor, on visitors clothing and boots. Salts are also concentrated from wetting/drying cycles, which may be particularly important in Antarctica given low flushing rates and the drying effects of winds. NSS deposition could be concentrated by drying since the air catchment covers one tenth of Antarctica funnelled into a small coastal area (Adolphs & Wendler 1995) and both ablation and blowing snow volumes are known (Madigan 1929) to be exceptionally high.

Table 5.7: Salt processes affecting AAE main hut

<table>
<thead>
<tr>
<th>Location</th>
<th>Deposition processes</th>
<th>Removal/outflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoors</td>
<td>- Inundation near shoreline (periodic)</td>
<td>- Flushing by rain, sleet, falling snow (all rare)</td>
</tr>
<tr>
<td></td>
<td>- Sea salt aerosols carried by air movement including vortex over the headland</td>
<td>- Meltwater flow dissolves deposited salt aerosols</td>
</tr>
<tr>
<td></td>
<td>deposited on exterior of building and absorbed into wood</td>
<td>- Corrosion removes salts from surface only</td>
</tr>
<tr>
<td></td>
<td>- Non-sea salts in blowing snow from polar plateau deposit onto snow drifts</td>
<td>- Drainage removes dissolved salts</td>
</tr>
<tr>
<td></td>
<td>Summer deposition rate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Na+ 6.7 mg/m².day</td>
<td>Salts will leach selectively according to temperature and solubility.</td>
</tr>
<tr>
<td></td>
<td>Cl⁻ 5.5 mg/m².day</td>
<td>Removal by meltwater is expected to be occur but less efficiently (perhaps &lt;40%)</td>
</tr>
<tr>
<td></td>
<td>SO₄²⁻ 2.4 mg/m².day</td>
<td>than from rain. Removal of salts by corrosion is also expected to be lower (&lt;5%).</td>
</tr>
<tr>
<td></td>
<td>Total salts deposited 20.9 mg/m².day</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total salts in hut per year= 20.9 x 300 m² x 365 days = 2,288.6 g/yr deposited on</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the exterior of the hut</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not known- this will depend on how much salt is absorbed into the porous wood, but</td>
</tr>
<tr>
<td></td>
<td></td>
<td>this could be high.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sublimation and evaporation rates are high of meltwater less any removal by</td>
</tr>
<tr>
<td></td>
<td></td>
<td>melting (unknown) and corrosion (low).</td>
</tr>
<tr>
<td>Indoors</td>
<td>- Salts in meltwater from the roof flow into the hut</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Salts in meltwater from snow drifts and the ground into the hut</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Carried on visitors’ boots</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Clearing (for conservation program)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Flushing by meltwater flow over walls and</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Absorbed in porous materials such as wood, porous stone, corrosion products</td>
<td></td>
</tr>
<tr>
<td></td>
<td>on the interior of</td>
<td></td>
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<td></td>
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</tbody>
</table>

Blanchette, Held and Farrell (2002) Table 3 shows that old snow from the roof of Cape Evans hut is 18 times the Cl⁻ concentration of newly fallen snow. Roof meltwater contained 12,283 ppm Cl⁻. Cape Evans experienced higher deposition, but lower sublimation. Chloride concentration in snow inside Cape Royds hut was high (1298 ppm), low inside Discovery hut (77ppm). 
5. Salts

and clothing
- Capillary action carries salty water from subfloor to interior of hut
- Salt ingress as aerosols blown into the hut
Mason (1999: 78) found indoor deposition is approx 1/3 of exterior deposition. If this applies at AAE main hut then total annual salts deposited inside = 762.9 g/yr

floor
- Drainage through the floor
Quantity of salt egress is impossible to estimate and is likely to be highly variable within the hut.

the building
- Re-distribution of salts with moisture circulation within the hut.

Blanchette, Held and Farrell (2002) investigated the various means by which salts penetrate inside the three Ross Island huts. They provided quantitative measurements of salt concentrations in timber samples, meltwater and snow which are particularly useful evidence for conservators in understanding the scale of risks. For example, fresh snow had low salts whereas older snow from roof had >5,000ppm Na+ and elevated concentrations of chloride, potassium, magnesium and sulphur. Windblown snow appears to bring significant quantities of salt.

5.5.4 Effects of rain, meltwater and other rinsing (Research question 4)

It is widely known that rain is rare in Antarctica, however limited precipitation data is available, shown in Table 5.4. Rain is more common and overall precipitation is higher in the Antarctic Peninsula due to its more northerly location and greater marine influence. Ross Island rarely experiences rain due to persistently lower temperatures.

One problem in measuring precipitation in Antarctica is the impossibility at some sites of distinguishing falling snow from blowing snow, the latter often being associated with katabatic winds. Table 5.4 shows that Mawson, with predominantly katabatic winds, has lower salt deposition than Davis, where winds are lighter and northerly to easterly. Other sites with predominantly katabatic winds (Dumont d’Urville, Cape Denison, and Cape Adare) would therefore also be expected to have lower salt deposition rates than the Antarctic Peninsula and Ross Island sites, but effects such as transport and concentration via wetting/drying cycles must also be considered.

24 These are similar to processes occurring at Cape Denison.
25 Comparative Australian data is given in Appendix H
The possible forms of flushing of salts from surfaces are surface erosion by wind (at katabatic sites, mainly occurring in winter) and meltwater flows (obviously, in summer). The latter is expected to be a much more significant effect judged by the large volumes of water observed dripping inside the AAE hut and evident from water stains at other sites (Table 4.1).

The increased corrosion risks due to effects of sheltering (which reduces surface flushing) are well documented. It is therefore particularly important to examine under verandahs and inside wall cavities to determine ‘worst case’ risks\textsuperscript{27}. Blanchette, Held and Farrell (2002) again provide useful quantitative comparative measurements of salts in timbers exposed and unexposed to salt deposition at Ross Island. Wood is porous so salts are easily absorbed and are difficult to remove using surface treatments, such as rinsing.

5.5.5 Defibring of wood (Research question 5)

Two different phenomena have been called ‘defibring’\textsuperscript{28}: one causes separation of wood fibres from the surface by chemical action that breaks down the fibre structure (eg Wilkins and Simpson 1988), while the second is due to photo-oxidation by depolymerisation of lignin (Kaila 1988). The appearance typical of defibring timber in Antarctica is shown in figure 5.1. This shows that the surface of the timber, originally dressed tongue and groove Baltic Pine, which has become ‘furry’.

\textsuperscript{26} Although similar vortex phenomena to that at Cape Denison may exist at these sites.
\textsuperscript{27} As discussed in Chapter 4, spaces between inner and outer walls and the roof are prone to condensation because of temperature differences and snow is often trapped inside which can then melt due to solar warming of exterior surfaces. This means that RH is often higher in these locations and temperatures are relatively high, which may lead to greater risks of salt concentration, defibring, corrosion and biodeterioration.
\textsuperscript{28} Various different spellings are also used, Blanchette, Held and Farrell use ‘defibration’.
Wilkins and Simpson identified defibring of the first type in roofs in Sydney, Australia. Their diagnosis was based on association with salts as the affected locations (in roofs) were all close to the sea. The typical case was in 40-60 year old houses at mid roof on the north-facing side. They found concentrations of all elements in the timber was greater than that typically found in normal heartwood, especially Na with a 3000 fold increase, then Mg, Zn, Ca, P, Mn, K, Fe. They concluded that defibring is initiated by chemical breakdown of the cell wall of both hardwoods and softwoods. Fissures in the middle lamella were apparent before thick walled fibres separated indicating changes in the nature of the lignin in the middle lamella early in the defibring process. Thick walled tracheids and fibres were often found to separate by destruction of the bond between the middle lamella and the primary wall with little other physical damage to the cell wall apparent. Transverse checking of thick walled fibres also occurred.
In contrast, thin-walled early wood tracheids frequently showed mechanical damage and erosion of the secondary wall layers before separation of cells. In hardwoods, defibring sometimes appeared to result in more rapid separation between radial fibre walls frequently resulting in the presence of radial files of cells. The process progresses to complete disappearance of the cell wall. No fungi hyphae were observed, no bacterial erosion pits, no rot. The pH was unaffected but could be due to the released acetic acid volatilising rapidly. Moisture content was high, up to 35% instead of the expected <15%. The relative proportions of the elements present in the defibred wood approximated that of sea water though Mn was a little high. Ray parenchyma appears most, and vessels least, severely affected by the process.

Temperature and salts were implicated since defibring is most common on the north side of roofs. Elevated temperatures cause changes in the chemistry of the cell walls, especially degradation of hemicellulose and cellulose which releases organic acids especially acetic acid. This can further decompose the cell wall by hydrolysis causing delignification. Thus defibring may accompany or enhance the thermal degradation.

Kaila (1988) proposes a different mechanism for erosion of timber that results in a raised texture of denser latewood cells rather than the distinctive ‘furry’ appearance termed ‘defibring’ by Wilkins and Simpson. Kaila called this ‘defibration by photo oxidation’, which results in the textured surface similar to corrasion. He states the process results in progressive darkening of the (sheltered) timber surface, which becomes silvery if washed by rain.

He concluded:

“Lignin acts as cement and cellulose as strength-giving reinforcement. More important than the decomposition of lignin of the cell walls is the decomposition of the middle lamella which cements the cell walls together. It consists mainly of lignin (70%) and is thus rapidly destroyed. Molecules of cellulose are depolymerised by strong light in the presence of water. Tensile strength is lost and this renders wood susceptible to microcracking”.

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29 Pure cellulose absorbs little UV, but Kuo and Hu (Kuo, M & Hu, N 1991, 'Ultrastructural Changes of Photodegradation of Wood Surfaces Exposed to UV', Holzforschung - International Journal of the Biology,
The described results of both processes are similar, as both involve destruction of lignin and separation of the middle lamella, but have different causal agents: salts in the first mechanism and photo-oxidation in the second. Defibring in Antarctica appears to be the former type as reported occurrences are associated with salts and the texturing effects described by Kaila are considered to be produced by selective erosion of the weaker thin walled cells by wind action, discussed in Chapter 7. Deterioration processes relating to photo degradation are described in Chapter 8.

The author’s defibring observations at Cape Denison were described in section 5.2.3 and in publications 30. No other description of defibring phenomena have been found in any Antarctic publication before 1988 although the problem appears to be longstanding. Harrowfield (1990, 1991) described defibring affecting the buildings at Cape Adare. Clark and Wishart (1989) confused the informal term ‘Antarctic wood fur’ (defibring) with corrosion damage caused by windborne particles:

“The wind can blow extremely strongly at Wilkes scouring the paint from the wooden walls facing in the prevailing direction and eroding unprotected surfaces to produce a condition known as Antarctic fur” (ibid).

The defibred timber samples collected from Cape Denison exhibit fibres up to 7mm long curved up from the surface and were bleached a silvery-white colour. Bleaching is commonly associated with defibred timber at the Ross Island sites (Blanchette, Held and Farrell 2002) and at Australian sites and Dumont d’Urville (author’s observations, Table 5.1). While no detailed study of this association has been undertaken, the observations of Blanchette, Held and Farrell (2002: 314) that defibring is always associated with water suggests ‘bleaching’ may be caused by chemical leaching of coloured lignins that bind the cells together. Loose fibres from defibred wood on the AAE Memorial and BANZARE Proclamation plaques repatriated to Australia produced a strong reaction with silver nitrate, indicating the presence of halides. The corrosion on the bronze boxes containing the plaques also indicates halides, so there is a strong association with salts even

Chemistry, Physics and Technology of Wood, vol. 45, no. 5, pp. 347-53.) cite evidence that UB absorbed by lignin in wood is transferred to cellulose, causing depolymerisation.

30 Hughes 1986 and Hughes 2000, the latter attached as Appendix G.
though both are over 200 metres from the nearest point of the sea. There is a common expectation (stated in DEWHA 2008) that salt deposition at Cape Denison is low due to katabatic winds. Salts trapped in the boxes cannot be flushed away and periodic drying may concentrate the salts inside the box. Temperatures are periodically elevated in summer due to solar warming so salts, heat and moisture are present which favour defibring. Any loose fibres are protected from corrosion but would be blown off elsewhere on the site but would be blown off elsewhere on the site.

SEM examination of the timber samples (described in 5.3.5) was undertaken at the SEM facility of the Australian Antarctic Division during 1986 and 1991. The samples were coated with gold under vacuum. Images 0001 and 7006 in figure 5.8 show the typical appearance of two different segments of the larger sample, which is significantly defibred and ‘bleached’ by water action on all surfaces. Image 0003 shows more detail of the lower left area of image 0001 which was typical of the appearance of all defibred timber surfaces of the samples. Wood cells have separated from one another in every sample and are loosely arranged above the surface. The presence of halides was also confirmed on these samples using silver nitrate.

Image 0023 in figure 5.8 shows a side view of the sample shown in image 0001 illustrating the progressive loss of fibres from the surface. The point of separation is at the middle lamella as shown by comparison with figure 5.15. The middle lamella is mainly composed of lignin which is known to be more easily dissolved by aqueous solutions than other parts of the wood structure that are primarily composed of cellulose (Butterfield & Meylan 1980: 8). These images were compared with sections of the same sample that was affected by corrosion and ‘silvery’ weathering (image 6004 in figure 5.8) without defibration and synthetically corroded new timbers (discussed in Chapter 7). Loose defibred fibres were frequently twisted (image 0003) but were generally not split or broken.  

While this is not conclusive evidence that defibring is caused by salts rather than freeze-thaw damage or general weathering, the SEM examination of these Cape Denison samples showed the deterioration was consistent with chemical dissolution of lignins that bind together the wood cells.
5. Salts

at the middle lamella, as described by Wilkins and Simpson in temperate Australia and by Blanchette, Held and Farrell (2002) at Ross Island sites. No defibring was found at any location without evidence of salts. While weathering by UV and water produces chemical damage such as loss of lignin in the middle lamella, transverse checking of tracheids and thinning and other damage to the cell walls, the detachment and curving of fibres affected by defibring is remarkable particularly for the early loss of strength in the middle lamella with less damage to the cell wall.

Profuse deposits of salts were visible on the exterior of the Ross Island huts (eg figure 5.16). At some sites defibring damage was only visible in locations where the surface was protected from corrasion. For example, at Cape Adare timber up to one metre above ground is corraded and defibring is evident above that level (figure 5.17) implying that defibring was removed by corrasion\textsuperscript{32}. Defibring is therefore likely to be more common than suggested by a basic visual examination and a combination of defibring and corrasion could synergistically accelerate the rate of loss of timber thickness.

Figure 5.15: Structure of wood cells, (Butterfield and Meylan 1980: 8)

\textsuperscript{31} Basic pH testing of wood and snow samples was done using Merck test strips which were all neutral. There are few penguins in the vicinity of the hut and no guano was evident at either visit. High pH can dissolve cellulose.

\textsuperscript{32} Harrowfield (2006: 301) states “Defibration, due to high concentrations of salts such as sodium chloride, under which melt water with salts in solution gently flows over the exterior … has not been observed at Cape Adare” but was evident to this author in 1993 (figure 5.17). A possible explanation is that evidence of defibring is removed by periodic corrasion events that carry smaller particles higher above the ground than normal.
Fig. 2. A schematic diagram to illustrate the general structure of the cell wall of axially elongated wood elements and the dominant, helical orientation of the cellulose microfibrils within each wall layer. ML, middle lamella; P, primary wall; S₁, outer layer of the secondary wall; S₂, middle layer of the secondary wall; S₃, innermost layer of the secondary wall; HT, helical thickening; W, warty layer.
Where significant corrosion occurs, erosion of the wood surface may remove some salts, although to effectively remove salts the corrosion rate would have to exceed the deposition and absorption rate. Corrosion is also quite localised at many sites due to vortex formation around
buildings (discussed in Chapter 7). Therefore, just because defibring is not visible at a particular time does not mean it is not occurring.

Blanchette, Held and Farrell (2002: 314) demonstrate that meltwater also rinses off loose fibres. Defibred wood at the exterior of the Discovery Hut had 98,650 ppm sodium, compared to 2073 ppm for interior timber and sound modern timber grown in the US had seven ppm. Wet defibred wood fibres had 3896 ppm sodium, indicating meltwaters had leached some salts. Fresh snow at Cape Evans had low salts whereas older snow from the roof had over 5,000 ppm sodium and elevated concentrations of chloride, potassium, magnesium and sulphur. At the Discovery Hut the highest salts were measured on the lower levels of the verandah, 246,000 ppm sodium. At Cape Denison, sodium levels in fresh snow were low except very close to the sea. The highest sodium level measured was under 4,000 ppm close to Boat Harbour.

Blanchette, Held and Farrell (2002: 316) identified the chemical species present and convincingly implicate sodium, which is present in very high levels in defibred wood, particularly where salts are concentrated by drying and not washed off (such as the porch at Cape Royds). Sulphur, magnesium and calcium concentrations were also elevated in defibred wood. They note there are high levels of salts inside the huts in locations where defibration is not evident (ibid: 316, 318), implying that moisture is required for damage to occur. Other Antarctic factors cited included “high UV light intensity, high amounts of sulphur, freeze-thawing of wood” (ibid: 321) that may synergise damage. The association of defibring and bleaching was discussed, noting loose fibres inside the Cape Royds hut retained a yellow-brown colour.

Sulphates, especially thenardite were found by the author to be prevalent in the Ross Island samples analysed (Table 5.3). Thenardite is known to be exceptionally damaging to stone through formation of supersaturated solutions that crystallise in pores (1999) (Rodrigues-Navarro

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33 This contrasts with Simpson and Wilkins who found defibring of timber inside roof spaces where water is also presumed to be absent or infrequent.
34 Thenardite is (anhydrous sodium sulphate) and has unusual chemical properties including formation of a stable heptahydrate at low temperatures, varying aqueous solubility in different temperature ranges, formation of double salts, and reduced solubility in the presence of NaCl. Damage is not due to hydration pressures from formation of mirabilite (Na₂SO₄.10H₂O).
and Doehne 1999). While the author has previously discussed\(^35\) and refuted evidence that freeze-thaw processes produce identifiable damage on the basis that the \(~10\%\) volume expansion is insufficient to cause damage to relatively flexible wood cells, the expansion of thenardite crystals\(^36\) may present a greater risk and should be further investigated. If this is the case, then removal of thenardite should be a focus for further research. Thenardite is not uncommon in Antarctica (Gore et al 1996).

Blanchette, Held and Farrell (2002) note that removal of surface salts does not treat salts that are absorbed within the wood but did not propose treatments\(^37\). Poultices (to extract salts by capillary action) or coatings (that can prevent damage at the surface) are routine conservation treatments could be investigated. Bickersteth et al 2008, who report the latest treatments of artefacts and buildings for the NZAHT, did not report any salt treatments. The fact that significant defibring damage can occur in less than a decade (Blanchette, Held and Farrell 2002: 314) indicates treatment development should be a high priority.

5.5.6 Relationship of salt deposition rates and deterioration risks (Research question 6)

Table 5.1 shows Cape Adare suffers the greatest extent and severity of salt problems, followed by the sites on Ross Island.

Unfortunately measurements of atmospheric salt deposition are too few (and use inconsistent methods), preventing proper comparisons between sites. Table 5.4 shows atmospheric aerosols are much higher at Davis than at Mawson, with the inferred reason being the katabatic winds at the latter\(^38\).

Pluviometer measurements do not include atmospheric deposition, so these will produce a lower salt measurement than a salt candle. Artigas\(^39\) has exceptional chloride deposition rates (180.1

\(^{35}\) Chapter 4.

\(^{36}\) Rodrigues-Navarro and Doehne (1999) showed that both expansion from hydration to form the decahydrate, mirabilite, and particularly the crystallization pressure, were exceptional among common salts.

\(^{37}\) This was outside the scope of their research although preventive treatments were identified.

\(^{38}\) These measurements used the same method and are therefore able to be compared.

\(^{39}\) Artigas measurement was by pluviometer and Cape Evans by salt candle.
mg m\(^{-2}\) day\(^{-1}\)) due to its marine climate and rates at Cape Evans are quite high (45.4 mg m\(^{-2}\) day\(^{-1}\), seaward side of hut). This suggests that Antarctic Peninsula sites should have greater salt problems, although this may be offset by flushing from rain and other precipitation.

The net effect of salt deposition and flushing of the surface is expected to be the most important factor determining the rate of defibring. However, this net effect is difficult to measure since it is highly localised and there are no standardised methods that can account for effects from blowing snow. The worst risks occur where deposition is high and flushing is low. The highest retention of salts in corrosion products was found at Davis, which were triple the retention found at marine sites in Australia\(^{40}\).

The measurements by Blanchette, Held and Farrell (2002) of concentrations in snow and timber are valuable in identifying salt concentrations on the surface of the buildings. They highlight the issue of penetration of salts into the porous timber. At sites apart from the relatively ‘rainy’ Antarctic Peninsula, meltwater appears the most significant source of salt removal but this is probably quite variable from year to year\(^{41}\).

It is important to measure all salts deposited and to consider their chemical properties, as this may affect retention and increase risks. Many researchers (including the author) presumed the dominance of chlorides, thereby missing the potential risks posed by other salts, particularly thenardite.

Condensation cycles inside buildings on Ross Island promote transport of salts and risk spreading damage. Thenardite is likely to accumulate in locations inside buildings where frequent wetting and drying cycles or where poor drainage occur, so horizontal (or cupped) surfaces such as window sills and beams inside roofs and walls allow salts to accumulate over time. Salt

\(^{40}\) It would be useful to have consistent measurements of aerosols, salt candles and pluviometer data and matching climate for representative sites in the Antarctic Peninsula, Ross Island and Mawson to make comparisons of the relative importance of different modes of deposition and flushing.

\(^{41}\) The amount of snow at Cape Evans and at Cape Denison is known to vary from year to year. At Cape Denison flushing of salts from the roof would depend on the height of snowdrifts around the building as snow on the apex does not appear to remain for long periods. Significant volumes of meltwater were observed flowing over the roof and wall of the AAE Main Hut during the author’s 1997 visit, but not in 1985 (which occurred earlier in summer).
chemistry in mixed solutions varies according to temperature (Campbell and Claridge 1987) adding additional complexity in understanding processes.

5.5.7 Effectiveness of conservation treatments for salt-related deterioration problems (Research question 7)

The key issues for conservators regarding defibring are the rate at which damage occurs (to determine priorities for intervention) and how this damage can be prevented and treated. Where artefacts can be removed from ongoing exposure, then desalination techniques may be used to stop further damage. However, where this is not possible, for example, inside the Ross Island huts, or for exterior cladding of buildings, there are few established methods suited for in situ preservation. Treatments undertaken at the Ross Island sites include brushing and vacuuming to remove deposits from the surface of furniture and artefacts (Maxwell & Viduka 2004) and replacement of damaged cladding (Blanchette, Held and Farrell 2002: 314). Some artefacts have been treated in a recently-established conservation laboratory, mainly conventional washing treatments of textiles and paper before replacement on display (Bickersteth et al 2008).

Blanchette, Held and Farrell (2002: 318-321) suggest the following measures to prevent defibring:

a. reduce snow accumulation on and near the huts; and
b. improve drainage to reduce moisture migration up the walls;
c. divert water flows from the roof and walls
d. reduce sources of moisture including getting visitors to take off outdoor shoes to wear slippers inside; and
e. removal of accumulated salts\(^\text{42}\).

These methods would improve efficiency of current conservation practices and could be implemented at low cost. In addition, a number of approaches could be considered where extreme damage is occurring including:

\(^42\) No method is specified, other than that it should be non-abrasive, noting the difficulty of removing salts absorbed into the wood.
- Use of sacrificial coatings such as cellulose ethers that prevent direct contact of the salt with the vulnerable surface but will be corraded away within five years; and
- Poultices of paper sheeting\(^{43}\) to extract salts from affected materials and reduce further damage to timber fibres.

Both these treatments would permit salts to recrystallise on the coating or poultice rather than in the timber so it would reduce damage. The effectiveness of these treatment strategies could be tested in a salt spray/fog chamber using a salt composition to match that occurring in Antarctica. Acceleration of deterioration can be simulated by producing wetting/drying cycles at low temperatures. Experimental techniques can refined using field tests of various poultice materials and methods on aged (but not historic materials) to ensure ethical practice.

The rate of defibring damage at Cape Evans appears to be slow but significant (Blanchette, Held and Farrell 2002: 314) with original boards requiring replacement in 1991 (ie after 80 years exposure). New boards were visibly affected by 1999 (eight years’ exposure). The rate of damage is difficult to measure at other sites such as Cape Denison and Cape Adare where defibring occurs with corrosion and combined damage may be synergised and even more rapid, although possibly less visible (discussed further in Chapter 11).

*Outdoor artefacts and buildings*

The risks of salt-related damage are highest for outdoor artefacts and exteriors of buildings, especially at sites with low rainfall and onshore winds such as the Ross Island sites. Wind direction affects the rate of salt deposition and the amount of rainfall affects the amount of surface flushing. The degree of risk therefore depends on the ratio of deposition to flushing at each site.

Most timbers used for the early huts at Cape Denison and in the Ross Dependency were unpainted, although *Operation Tabarin* huts in the Antarctic Peninsula appear to have been painted or treated with bitumen, which would reduce salt absorption by wood (figure 2.28). The
AAE hut timbers were carried as deck cargo and were covered with salt spray during the voyage. These salts are unlikely to have been washed away during construction, since there was no rain during that period.

Use of clear protective coatings on previously unpainted, aged timber is fraught with ethical and aesthetic risks. It is difficult to find coatings that are durable, able to be applied thinly and able to be removed if problems arise. The author field tested a range of coating, discussed in Chapter 7 as a potential treatment to minimise wind damage but none were found suitable although some may be suitable as sacrificial coatings to prevent defibring at less windy sites. While defibred outdoor timbers could be treated using poultices (eg paper pulp) to remove salts, these may prove impractical if wind could strip off the poultice and rapid drying and/or freezing may reduce its effectiveness. Such treatments are labour-intensive and salt deposition would recur unless a preventive treatment, such as a protective coating, could also be applied.

Sacrificial ‘breathable’ coatings of cellulose ethers may be more suitable at less windy sites and several were field-tested by the author at Mawson Station, also discussed in Chapter 7. These form a barrier to absorption of salt into the pores of the timber and make it easier for salts to be cleaned off the surface. Cellulose ethers tested did not to darken or discolour samples of non-historic ‘Baltic pine’. Cellulose ethers are used for graffiti protection since they can be removed easily (if required) with hot water or steam and can be applied as a nearly invisible thin transparent film. The long-term durability and solubility of cellulose ethers is well-documented in the conservation literature (eg Feller and Wilt 1989), and they appear to wear off with the weather and corrosion after approximately five years in Antarctica (authors observation, discussed in Chapter 7). Such treatment would not require significant costs or labour nor increase fungal risks.

Apart from these prospective treatments there are few other feasible alternative approaches to replacement or overcladding of the timbers, which prevents the original building fabric being seen.

\[43\] Note that paper pulp would not be acceptable under Antarctic environmental guidelines because it could blow
Some artefacts in the Ross Dependency huts have been relocated inside buildings to reduce risks such as wind damage and to improve security. There is a strong case for doing so where significant artefacts would otherwise be lost. However, in 1993 many of these artefacts were covered in salt, and bringing such artefacts indoors without desalination can increase corrosion and defibring damage of those artefacts (and possibly adjacent items) due to the high RH inside the huts.

Artefacts that are brought inside the huts for protection or display should be treated to remove salts to reduce the total amount of salt inside the building and prevent transfer to other artefacts. For example, a sledge inside the Cape Royds hut sparkled with salt crystals and also had significant defibring, much greater than that on any other comparable items inside the hut (figure 5.18). Coal inside the Discovery Hut was also covered in salts (figure 5.19). Poultice treatments may be suitable for such artefacts and could be undertaken at the laboratory recently established at Scott Base.

Figure 5.18: Sledge inside Cape Royds hut (author’s photo 1993)
Note: the first image gives a general view of the sledges on which upward curving wood fibres can be seen (blue arrow). The second image is a closer view showing numerous fine wood fibres rising above the surface.

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44 The only artefacts affected by defibring inside the huts appear to have been brought in from outdoors.
45 An evaluation of the broader issues of relocation of artefacts is given in Chapter 11.
Figure 5.19: Coal covered in salts, *Discovery* Hut (author’s photo 1993)
The ASPA management plans for the Ross Island sites now recognise some of these risks and require removal “of any clothing made wet by sea water or any sea ice crystals from boots, as salt crystals accelerate corrosion of metal objects” (page 4, ATCM XVIII, June 2005)

*Salt ingress into buildings*

Salt ingress is an obvious problem in the Ross Island huts despite being comparatively air tight, having light winds and the overcladding with Butynol, although membranes and overcladding may not be the best approach. Once salt enters the building it may be transported within the building by meltwater, capillary action and condensation cycles, evident by the salt trails that appear to be associated, in some locations, with the overcladding. Investigation is required inside roof cavities to establish if leakage or condensation is occurring.

Blanchette, Held and Farrell (2002: 316) provided a detailed analysis of salt ingress and noted high concentrations of salts where windblown snow enters the Ross Island huts. They recommended more boot brushing to ameliorate the problems of visitors bringing in moisture and salts on clothing and footwear. However, more comprehensive control of salt ingress appears necessary.

Sensors are available\(^{46}\) that could measure salt deposition within wall cavities and throughout the hut. This could help identify sources of ingress, and determine whether condensation cycles are involved. If condensation and/or melting are involved, then a review of the use of vapour barriers/retarders may be required to determine whether a more vapour permeable covering or a lighter colour\(^{47}\) should be used. Moisture absorption by salts inside buildings in marine environments can promote wetness (Ganther, Norberg & Cole 1996: 2069).

*Artefact treatments*

Brushing and vacuuming of artefacts affected by surface salts inside the Ross Island huts is said to have reduced problems by removing salt deposits (Bickersteth *et al* 2008) but this is labour

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\(^{46}\) See also [http://www.solve.csiro.au/0506/article1.htm](http://www.solve.csiro.au/0506/article1.htm)
intensive and takes a significant proportion of the available time of site personnel. This approach is unlikely to remove salts that have penetrated into porous materials such as timber, paper or clothing which require even more labour-intensive immersion treatments.

*Cape Denison plaques enclosed in bronze*

This well-intentioned treatment failed to keep out windborne particles, leading to corrosion of the box and defibring and staining of the wood, requiring repatriation to Australia for treatment and storage. This showed that even a tight rubber-on-metal seal is ineffective against katabatic winds suggesting sealing of whole buildings might also be ineffective. The metal box trapped moisture and salts and the warmth from solar radiation accentuated the conditions that promote defibring and corrosion with no easy way to remove moisture once it is inside the box.

*Overcladding, AAE main hut*

Any material that decreases vapour transmission will risk causing condensation if the surface is colder than the surrounding air. This can easily occur in the wall space or ceiling where there is a difference between interior and exterior temperatures. If condensation moisture forms in the wall space, salt deposits can deliquesce and form concentrated solutions, damaging timber and corroding metal fasteners in locations where damage cannot easily be detected.

Overcladding using timber and/or polymer membranes (figure 5.20) has been used to prevent ice ingress and prevent corrosion of several Antarctic historic huts. While this may decrease the risk of salts penetrating the building via ingress from the roof (but not walls and doors), it could increase moisture and retention. Blanchette et al (2002: 316) noted there was “no visible defibration” inside the *Nimrod* and *Terra Nova* huts although significant salt accumulation was present, although there was defibration inside the porch of the *Nimrod* hut. If overcladding reduces the salt ingress inside buildings then it may be effective in reducing defibring risks, but if local condensation and salt concentration occurs in between the layers of timber then defibring may occur and the risk should be assessed via inspection.

47 A lighter colour would reduce heat absorption and reduce melting risks.
5.5.8 Implications for site management (Research question 8)

_Prevention_

While brushing and vacuuming used at Ross Island sites removes salt once it is deposited, finding methods to prevent or reduce salt ingress would be more effective. This would require testing of suitable materials inside wall and roof cavities to find optimal methods to prevent ingress and manage condensation.

Preventive strategies could also include use of suitable temporary covers over artefacts displays when visitors are not present\(^{48}\). Measurement of salt deposition above and below the covers could determine whether these strategies are effective. Buildings and artefacts buried in snow that does not melt appear to be protected from salt deposition\(^{49}\).

Mason (1999: 22) considered that tourist vessels cutting through sea ice may cause an increase in salt deposition at the Ross Island sites and recommended “tourist vessels [be] required to stop

\(^{48}\) These are currently used to cover artefacts to prevent snow and hoarfrost gathering on artefacts in the AAE main hut.

\(^{49}\) “The artefacts encased in ice were well-preserved. The preservation qualities of constant below zero temperatures on artefacts is exemplified by a zinc-plated cannister from the 1899 expedition containing an enamel plate, fry pan and teaspoon individually wrapped in brown paper in almost new condition.” (Harrowfield 1991)
Further out in the sound” to help manage corrosion risks. Evidence for this damage would need to be strong because this would impose significant costs and difficulties for tourist operators who often use helicopters to land tourists. Curran et al (2006) found that salt deposition in from particles blown off sea ice is greater than that from open sea. This could be verified by measuring salt deposition\textsuperscript{50} at Cape Evans or Hut Point comparing periods with and without sea ice.

**Treatment**

Removal of ice inside buildings allows salts to deposit directly on the surface of artefacts and building materials. Any factors that increase effective permeability of the building fabric (such as loss of ice from the verandahs of the AAE hut) may increase the rate of deposition.

The venturi model proposed by Ambrose and Godfrey (1998) extracts inside air from a building, but unless the building is completely sealed then air ingress will occur to equalise the pressure difference. This air ingress could bring salts inside the building and the ablation could then concentrate the salts. Again, salt measurements should be used to quantify risks.

**Recommendations for further research**

While much additional research could be done to improve knowledge of salt damage processes to improve treatment, funding is unlikely to be available so priorities must focus on developing practical treatments.

The key priorities are:

1. Measurement of deposition and inspection for damage where risks are highest inside wall/roof cavities (for example, using sensors described in Ganther, Norberg Cole 1996).
2. Investigation to determine the source of leaks and gaps to prevent or reduce salt ingress.
3. Analysis of all salts deposited, not just chlorides, and evaluation of the risks from thenardite.

\textsuperscript{50}Thus the need to prevent visiting ships anchoring close to shore could be resolved and the priorities and feasibility of various treatments could be considered.
4. ISO 9225 salt candle measurement of salt deposition inside buildings to quantify risks to artefacts and fasteners and determine whether deposition rates are higher or lower when sea ice is present.

Ideally both salt candle and pluviometer measurements should be undertaken to compare total atmospheric deposition (salt candle) versus salts contributed by drift snow (pluviometer) to quantify risks from ice removal or natural ablation.

It is important to field test any membrane material before it use for treatments in any historic building to determine whether it may reduce vapour transmission or cause condensation problems.

Several investigations were proposed in the chapter for development of sacrificial coatings for timber to minimise salt deposition/penetration into timber and stop defibring damage at the surface. These require both laboratory testing of durability (which can accelerate weathering for faster evaluation) and field testing in Antarctic conditions to simulate potential effects on building materials in use (eg trapping of moisture).

5.6 SUMMARY

1. Salts caused deterioration problems at all coastal Antarctic historic sites, particularly at Cape Adare and the Ross Island sites.

2. Sites with katabatic wind regimes generally have lower salt deposition rates, but the higher chloride: sulphate ratio measured at Cape Denison indicates local vortex effects at Cape Denison may draw air from the sea or sea ice, increasing localised deposition.

3. Thenardite (anhydrous sodium sulphate) was the predominant salt found in deposits inside the Ross Island huts. In analysing salt deposits at Antarctic historic sites all ions must be considered, not just halides. Thenardite is known to be extremely damaging to stone because of hydration expansion and its role in defibring of wood should be further examined.
4. Blanchette et al (2002) demonstrated that defibring is associated with salts and wetting/drying cycles, not ‘freeze-thaw damage’ but further work is required to apply their research and develop conservation treatments and preventive strategies to reduce salt ingress, which may be more effective than current methods that remove salts after they have deposited. Sacrificial coatings and poultices for timber could be considered.

5. The rarity of rain leads to increased salt damage, since melting snow is comparatively ineffective in flushing surfaces, however, wind can remove evidence of defibring, so salt risks may be unsuspected.

6. Quantifying salt ingress and transport within buildings using ISO 9225 salt candle measurements and salinity sensors could help to assess these risks.

7. Condensation on vapour barriers and drying winds could concentrate salts inside wall spaces risking damage where it is most difficult to monitor.

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5. Salts


6. CORROSION AND OTHER DAMAGE TO METALS

Figure 6.1: Corrosion affecting tinplate and galvanised steel artefacts in the meltwater zone beside the AAE main hut, Project Blizzard 1985

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Corrosion in aqueous solutions

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Tin pest

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6. Corrosion and other damage to metals

6.1 AIM AND INTRODUCTION

6.1.1 Objectives and scope

The aim of this chapter is to:
- document the extent and severity of corrosion occurring at Antarctic historic sites;
- briefly review other damage to metals, including ‘tin pest’;
- quantify the environmental factors involved in corrosion in Antarctica;
- evaluate available information on previous treatments of corrosion; and
- thereby consider what treatments will be effective in Antarctica.

Initial observations by the author at Cape Denison in 1985 found corrosion to be prevalent (Hughes, JD 1986) despite previous advice had been that corrosion does not occur in Antarctica because of the ‘dry cold’. Numerous metal artefacts and building components were corroded, including mild steel nails (figure 6.18), lead sheeting (figure 6.19), aluminium wire, tin-plated steel fuel containers (figure 6.1), cast iron (figure 6.5), galvanised steel and various copper alloys (figures 2.19), including items inside buildings (figure 6.30). Some artefacts and building elements, such as roof gutters and ridge capping, were completely corroded through (figure 6.3), others had blisters, pitting and iridescent appearance suggesting salts (figure 6.2).

Although individual items are of low intrinsic value together they contribute evidence about the life and work of the Australasian Antarctic Expedition at the site and are of significant interest to visitors as well as heritage researchers. Examples include food tins, galvanised fuel containers, an abandoned cast iron stove and a lantern that illustrate the difficulties of life during an important early scientific expedition dating from the early exploration of the Antarctic continent (Hayman, Hughes & Lazer 1998). Wire used for the radio mast is physical evidence of the expedition’s pioneering use of radio communication in Antarctica. Lazer, an archaeologist who has conducted extensive work at Cape Denison, strongly recommended that artefacts should remain on site to preserve the integrity of the site in the context in which the artefacts were used (Hayman, Lazer and Hughes 1998).

However, climatic conditions are known to make in situ outdoor preservation extremely difficult. Furthermore, conserved artefacts would be expected to re-corrode due to high
relative humidity known to exist inside many historic buildings. Preliminary testing of metal coupons coated with common corrosion treatments exposed at Cape Denison during summer 1984-85 and 1985-86 all failed within short periods (Hughes, JD 1986), indicating that development of effective conservation treatments meeting ethical requirements would be a significant challenge. This chapter therefore examines the environmental factors that cause corrosion and the measurement of rates of corrosion in detail, since this is fundamental in determining what treatments may be feasible. Observations of corrosion of historic metals, in the absence of long term corrosion data, can provide useful insights into corrosion in severe climates.

Figure 6.2: Memorial Cross bar end-band, Cape Denison, author’s photo 1985;
Note: The cross bar has blown onto the ground. The surface of the iron alloy fitting (original location shown in AAE photo at right) is now extensively pitted.
Figure 6.3: Corroded valley gutter AAE main hut, 1997, author’s photo
Note: Living hut roof is at left of image, Workshop roof at right.

Figure 6.4: Horlicks can, AAE main hut, author’s photo 1985
6. Corrosion and other damage to metals

Figure 6.5: Rusted cast iron stove outside Mawson's Hut, Project Blizzard 1985

Figure 6.6: 'Webb's Lantern', in situ near Magnetograph House, Cape Denison, Project Blizzard 1985
6.2 LITERATURE AND GAPS IN KNOWLEDGE

6.2.1 Corrosion types

There are two main categories of corrosion: atmospheric corrosion, and processes that occur when metal is immersed in ionic solutions.

Atmospheric corrosion

The theoretical basis of atmospheric corrosion is well-established and has been described by Brundett (1990) and many others. Two key steps occur in atmospheric corrosion (ibid): formation of an oxide layer (by a chemical reaction which is independent of temperature) and formation of an adsorbed water layer which increases exponentially in thickness becoming progressively more electrolytic in character (and consequently is RH dependent). The resulting corrosion cells are influenced by factors such as differential aeration, presence of different atoms in the crystal lattice, pores in the protective oxide layers and presence of grain boundaries.

Brundett (ibid: 60) examined condensation at sub-saturation humidity in microscopic crevices in the surface of a metal, which allows corrosion to occur. In small crevices, the saturation vapour pressure above the liquid surface may be so reduced that condensation can occur. Conditions for wetness are also partly determined by the relative surface area and the ‘wettability’ of the metal surface. If trace chemical contaminants are present in the air then these can form a fine surface film of salt, which may be hygroscopic. The presence of any soluble salt will enhance condensation because the vapour pressure above salt solutions is lower than that above pure water.

A widely-used standard methodology for measurement of atmospheric corrosion rates of metals is defined in the International Standard ISO 9223 on ‘Corrosion of metals and alloys-Corrosivity of atmospheres-Classification (1992)’. The standard provides a concept called ‘Time of Wetness’ (TOW), described as "the period during which a metallic surface is covered by adsorptive and/or liquid films of electrolytes that are capable of causing atmospheric corrosion".
The standard points out that “wetting of surfaces is caused by many factors, for example dew, rainfall, melting snow and a high humidity level”. The standard states that TOW can be estimated as the length of time (hours/year) when the relative humidity is greater than 80% at a temperature greater than 0°C. The 80% RH criterion was derived by empirical observation that above that humidity level corrosion rapidly increases. A note in the standard qualifies this criterion and indicates that other factors such as metal type, object orientation, corrosion products, and pollutants on the surface, may influence the TOW. However, the standard considers “the criterion usually sufficiently accurate for the characterisation of atmospheres”.

The concept of TOW thus reinforces the notion of ‘no corrosion because of the dry cold’ since temperatures in Antarctica are frequently below 0°C and because the characteristic low precipitation (in the form of snow) is usually interpreted as implying low humidity. However, Chapter 4 showed Antarctica is not universally cold and dry.

Atmospheric corrosion rates can provide useful comparisons of corrosion conditions between sites since they are only concerned with the atmosphere (including pollutants) and the metal coupon, which can also be standardised by composition and size to improve comparability. Once the corrosivity is known for a site it is possible to determine what type of treatment may be applicable, for example, what type of protective coatings may need to be applied. If corrosivity is higher than would be expected from climatic data then the causes should be investigated. Atmospheric corrosivity data enables comparison of the corrosivity of Antarctic conditions with corrosivity in temperate regions where there is more data about the suitability of various treatment methods.

Measurement of rates of atmospheric corrosion was preferred over other forms of corrosion since this provides a fundamental measurement representative of the site. Other forms of corrosion such as galvanic corrosion, involve two metals, a dielectric and polarisation effects, which are highly localised.

**Corrosion in aqueous solutions**

The theoretical basis of corrosion involving aqueous solutions has been extensively reported in the literature (e.g. Brundett 1990) and covers the characteristics and identification of galvanic corrosion, crevice corrosion, pitting, intergranular corrosion, selective leaching, erosion corrosion and stress cracking corrosion. Information on identification of corrosion
types and the effects of salts in increasing corrosion reactions and depression of freezing point have been widely published.

**Physical damage**
Crushing, stresses, abrasion or erosion can damage the structural integrity of buildings and artefacts. The causes of such damage are normally evident. Physical damage may also increase corrosion rates, for example via stress-cracking corrosion.

**Tin pest**
Tin pest is thought to damage metals in cold climates due to allotropic transformations at low temperatures and should theoretically be present in Antarctica. Stambolov (1985: 147) states:

"Tin … may exist in three different crystallographic modifications. At temperatures between 13.2°C and 161°C its atoms are packed in tetragonal crystallites and tin exhibits metallic properties. Below 13.2°C it acquires a gray appearance and disintegrates as a powder... According to Cohen this decomposition develops very slowly and attains its maximum value at about -48°C".

**6.2.1 Arctic literature**

**Arctic corrosivity studies and climate**
Brass (1999) discussed depression of freezing point and its effect on corrosion rates in the Arctic. His phase diagrams provide rare quantitative data on the effects of salts and their interactions at different temperatures.

"The ternary phase diagrams of two chloride salts and water demonstrate that freezing leads to concentration of salts in residual brines capable of participating in corrosion reactions to temperatures below -50°C. The saltier the initial solutions, the more liquid remains unfrozen at lower temperatures."

Divine and Perrigo (1986) provide a comprehensive overview of Arctic corrosion studies including research on widespread air pollution from industrial and mining activity and use of de-icing salts, which have a significant localised effect on corrosion. By comparison, industrial activity is absent in Antarctica and the impact of isolated scientific stations is expected to be limited.
Mikhailov, Syloeva & Vasilieva (1992) measured corrosivity for carbon steel and zinc at 29 sites in eastern Siberia including severe cold climates both on the coast and inland.

The National Association of Corrosion Engineers (NACE) publishes information from its Cold Climate group which focuses on industrial corrosion research in Alaska. In the 1990s several studies were undertaken which correlated corrosion rates against temperature, humidity and pollutants. The 2001 NACE cold climate corrosion conference in Alaska presented several papers with both Arctic and Antarctic measurements and relevant data are discussed in the later sections of this chapter.

**Corrosion at Arctic historic sites**

No quantitative corrosion rate measurements are available for true Arctic historic sites\(^1\). Numerous references provide qualitative evidence that corrosion is significant at coastal Arctic sites. Croome (2004) presented a methodology for measurement and application of long term corrosivity measurements for preservation of cannon at a seventeenth century site near Churchill, Manitoba. While the climate is dissimilar to the Antarctic historic sites in this thesis the methodology is similar in approach in applying corrosion science to manage risks to historic artefacts.

Hett (1978) examined Kellett’s storehouse on Dealey Island and remarked:

“While low ambient temperatures have slowed down the rate of corrosion of iron and retarded the decomposition of organic materials, the removal of these objects to a warmer climate with extreme variations of relative humidity leads to a rapid deterioration”.

Limited environmental monitoring was undertaken at Dealey Island using a thermohygrograph, which itself was extensively damaged by corrosion (personal communication David Grattan, Canadian Conservation Institute 1999).

Hacquebord and Blankenstein (1993) found some small metal items remaining (mostly nails) at the site of Barents Hut on Novaya Zemlya and commented on the generally poor condition

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\(^1\) Personal communications to the author at NACE conference in Anchorage Alaska, February 2001 by Lyle Perrigo, US Arctic Research Commission and Dr Jan-Fredrik Henriksen, Norwegian Institute for Air Research.
of most of the site. Capelotti (1994) noted that salt air and warm summers had caused extensive corrosion at an early twentieth century site at Cape Wellman in Svalbard. Artefacts at most sites on Svalbard and the Franz Josef archipelago are said to be corroded (personal communication: Susan Barr, Riksantiksvaren, Oslo 2001).

6.2.2 Antarctic literature

Antarctic corrosion rate measurements (see Table 6.6)

Mikhailov et al (1993) measured corrosivity at Mirny, a Russian Antarctic base with a coastal climate and strong winds. TOW in Arctic Scandinavia, Russia and Canada are typically 1000-4000 hours while that at Mirny was 93 hours. Chloride composition in snow samples collected in the vicinity of Mirny varied eight fold although the offshore katabatic winds reputedly carry little salt. The authors considered that effective TOW might be affected when high relative humidity and salt deposition both occur. Mikhailov’s team found that many sites for which detailed meteorological records were available showed continual sub-zero temperatures, which according to ISO 9223 should have zero time of wetness and thus no corrosion.

Fahy (1990) measured corrosivity of aluminium coupons in the Ross Dependency comparing various alloys with different surface treatments including a range of anodised surface thickness. Fahy had to rely on others to place his specimens and some plates were exposed next to diesel generators at Scott Base. Aerosol pollutants affected results. Exposures were later repeated at unpolluted Arrival Heights which resulted in considerably less pitting of sample coupons.

King et al (1988) measured corrosivity of steel alloys at Cape Evans (10.83 μm/year) and at Vanda Station (0.87 μm/year) in the Dry Valleys. The rate measured at Cape Evans is comparable with suburban areas in temperate regions of Australia yet the site is surrounded by sea ice for 10 months of the year and air temperatures are rarely above 0°C.

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2 These ice-free areas are fed by cold air from the polar plateau and almost no rain has occurred for over a million years
Rivero et al (1996) used Mossbauer Spectroscopy to study corrosion products on low-alloy steel exposed at the Uruguayan Antarctic Peninsula station, Artigas, where the measured corrosivity was 40-66 μm/y for a one-year exposure with ISO TOW of 8919 hours/year.

Rosales and Fernandez (2001) measured corrosion rates for steel, zinc, cooper and aluminium at the Argentine Antarctic Peninsula station, Jubany. TOW was directly recorded using Pt/Ag electrodes on an alumina substrate and compared with the ISO TOW estimated using climatic data. High corrosion rates were measured for all metals, discussed in section 6.5.2. They concluded that in the presence of a marine salt, liquid water monolayers could form at the metal surface under ice layers resulting in corrosion at temperatures below 0°C.

Observations of corrosion at Antarctic historic sites

Useful qualitative reports on corrosion are available from historic sites and artefacts at Nordenskjold's hut (Comerci 1983); Byrd's 1940 East Base (Broadbent 1992); Wilkes (Clark and Wishart 1991) and at abandoned British bases (Cochran & Collinge 1994) and all the Ross Dependency sites (Harrowfield 1988). Some photographs included in the reports clearly show that corrosion is severe.

Whilst corrosivity measurements were outside the scope of Mason’s (1999) study of the Terra Nova hut, he was able to make detailed examination of artefacts inside the hut and reported corrosion on the underside of stoves, brackets, tin cans and other items. He found some filiform corrosion and pitting, details of which are discussed later in this chapter.

Maxwell and Viduka (2004) reported on several years of observations of qualitative tests on commercial corrosion inhibitors and coatings trialled at the Ross Island huts. They utilised temperature and RH measurements inside the huts undertaken by Held et al (2005) and observed that condition of artefacts inside the building varied according the microclimate conditions with the worst corrosion occurring in conjunction with high RH and poor air circulation and condensation. Their results showed poor performance of the various coatings tested, which included tannic acid, oxalic acid, sulphonates and other corrosion converters in various wax and lacquer polymers. They concluded that some preventive conservation

3 The citations are provided in the references for Chapter 2.
4 This was not possible for the author of this thesis.
approaches may be useful but that conservation treatment with the limited available facilities was not currently practical. This paper is considered in further detail in the discussion.

**Tin Pest**

Gilberg (1991: 4) reviewed alleged observations of tin pest in museum collections and stated:

“Though the mechanism by which white tin is transformed to grey tin is not yet fully understood, it is generally believed to occur through a process of nucleation and growth of the grey tin by diffusion at the surface of the metal….

The rate of transformation is dependent upon a number of factors including temperature, presence of grey nuclei, metallographic structure, degree of cold working and annealing, presence of electrolyte, and purity of the metal. All of these factors are interrelated, thus making it extremely difficult to define the exact conditions under which the transformation of white tin to grey tin may occur.”

Stambolov (1975: 148) studied artefacts from Barents’ Hut and stated:

"It may be concluded from the condition of the tin objects in the find on Nova Zembla [Novaya Zemlya] that low temperature is not the initiator of 'tin pest'. Left by Dutch sailors in 1597 and discovered by a Norwegian captain in 1871, these tin objects have spent about two and a half centuries in a polar climate without any damage. The analysis of one candlestick from the find on Nova Zembla showed a composition of 80% tin and 20% lead, while the solder on it consisted of 100% tin. Neither the alloy nor the pure tin was attacked and X-ray fluorescence analysis detected no amounts of bismuth and antimony salts which, according to Remy obstruct the appearance of gray tin".

Gilberg (1991: 15) considered whether tin pest contributed to the death of Scott’s party during his South Pole expedition in 1911 from oil leaks which spoiled food supplies.

“It was believed at the time that the cans had been soldered with pure tin which when exposed to the extreme Antarctic cold turned to powder. However, when recovered a number of years later and analysed by the Tin research Institute, no evidence of tin pest was found”.
Huntford (1979: 307, 533) stated that poor soldering and/or evaporation were to blame whereas Gilberg (1991: 5) concluded that:

“Today is it generally accepted that the transformation of white tin to grey tin does not occur spontaneously but is confined to high purity metals and even then must be exposed to low temperatures for prolonged periods of time.”

Gilberg (1991: 16) cites tin pest as a “good example of the importance of understanding the mechanism by which antiquities corrode or decay if appropriate treatment methods are to be applied. In the case of tin, for many years this mechanism was unknown and as a result totally inappropriate measures were undertaken”. This statement is relevant for all conservation treatments at Antarctic historic sites.

Telluric corrosion

Boteler et al (1999) provided the first theoretical explanation of the propagation of telluric currents in metallic structures from variations in the earth's magnetic fields, which are more intense in higher latitudes close to the magnetic poles. The strongest effects are produced in long pipelines, such as those used to transport oil in Alaska (~1,000 km long). Maximum voltages are proportional to the pipeline length but the use of insulating flanges along the pipeline, along with cathodic protection and earthing of currents has been very effective.

Large bodies of tidal salt water produce telluric effects due to their relative motion with the earth's magnetic field (Martin 1994). From the theoretical discussion and examples cited in both papers it is apparent that there are no metal structures in Antarctica that would be of sufficient length, or are immersed in tidal sea water, to experience any significant corrosion from telluric currents.

In summary, the literature shows:

- At least six researchers have observed significant corrosion problems affecting diverse artefacts at more than ten Antarctic historic sites of different ages in diverse locations.
- Despite limited corrosivity data, available measurements show corrosivity is significantly higher than predicted by TOW estimated from temperature and RH using ISO standard

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5 Mawson’s air tractor was found immersed in Boat Harbour in 2010 (Mawson’s Hut Foundation website downloaded 30 April 2010).
9223 and that temperature may not be the dominant factor determining corrosion in cold conditions.

- There is serious doubt whether ‘tin pest’ and telluric corrosion may exist in Antarctica.

### 6.3 METHODOLOGY

#### Research questions

The following research questions need to be answered to develop effective metals conservation strategies for Antarctica:

1. Can corrosion occur below 0°C?
2. What is the relationship between air temperature, RH, TOW and formation of moisture films on metal surfaces in Antarctic climates?
3. Does corrosion occur under ice layers or is some other process involved?
4. Does surface warming allow corrosion to occur, producing higher corrosivity than predicted by ISO 9223?
5. Can temperature and RH data and TOW measurement be used to predict corrosion risks for a site?
6. How does the removal of ice from inside buildings impact on corrosion of artefacts and building elements?
7. How do salts affect corrosion rates in Antarctica?
8. How can the corrosion problems be managed?

Field observations, corrosivity measurements and some instrumental measurements were used to address these questions.

#### 6.3.1 Field observations and corrosivity coupon measurements (Research question 1)

**Sites examined**

Field observations of the condition of artefacts and metal building elements were undertaken at the 12 sites previously identified in Table 3.1. In addition to the short time ashore, it was not permitted to remove historic material for analysis so this limited some attribution of the composition of the metals observed. Photographs of sites in the Antarctic Peninsula, kindly
provided by colleagues, were examined to attribute corrosion behaviour in this warmer, more maritime Antarctic region.

**Observational method**

To use the limited time available at the sites effectively, a checklist of observations was developed to identify the type(s) of corrosion occurring at each site and to standardise the attribution of the severity of its effects (Table 3.2). Environmental characteristics in the immediate vicinity of the artefacts and building were noted to compare with corrosion impacts. Photographs were taken, where possible using a standard colour correction chart, to facilitate comparability of the images.

**Identification of type of corrosion.**

Photographs are included in the results section of this chapter illustrate the occurrence of diverse corrosion types in Antarctic conditions. Attribution of the actual type of corrosion present was based on the author’s professional knowledge as a metals conservator supplemented by reference to standard texts such as Brundett (1990). Tin alloys and tin-plated items were examined for signs of ‘tin pest’ although a sample would be required for confirmation of its presence.

**Corrosion rate measurements**

It was necessary to choose different locations for corrosivity measurements since many of the historic sites where field observations were undertaken had major logistical constraints or lacked suitable meteorological facilities.

**Selection of sites for coupon exposures**

Coastal Antarctic sites were chosen on the combined basis of climatic variation, presence of historic sites, availability of meteorological facilities and ease of contact with meteorological staff to arrange exposure and retrieval of the coupons. Sites in the interior of Antarctica were also chosen as an initial test of the hypothesis implied in ISO 9223 that TOW (and thus corrosivity) is zero in locations where temperature is consistently below 0°C. The least
accessible location (the Russian station at Vostok) was the most desirable for this study because of its high altitude, remoteness from the sea and particularly severe climate. Fortunately at the time of the study there was increased scientific activity although subsequently the station was closed due to the high operating costs. Sites where measurements were undertaken are shown in figure 6.7.

ISO Standard 9223 provides two ways to determine the corrosivity category of a given location:
- the environmental classification in terms of time of wetness and pollution; and
- classification based on corrosion rate measurement and standard metal specimens.

Further standard measurement techniques are given for measurement of pollution, ISO 9225 and determination of corrosion rate of standard specimens, ISO 9226). ISO 9225 and ISO 9226 can be applied to measure rates of atmospheric corrosion at historic sites in Antarctica and to compare with rates measured in more familiar temperate conditions.

Figure 6.7: Map showing location of measurements and corrosivity recorded in Antarctica
Measurement of corrosion rates (corrosivity) using coupons

ISO 9223 (1992) defines corrosivity:

“Corrosivity of the atmosphere: The ability of the atmosphere to cause corrosion in a given corrosion system (e.g. atmospheric corrosion of a given metal or alloy).

Corrosivity is thus a standardised measurement of the corrosion rate of a specific metal in the atmosphere, usually expressed in micrometers per year that provides information about the nature of the corrosive environment.

ISO 9226 Corrosivity of Atmospheres- determination of corrosion rate of standard specimens for the evaluation of corrosivity provides a correlation between atmospheric conditions and typical corrosion rates measured at hundreds of sites around the world where standardised corrosivity measurements have been made.

The method described in ISO 9226 (1992) uses coupons (ie flat metal pieces) of a standard alloy which are exposed to the atmosphere away from any sheltering effects for a standard period of time. This method was used by King et al (1988) for corrosivity measurements at Cape Evans and was chosen, with some small variations described below, because it is a widely known method for comparison of corrosion rates at different locations and has been used for over twenty years by the CSIRO Division of Building, Construction and Engineering for broad scale corrosivity surveys including a major corrosivity map of greater Melbourne (King, GA, Martin & Moresby 1982).

The coupons used are approximately 100mm long by 50mm wide and 3 mm thick with a weight of approximately 120 grams. Fuller details of the methodology of removal of the corrosion products from the coupon is given in King and Carberry (1992: 6) and King and O’Brien (1994). In brief, the loose corrosion products were gently scraped from the coupons using a stainless steel scalpel to remove loosely bound corrosion products which were saved

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6 Corrected mass losses W (g) were converted to corrosion rates in terms of thickness lost per year (microns/y) by the formula:

\[ \text{Corrosivity} = \frac{W}{Ap} \times 10^6 \times 365/t \]
for further analysis. The coupons were then cleaned in Clarke’s solution (concentrated hydrochloric acid with 5% w/w stannous chloride dihydrate and 2% w/w antimony trioxide). Two previously cleaned specimens were included with each batch to determine blank correction factors for removal of non-corroded steel.

Choice of metal to characterise site corrosivity

Various metals have been used to characterise site corrosivity including unalloyed carbon steel, zinc, copper and aluminium but most research carried out in Australia has used a standard low-alloy copper bearing steel and this was also used for the exposures in the research for this thesis. It is essentially a low carbon or ‘mild’ steel, but the addition of about a quarter of a per cent of copper renders the corrosivity relatively insensitive to the minor variations in composition that would be expected in different batches.

Blanks were included in the cleaning process and the blank losses subtracted from the specimen losses when calculating the corrosion rates. Several batches of this steel were used to supply specimens for this project. Ten of the specimens were from a batch of composition C 0.18, Mn 0.76, Si 0.05, P 0.017, S 0.018, Mo 0.003, Sn 0.003, sol Al 0.011. Cr 0.125, Ni 0.295, Cu 0.235%. Other batches were very similar to this composition.

While it would be desirable to also conduct coupon measurements for copper, zinc and aluminium to represent the other metals found at Antarctic historic sites, this was not possible for various resource and logistics reasons previously discussed. Steel is the most prevalent metal at the sites, so steel corrosivity measurements are valuable in the interpretation of risks for major structural fasteners, and steel is most commonly used for broad scale corrosivity studies (eg King and Carberry 1992).

Preparation of coupon kits for deployment in Antarctica

Coupons were mailed to project participants as a kit containing the weighed, numbered coupon, an attachment assembly to enable installation on a weather station (figure 6.9) or

\[
\text{Corrosion rate} = \frac{\text{A} \times \rho \times t}{\text{A}}
\]

where A is the total area of the specimen exposed (mm²), namely the two faces plus four edges minus the area protected by mounting washers, \( \rho \) is the density of the steel (in kg/m³), and \( t \) is the exposure time in days (King, Sasnaitis and Terrill 1985).
6. Corrosion and other damage to metals

research facility (figure 6.10); disposable polyethylene gloves for handling the coupon during installation and retrieval to prevent contamination; instructions; and an engraved sign explaining the project and requirement that the coupon not be touched. Where possible a sachet of desiccant was provided for return with the exposed coupon to prevent post-exposure corrosion, in other cases it was requested that this be done.

Figure 6.8: Corrosivity coupons *in situ* at AWS LGB 10, Vostok and Signy
6. Corrosion and other damage to metals

Figure 6.9: South Pole corrosivity measured at the Clean Air Building
a. Clean Air Building, South Pole, US National Science Foundation photo
b. Coupon attached to frame on uppermost level of the building
c. Detail of corrosion coupon assembly, coupon is at lower left

The corrosivity measurements are tabulated with other environmental factors in Table 6.2.

Role of the author in carrying out the corrosion measurements.

The author was principally responsible for developing the overall rationale of the study of corrosion at Antarctic historic sites, identifying the exposure sites, some minor design modifications of the equipment, liaison with Antarctic personnel, discussion of the appropriateness of the methodology for Antarctic conditions and interpretation of the results for conservation of historic metals. George King, David O’Brien and Wayne Ganther of

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7 Downloaded from US National Science Foundation website, 25 April 2010
CSIRO carried out the preparation of the coupons from steel made by the Australian steel manufacturer BHP as well as processing of the coupons.

**Comparison of the coupon method and ‘wire on bolt’ methods**

‘Wire on bolt’ systems such as the ‘CLIMAT’ and ‘ATCORR’ are popular for measuring corrosivity providing a relatively quick method for measuring corrosion. Details of these systems and usage are available in Doyle and Wright (1982) but basically these use assemblies of wire (zinc for CLIMAT and aluminium for ATCORR) wound around a bolt held in a small frame of non-conducting plastic. Two different metals are chosen for the wire and the bolt so that galvanic corrosion will occur causing an accelerated weight loss from the wire (the anodic metal).

This method is appropriate for highly corrosive environments, for example to identify risks and treatment for threatening components in an industrial complex. Its shorter exposure period (usually 3 months) and lower weight loss mean it is less accurate than coupon methods for comparison between sites, particularly where corrosion rates are not expected to be particularly high but it is useful for Antarctic sites since it is very robust and the short exposure is useful for less accessible sites.

Figure 6.10: CLIMAT assembly on top of test racks at Cape Denison, author’s photo 1997
While CLIMAT tests offer some benefits, the coupon method was selected for comparative measurements of corrosion in Antarctica since:

- it is preferable to use only one method for comparing corrosivity at all sites; and
- corrosion rates in inland Antarctica were expected to be low so the more accurate coupon method is preferred.

In addition, the coupon method is arguably more consistent since corrosion effects on a flat plate are averaged over a larger surface. The weight of the ISO coupons is typically approximately 120 grams (with weight loss of up to 20 grams at a severe site) by comparison with CLIMAT wire of approximately 1.4 grams (with a correspondingly small weight loss). The longer exposure period of the ISO coupon method (one year) offers a more precise value for percentage weight loss and a potentially more accurate measurement as it takes account of the strong seasonal variability of temperatures known in Antarctica.

Discussions with George King, then at CSIRO identified some concerns about ambiguities arising in a long term survey of marine corrosion which involved extensive comparison between the CLIMAT and coupon methods, described in King and O’Brien (1994).

### 6.3.2 Measurement of surface wetness, temperature and relative humidity conditions to improve understanding of TOW criteria (research question 2)

Since the 1980s many instrumental methods and electronic sensors have been developed for the measurement of parameters involved in corrosion. Patel (1993) described the ‘Wetcorr’ instrument developed at the Norwegian Institute of Air Research which uses humidity in the atmosphere to generate a current which can be measured. The instrument’s sensors can be placed in the atmosphere, or on the surface, or inside small wall spaces where corrosion can be critical. The devices measure the time (in hours) for which a film of moisture sufficient to support corrosion exists on the surface of a small gold grid.

CSIRO developed small electronic instruments to measure corrosion as part of the research undertaken following the 1989 earthquake in Newcastle, Australia. These research instruments are relatively expensive which constrained the use of instrumental methods in
6. Corrosion and other damage to metals

this research although they would be useful for monitoring conditions in wall spaces and other critical locations in Antarctic historic buildings.

Terra Nova Bay experiment (research questions 1, 2, 4, 5 and 6)

Instrumentation requirements were identified jointly by King and Ganther and the site selection and logistics plans for this study were primarily by Hughes. The instruments were prepared by King and Ganther and the apparatus was installed by Italian Antarctic expeditioners (Grigioni and Pellegrini) who also provided climatic and topological information. Details of the methodology were published in King, Ganther, Hughes, Grigioni and Pellegrini (2001), bound into this thesis as Appendix I.

A range of sensors measured air temperature, surface temperature, RH, and surface wetness to correlate with a ZINCORR wire on bolt corrosivity measurement. The location selected was an Automatic Weather Station at Enigma Lake (74°43’S 164°02’E, altitude 210 metres and less than one km from the seas/sea ice) near the Italian base at Terra Nova Bay. The site was known from climatic data to have air temperatures consistently below 0°C.

The location was distant from potential anthropogenic pollutants (such as from diesel generators) that would have been a problem at other sites such as McMurdo Base or Scott Base. Salt deposition was thought to be minimal due to predominance of katabatic winds that blow from the polar plateau. Yearly mean and extreme values of temperatures (°C) are −15.1, −24.5 (min), -4.0(max). The air temperature exceeds −5°C only in January and relative humidity is about 40% in the cold season and 50% in the warm season. Additional details are given in Appendix I.

Plotting and correlation of surface wetness and temperature and relative humidity data

The method for correlating this data obtained from the instrumented plates exposed at Terra Nova Bay is described in detail in Appendix I. Briefly: this involved plotting ‘dots’ to indicate wetness occurrences vs temperature (y axis) and relative humidity (x axis). The plotted data included both air temperature and surface temperature of the instrumented metal plate to address research question 4 on whether solar warming of the surface will allow corrosion to occur even when air temperature is below 0°C.
Cape Denison instrumental experiment (research questions 2, 5, 7)

This experiment was devised in considerable haste when it became possible to send instruments to Cape Denison and permission was gained to mount these on the Workshop roof of the historic Main Hut which had been overclad with non-historic timber.

The purpose was to obtain corrosivity rates for this important historic site and to link this to simultaneous measurement of climatic data (air and surface temperature, relative humidity) and salt deposition for a coastal location with a ‘warmer’ Antarctic climate. The experiment is described and published in Hughes, King and Ganther (2001) bound as Appendix L to this thesis.

The equipment comprised:
- duplicate coupons of an unalloyed carbon steel and triplicate coupons of zinc (for mass-loss corrosivity measurement)
- a Zincorr unit
- a salt candle (ISO 9225); and
- one of the zinc coupons was instrumented to measure both surface temperature and TOW (using a gold grid sensor).

Figure 6.11: Gold grid sensor attached to coupon, CSIRO photo
6. Corrosion and other damage to metals

Figure 6.12: Apparatus used for the Cape Denison experiment, CSIRO photo.
(This was installed on the apex of the Workshop.)

Figure 6.13: TOW sensor, CSIRO photo

The apparatus was designed for ease of installation and to cope with extreme winds. The equipment faced geographic north and was located on top of the re-clad Workshop approximately 50 metres from the sea. Sensors and coupons were well-sealed and packed to prevent premature corrosion.
Hourly temperature and RH data were available from the monitoring system used for the AAE main hut. These data were used to calculate TOW using the ISO criteria and the TNB criteria.

**ZINCORR measurements, Cape Denison**

A ZINCORR unit comprising zinc wire wrapped around nylon, iron and copper bolts was used to measure the summer seasonal corrosion rate. Although wire-on-bolt corrosivity measurement systems are inherently less accurate they are less vulnerable to wind damage since the three bolts offer less resistance than the flat coupon. The combination of zinc wire and the iron or copper bolts provides a galvanic coupling which accelerates corrosion enabling corrosivity to be measured in a short time. ZINCORR provides greater sensitivity than ATCORR in mildly corrosive environments (Ganther, Cole & King 1999).

### 6.3.4 Effect of salts on corrosion (research question 7)

Methods for measurement of salt deposition (ISO 9225 ‘salt candle’ method) and salt data discussed in Chapter 5 are used to consider the acceleration of corrosion. ISO 9225 provides guidelines on corrosion rate expected in environments classified according to salt deposition rates.

### 6.3.5 Management of corrosion (research question 8)

As discussed in Chapter 3, a review of corrosion risks was prepared using Standard AS 4360, including assessment of effectiveness of conservation treatments and preventive methods.

### 6.4 RESULTS

#### 6.4.1 Site survey observation data
Table 6.1: Summary of corrosion observations at the sites

Note: deeply shaded rows indicate sites with katabatic wind regime. Cape Adare experiences periodic orographically forced katabatic winds with significant marine influence.

<table>
<thead>
<tr>
<th>Site, date of earliest building</th>
<th>Major topographic features</th>
<th>Closest distance from the sea (metres), salt deposition</th>
<th>Climate</th>
<th>Wind regime, annual average wind speed.</th>
<th>Types and severity of corrosion observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mawson Station, 1954</td>
<td>Situated on SE shore of Horseshoe Harbour, on a small ice-free rock outcrop (900 by 700m) adjacent to the continental ice cap, Framnes Mountains approximately 20 km to the south.</td>
<td>100-170 metres from shore of Horseshoe Harbour Some defibring in older buildings, salt crystals on rocks near harbour (fig 5.2). Iridescent rust inside buildings, especially aircraft hangar (fig 6.27).</td>
<td>Mean annual daily max - 8.4°C, Mean annual daily min -14.3°C Mean annual daily sunshine 5.0 hours (BOM website) Mean max Jan= +2.5°C.</td>
<td>Katabatic 11.1 m/s, dominant SE (measured 1964-1983 (Streten 1990))</td>
<td>Significant but variable atmospheric corrosion. Differential aeration. Meltwater pools around lower walls of many buildings Some galvanic corrosion in aircraft hangar. Pitting in aluminium building panels caused water ingress.</td>
</tr>
<tr>
<td>Rumdoodle Hut, 1972⁸</td>
<td>Elevation: 498m On mountain slope near Mt Rumdoodle</td>
<td>18 km from Mawson Station No evidence of salt deposits.</td>
<td>Data not available but colder than Mawson due to altitude.</td>
<td>Katabatic from polar plateau,</td>
<td>Condensation problems leading to spots of corrosion inside building. Streaks of rust on exterior cladding.</td>
</tr>
<tr>
<td>Davis Station, 1957 Except Old Paint Store, moved from Heard Is in 1964, fig 2.15.</td>
<td>On flat terrain, elevation 18 m, near saline lakes in the Vestfold Hills (whose altitude ranges to 158 metres) 100m ± 10m (at Old Paint Store. Salty taste in the water supply. Stepped halide crystals on windows of the Mess Hut.</td>
<td>50-200 m from shore (for older buildings) Mean max Jan +3.1 °C Max max Jul &amp; Aug -14 °C. Mean daily minima: ~ -1 °C Jan to ~ -21 °C in August. Mean annual daily sunshine 4.2 hours</td>
<td></td>
<td>Non-katabatic, mainly ESE, 4.6 m/s (BOM website)</td>
<td>Significant but variable atmospheric corrosion. Differential aeration Erosion corrosion of metal panels by windborne sand (fig 6.24). Iridescent rust on eroded steel panels of 1950s buildings (fig 6.24). Corrosion blisters from salts under painted steel of new buildings.</td>
</tr>
<tr>
<td>Platcha Hut, 1961</td>
<td>Situated at the head of a small fjord, surrounded by hills to ~150 m</td>
<td>&lt;20 metres from fjord connected to the sea.</td>
<td>Data not available but expected to be colder overall</td>
<td>Katabatic, from polar plateau, Windspeed data not found.</td>
<td>Significant but variable atmospheric corrosion.</td>
</tr>
<tr>
<td>Site, date of earliest building</td>
<td>Major topographic features</td>
<td>Closest distance from the sea (metres), salt deposition</td>
<td>Climate</td>
<td>Wind regime, annual average wind speed.</td>
<td>Types and severity of corrosion observed</td>
</tr>
<tr>
<td>-------------------------------</td>
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</tr>
<tr>
<td>Dumont d’Urville, 1951</td>
<td>Surrounded by polar plateau to the south but located on a group of small islands linked to the land by permanent ice.</td>
<td>100 ± 20m from sea, Prevalent defibring of wood.</td>
<td>Month mean max (Jan)= +0.8°C; Month mean (Aug) -16.8°C</td>
<td>Katabatic, SE Annual average windspeed 8.5 m/s (Wagenbach et al. 1998)</td>
<td>Significant but variable atmospheric corrosion. Iridescent rust on most steel surfaces. Differential aeration Corrosion fatigue due to bending in high winds (steel panels). Extensive meltwater. Emergent corrosion on painted steel panels.</td>
</tr>
<tr>
<td>Cape Denison, 1912</td>
<td>Surrounded by polar plateau to the south, located on very small harbour surrounded with slope of polar plateau rising to 700 feet (213 m) within 1.5 km of the hut (see fig 5.13).</td>
<td>40-50m (AAE main hut), Defibring. Salt in ice and snow measured ranging 15-3980 ppm chloride.</td>
<td>Max temp +8.1°C; Min -32.2°C, mean -14.8°C (external sensor data reported in Ganther et al 2002) AAE data: Mean Jan 1913= -0.94°C Mean Jun 1913 = -21.33°C</td>
<td>Severe katabatic Annual average windspeed 19.2 m/s (Madigan 1929) S to SE dominant.</td>
<td>Significant but variable atmospheric corrosion. Necking of nails (differential aeration). Corrosion fatigue of the ridge capping &amp; valley gutters (fig 6.3). Meltwater (fig 4.1) Bronze disease on plaque boxes (fig 2.19). Iridescent rust on bolts on crossbar of the Memorial Cross (figure 6.2).</td>
</tr>
<tr>
<td>Cape Adare, 1895</td>
<td>Low, gravelly triangular peninsula projecting approx 1,500m from the base of steep cliffs ~400m high; occasionally swept by waves, amidst large penguin rookery.</td>
<td>100m ±20m Extensive defibring on most exterior timbers. Salt spray was abundant over the entire area of the huts.</td>
<td>Extreme range during Feb 1899 to Jan 1900 was -41.94°C to +9.28 °C (Bernacchi 1901)</td>
<td>Katabatic with orographic forcing, Mean windspeed 12 kph= 3.3 m/s (Harrowfield 2006) ESE (41% of time)</td>
<td>Significant but variable atmospheric corrosion. Abundant meltwater. Erosion corrosion of metal bands on barrels by windborne scoria causing barrels to spring open (fig 4.1).</td>
</tr>
</tbody>
</table>
6. Corrosion and other damage to metals

<table>
<thead>
<tr>
<th>Site, date of earliest building</th>
<th>Major topographic features</th>
<th>Closest distance from the sea (metres), salt deposition</th>
<th>Climate</th>
<th>Wind regime, annual average wind speed.</th>
<th>Types and severity of corrosion observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cape Evans, 1911</td>
<td>Low area of beach affected by erosion. ~25km from Mr Erebus.</td>
<td>70-120m ±10m Extensive defibring (fig 5.3), salt 'runs' inside hut. Salt deposits were mostly sulphate (see Chapter 5).</td>
<td>No recent external data available but expected to be similar to McMurdo and Scott Base (~20 km south).</td>
<td>Non-katabatic, no recent external data available. Expected to be similar to McMurdo and Scott Base.</td>
<td>Significant but variable atmospheric corrosion. Erosion corrosion by windborne sand polishes Aurora anchor. Meltwater pools in many locations around the hut. Crinkled mirror backing (fig 6.31)</td>
</tr>
<tr>
<td>Cape Royds, 1907</td>
<td>Low area of bare rock and gravel with meltwater pools. ~20km from Mr Erebus. Adjacent to large penguin rookery and salt pan.</td>
<td>120m ± 10m Defibring, extensive salt deposits (fig 5.9, 5.12) &amp; inside hut (fig 5.5). Salt deposits were mostly sulphate.</td>
<td>Not available but expected to be similar to McMurdo and Scott Base (~20 km south).</td>
<td>Non-katabatic. See fig 7.7. comparing C Denison and C Royds.</td>
<td>Significant but variable atmospheric corrosion. Galvanic corrosion on motor car hub (fig 6.29), corrosion of plaque (fig 6.22) Extensive water stains indicate regular meltwater flows.</td>
</tr>
<tr>
<td>Hut Point, 1902</td>
<td>Rocky headland ~800m from McMurdo Base, ships dock nearby.</td>
<td>&lt;50m Defibring, salt 'runs' inside hut. Salt deposits were mostly sulphate.</td>
<td>As for McMurdo Base.</td>
<td>Non-katabatic. As for McMurdo Base.</td>
<td>Significant but variable atmospheric corrosion. Meltwater immersion of some artefacts.</td>
</tr>
<tr>
<td>Scott Base, 1957 Trans Antarctic Expedition Hut, Others 1970s-90s</td>
<td>Located on low headland surrounded by glaciers on southern end of Ross Island, more exposed to</td>
<td>~50m Salts evident on the ground and as crystals on windows.</td>
<td>Mean daily max (Jan)= -1.2°C, mean daily min (Aug) -34.4°C Mean annual temperature</td>
<td>Non-katabatic. Winds are predominantly NNE, mean monthly velocity range from 4 m/s (Jan) to 5.5 m/s</td>
<td>Significant but variable atmospheric corrosion. Spots of rust emerging on recently painted lime-green</td>
</tr>
</tbody>
</table>
6.4.2 Corrosivity measurements

Table 6.2: Corrosivity coupon measurements in coastal and inland Antarctica

<table>
<thead>
<tr>
<th>Site</th>
<th>Lat. °S</th>
<th>Elevation (m)</th>
<th>Km. from sea</th>
<th>Days exposed</th>
<th>Mass loss (mg)</th>
<th>Blank loss (mg)</th>
<th>Corrosivity µm/yr</th>
<th>Blank loss %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signy</td>
<td>60°43'</td>
<td>&lt;10</td>
<td>&lt;1</td>
<td>365</td>
<td>3.0863</td>
<td>0.0423</td>
<td>36.4</td>
<td>1.39</td>
</tr>
<tr>
<td>Rothera</td>
<td>67°34'</td>
<td>&lt;10</td>
<td>&lt;1</td>
<td>365</td>
<td>2.2808</td>
<td>0.0282</td>
<td>27.1</td>
<td>1.25</td>
</tr>
<tr>
<td>Mawson</td>
<td>67°36'</td>
<td>&lt;10</td>
<td>&lt;1</td>
<td>372</td>
<td>0.2956</td>
<td>0.0103</td>
<td>3.35</td>
<td>3.6*</td>
</tr>
<tr>
<td>Vanda</td>
<td>77° 35'</td>
<td>94</td>
<td>80</td>
<td>360</td>
<td>80.1</td>
<td>5.4</td>
<td>0.87</td>
<td>7</td>
</tr>
<tr>
<td>Robertskollen</td>
<td>71° 29'</td>
<td>400</td>
<td>120</td>
<td>377</td>
<td>65.0</td>
<td>5.1</td>
<td>0.70</td>
<td>9</td>
</tr>
<tr>
<td>LGB00</td>
<td>68° 39'</td>
<td>1830</td>
<td>186</td>
<td>786</td>
<td>35.8</td>
<td>4.2</td>
<td>0.18</td>
<td>13</td>
</tr>
<tr>
<td>LGB35</td>
<td>76° 03'</td>
<td>2340</td>
<td>780</td>
<td>380</td>
<td>15.3</td>
<td>4.2</td>
<td>0.13</td>
<td>38</td>
</tr>
<tr>
<td>LGB10</td>
<td>71° 17'</td>
<td>2616</td>
<td>390</td>
<td>777</td>
<td>22.5</td>
<td>4.2</td>
<td>0.10</td>
<td>23</td>
</tr>
<tr>
<td>Vostok</td>
<td>78° 28'</td>
<td>3488</td>
<td>1200</td>
<td>347</td>
<td>6.9*</td>
<td>2.9</td>
<td>0.05*</td>
<td>77*</td>
</tr>
<tr>
<td>South Pole</td>
<td>90° 00'</td>
<td>2800</td>
<td>1300</td>
<td>1364</td>
<td>12.3</td>
<td>2.9</td>
<td>0.03</td>
<td>31</td>
</tr>
</tbody>
</table>

* = mean of two specimens.

Note: The percentage blank loss = (Blank loss x 100)/ (Specimen mass loss - Blank loss)

6.4.3 Terra Nova Bay experiment data (following page)

Figure 6.14: Wetness on instrumented plate as a function of air temperature and RH
(from King et al 2001)

Note: Each dot or circle represents the presence of a film of moisture on the gold plate at a certain temperature and RH. The extent and thickness of the film (the degree of wetness) is reported by the size of the circle, discussed in detail in Appendix I. The 100% event at T=0°C and RH=45% at the upper left is an outlier event at the end of the recording period.
6. Corrosion and other damage to metals

Figure 6.15: Frequency histogram of temperature difference between air and steel surface (King et al. 2001)
6.4.5 Data from Cape Denison experiment during 27.12.2000 to 8.1.2001 (14 days)

Table 6.3: Cape Denison TOW calculations, chloride deposition and Zincorr measurement

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid TOW (%)</td>
<td>13.2 (of time)</td>
<td>Using gold grid sensor</td>
</tr>
<tr>
<td>ISO 9223 TOW (%)</td>
<td>2.0 (of time)</td>
<td>Using exterior location from environmental monitoring system in AAE main hut</td>
</tr>
<tr>
<td>King TOW (%)</td>
<td>31.8 (of time)</td>
<td>Using exterior location from environmental monitoring system in AAE main hut</td>
</tr>
<tr>
<td>Cl-deposition (ISO 9225 Salt candle)</td>
<td>5.5 (mg/m2/day)</td>
<td>Shorter exposure time than specified by ISO 9225</td>
</tr>
<tr>
<td>Zincorr (% mass loss)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nylon</td>
<td>0.12</td>
<td>Nylon 0.9 (normalised to 3 months)</td>
</tr>
<tr>
<td>Iron</td>
<td>0.42</td>
<td>Iron 3.23 (normalised to 3 months)</td>
</tr>
<tr>
<td>Copper</td>
<td>0.54</td>
<td>Copper 4.10 (normalised to 3 months)</td>
</tr>
</tbody>
</table>

Exposure time 14 days (instead of 30 days) was shorter than desirable due to logistics constraints.
Zincorr units can be exposed for any reasonable period but the mass loss was normalised to three months as this is the usual period used for these measurements.

The index in the table above gives a linear adjustment which does not take into account any time or seasonal dependence of corrosion. In general, the corrosion rate decreases with time of exposure. Further, the majority of the corrosion in Antarctica would be expected in summer when temperatures are higher. If it is assumed that the Antarctic summer lasts six months and that all corrosion occurred in this time the actual summer ZINCORR indexes would be twice that given above.

6.4.5 Risk management

Table 6.4: Risk matrix- corrosion (next page)
<table>
<thead>
<tr>
<th>Risk No.</th>
<th>The Risk What can happen and How it can happen</th>
<th>Consequence</th>
<th>Description and Adequacy of Existing Controls</th>
<th>Likelihood Rating (a)</th>
<th>Consequence Rating (b)</th>
<th>Overall Risk Level (a+b)</th>
<th>Risk Priority</th>
<th>Treatment controls</th>
<th>Risk rating after treatment/controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Metals exposed to outdoor conditions with intermittent seawater coverage and/or high salt exposure</td>
<td>Severe corrosion and delamination of most metals due to combined atmospheric and salt solution corrosion (eg Aurora anchor, Mawson aircraft hangar). Significant artefacts corrode right through (eg Webb’s lantern).</td>
<td>Impossible to control with existing technology. New treatments such as sacrificial anodes or impressed current may be possible for major artefacts. Removal of smaller artefacts offsite or indoors.</td>
<td>5</td>
<td>4 (major items) 3 (minor items)</td>
<td>9 8</td>
<td>High</td>
<td>Re-location of artefacts</td>
<td>As for indoor conditions - see Risk 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cathodic protection of selected, high-significance items</td>
<td>Not assessed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Use of protective coatings</td>
<td>None suitable where corrosivity &gt; 40 µm/yr</td>
</tr>
<tr>
<td>2</td>
<td>Metals periodically covered by meltwater zone (eg around AAE Main Hut).</td>
<td>Most metals severely damaged due to combination of high atmospheric corrosion plus other forms of corrosion eg pitting, erosion. Artefacts affected: oven, tin cans at C Denison</td>
<td>Impossible to control with existing technology. Drainage of water is unlikely to be practical in most locations. New treatments may need to be developed. Removal of smaller artefacts offsite or indoors.</td>
<td>5</td>
<td>4-3</td>
<td>9-8</td>
<td>High</td>
<td>Relocation</td>
<td>As for indoor conditions - see Risk 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Re-burial</td>
<td>As for Risk 5</td>
</tr>
<tr>
<td>3</td>
<td>Nails and other fasteners exposed to atmospheric corrosion and periodic high moisture</td>
<td>Structural failure (eg corrosion of bolt securing Memorial Cross leading to crossbar being damaged or lost). Corrosivity rate for most sites is equivalent to that occurring in outer urban temperate Australia.</td>
<td>Fasteners that are embedded in timber cannot be effectively treated with current technology. Structural damage to fasteners leading to loss of cladding from wind (Cape Denison).</td>
<td>4 5 (longterm untreated risk)</td>
<td>5 (failure) or 4</td>
<td>9</td>
<td>High</td>
<td>Replacement of nails not always feasible Over-cladding</td>
<td>Not assessed. Over-cladding may reduce risk depending on RH/moisture control.</td>
</tr>
</tbody>
</table>
6. Corrosion and other damage to metals

|   | Structural fasteners and artefacts inside buildings exposed to indoor air conditions (presuming low temperatures, high RH, some periodic meltwater) | Significant corrosion can occur due to high RH, rate is not measured indoors but appears to be moderate (Ross Island) to high (Mawson aircraft hangar). Significant risks from salts at Ross Island sites. | Few effective treatments are available for most items (eg tin cans). Some coatings may be adequate for items of durable metal or with thick cross-section (eg cast iron stoves treated with tannic acid). Control is not adequate in high corrosivity locations (eg Mawson air hangar). Climate change may increase risks. | 4-5 | 2-4 | 6-9 | high | Coatings | VPIs for enclosed spaces | Preventive measures | Not assessed | Effectiveness has not been assessed. |
|---|---|---|---|---|---|---|---|---|---|---|---|
|   | Structural fasteners and artefacts indoors and covered by ice | Corrosivity appears to be low where ice coverage persists for long periods. | Control of corrosion is fundamentally dependent on preserving ice coverage. Climate change may increase risks. | 2 | 2 | 4 | low | - | - | - |
|   | Artefacts taken off site for treatment and returned to the site | Bickersteth Clayton and Tennant (2008) state treatments have been successful | Artefacts returned to high RH and high salts may re-corrode. No long term studies linked to environmental monitoring are available to quantify risks. | 3-4 | 2-3 | 5-7 | medium | Monitoring of environmental conditions | Preventive strategies | Provides information on likely remaining risks | Not assessed |

**Likelihood Rating:** 1 rare, 2 unlikely, 3 possible, 4 likely, 5 almost certain

**Consequence Rating:** 1 insignificant, 2 minor, 3 moderate, 4 major, 5 catastrophic

**Level of Risk:** <5 low risk – manage by routine procedures, 5 medium risk – specify management responsibility, 6,7 high risk – needs senior management attention, >7 extreme risk – detailed action plan required
6. Corrosion and other damage to metals

6.5 DISCUSSION

6.5.1 Research question 1: corrosion occurrence below 0°C

Evidence from field observations

The field observations for each of the 12 sites (Table 6.1) found corrosion occurred at all the sites examined with significant effects at Cape Adare, all Ross Island sites, Mawson and locally severe effects at Davis.

Photographs by Sarah Hillary (a New Zealand conservator who visited several sites in the Antarctic Peninsula, figure 6.16, see also figure 2.25) and in publications concerning Wilkes (eg Clark and Wishart 1993, figure 6.17) also indicate significant corrosion affecting buildings and artefacts (including those indoors) at sites the author was not able to visit.

Figure 6.16: Corrosion at Port Lockroy, photos by Sarah Hillary 2001
(Note water stains down walls)
A broad range of corrosion types was found at most sites representing the main classes of corrosion:

- atmospheric corrosion, affecting all metals exposed outdoors and most indoors;
- corrosion in solutions of freshwater and seawater;
- galvanic corrosion;
- pitting;
- crevice corrosion;
- differential aeration corrosion;
- erosion corrosion;
- stress-cracking corrosion; and
- filiform corrosion.

Artefacts that are covered by frozen meltwater or buried in snow drifts for most of the year and only periodically exposed during summer were also corroded. Exposure for only a few weeks per year appears sufficient to produce significant corrosion.

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9 Examples are artefacts in the meltzone surrounding the Main Hut at Cape Denison
6. Corrosion and other damage to metals

Observations at Cape Denison

Many corrosion types were found at Cape Denison including ‘necking’\(^{10}\) of the nails securing the roof timbers. Most of the nails are raised above the surface, due to a combination of corrosion of the timber and strong winds that lift the boards. Necking is a form of differential aeration due to depletion of oxygen which promotes corrosion cell formation at the junction of the metal and wood and risks breakage of the nail.

Streaks of rust extend up to 20cm below rusty nails in the roof and walls. Damage to timber is evident around the nails from rust, which increases risks of boards blowing off.\(^{11}\)

Figure 6.18: Rust stains on timber of the AAE main hut, photo by Rupert Summerson 1995

The tearing of the lead sheeting on the Workshop roof is a remarkable indicator of the strength of the wind\(^{12}\). The lead failed as a method of preventing ice ingress since the vibration against raised nail heads perforated the lead.

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\(^{10}\) Narrowing of diameter of the nail below the head.  
\(^{11}\) Baker (undated) describes chemical interactions between corroding nails and degrading wood cellulose, including galvanic corrosion where metals of different types are used in close proximity in wood.  
\(^{12}\) See also further discussion and time-series images in Chapter 7.
There are conflicting corrosion observations by AAE and BANZARE participants. Fletcher (1984: 264-267) who visited the site during BANZARE stated:
"The shore party returned to the shop with cases of tinned food stuff that had been left in the open for 17 years. An 18-litre tin of petrol, without the slightest sign of rust, was later used to run the motor boat".

This is at odds with other observations by Mawson (1915) who mentions extensive corrosion affecting rubbish removed to clean up the site. This suggests that the petrol tin may have been excavated from ice, possibly accounting for its good condition. Unlike Mawson, Fletcher does not mention meltwater inside the hut.

‘Bronze disease’ severely affected (non-historic) copper alloy covers on two AAE plaques (figure 2.19), exposed during 1977 to 1985. Bronze was selected for its durability, but the risk of staining the enclosed timber artefacts was not adequately considered.

*Observations at Ross Dependency sites*

Significant corrosion of outdoor artefacts was observed at Cape Adare including artefacts indoors such as a stove which was streaked with red, active corrosion. Outdoor artefacts were

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13 Mawson also states "Cans rusted somewhat" (Jacka and Jacka 1988: 65).
14 This presumes the involvement of chloride ions due to proximity to the sea. Bronze disease is a serious corrosion problem that affects copper alloys from exposure to chlorides and moisture to form copper chlorides which can dissociate so the chlorides can form new corrosion cells in a cyclic process. The copper chlorides form blisters on the metal surface which leave a pitted surface.
covered in iridescent blisters. Barrel hoops had completely corroded through so the staves splayed outwards, appearing like flowers (figure 6.20), further damaged by corrosion.

At the Ross Island sites a large number of tin cans are affected by varying degrees of corrosion with those outdoor generally being the most badly affected (figure 6.20). Much conservation effort is expended on brushing/vacuuming tin cans displayed inside indoors although removal of significant deposits of salts on the ceiling, walls and other surfaces does not appear to occur\(^\text{15}\).

Figure 6.20: Corroded artefacts at Ross Dependency sites

Upper- tin cans outdoors at Cape Royds, author’s photo 1993
Lower- barrels at Cape Adare, author’s photo 1993

\(^{15}\) There is no mention in the conservation procedures for the huts.
Mason (1999: 28) noted the formation of condensation underneath artefacts resting on the floor due to moisture from under the floor and noted these artefacts may act as a ‘cooling fin’, increasing condensation.

In a number of locations original fasteners (presumably nails) have been replaced with cross-headed screws (figure 6.21), presumably to replace corroded original nails. Rust damages timber through a well-known reaction with cellulose, enlarging the diameter of the original nail hole, so a screw may be a more appropriate structural solution although it is aesthetically undesirable.

Water running off a bronze interpretation plaque on the wall of the Cape Royds hut (figure 6.22) has stained the timber below and appears to locally increase corrosion of the nails below, probably via galvanic corrosion. Bronze was probably selected for its corrosion resistance (and aesthetically appearance), but it is preferable not to attach it directly to the building and locate it separately on the main approaches to the building, as was done at Cape Denison (figure 6.23).

Figure 6.21: Cross-headed fastener used on Terra Nova hut, author’s photo 1993

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16 The plaque has now been removed, David Harrowfield, personal communication, Canberra 2009.
Filiform corrosion\textsuperscript{17} affects enameled plates at Cape Evans (Hughes 1986, Mason 1991: 26) and was also observed by the author on a (painted) tea box sent to Australia soon after the BAE expedition, now in the collection of the Power House Museum, Sydney.

\textsuperscript{17}This type of corrosion typically affects painted or enameled metals including aluminium alloys as well as ferrous metals. The cause is differential aeration and hydrolysis of metal ions resulting in increasing acidity in the region of dissolution via penetration of the coating by moisture and oxygen.
Notable observations at modern sites

Building design factors can be very important in producing corrosion problems. Thin walled structures, such as the steel wall-cladding at Davis (figure 6.24), are vulnerable to both corrosion (upper area of the panel) and corrasion (lower area). Corrasion removes the corrosion products and increases the rate of metal loss. Once the metal cladding is pierced moisture cannot easily drain or evaporate from inside the wall space, increasing corrosion of interior metal surfaces.

Figure 6.24: Corrosion and corrasion affects wall cladding in 1950s buildings at Davis Station, author’s photo 1993.

Numerous emergent spots of rust affect contemporary painted steel buildings at Davis (Mess building) and at Scott Base (figure 6.25). Durability testing (exposure tests) had been conducted at Davis to select suitable paints (Incoll 1991) but it was not possible to determine whether the same paints had been used or what surface preparation had been employed. Given the widespread expectation of low corrosion (discussed in Appendix F) the testing may have focussed on polymer durability rather than corrosion protection through use of galvanising or other corrosion protection suitable for marine environments.
6. Corrosion and other damage to metals

Figure 6.25: Rust spots on contemporary building at Scott Base, author’s photo 1993

Inferences from the observations

Corrosion appears to be associated with proximity to meltwater but it was not considered statistically valid to compare the prevalence and severity of corrosion versus environmental factors at each site since the data would be confounded by the differing numbers of metal artefacts. Later sites tend to have more metal artefacts, for example Wilkes has large numbers of fuel drums.

Even though early Antarctic historic buildings are predominantly made of timber, corrosion is a significant concern since their structural integrity is dependent on metal nails and fittings. Seemingly obvious treatments such as replacement with new nails are rarely appropriate since most nails are rusted in place, so dismantling risks further damage.

Based on the author’s field observations, metal artefacts and building elements that present the greatest conservation challenges at the sites are:

- Artefacts exposed outdoors in severe conditions where periodic immersion with seawater occurs (eg Aurora anchors at Cape Evans, figure 6.26)
- Artefacts exposed outdoors in severe conditions where relocations indoors is not feasible/desirable due to the importance of being in its historic context (eg items in melt zone at Cape Denison, aircraft hangar at Mawson, figure 5.2, 6.27)
6. Corrosion and other damage to metals

- Tin cans at the Ross Island sites (figure 6.28), due to their quantity and the extensive labour required using current conservation treatments;
- Nails, screws and components that are embedded in timber as part of composite artefacts (eg wheel, figure 6.29) or which are essential for the structural integrity of the buildings. These items are at high risk due to high RH exposure and the lack of effective in situ treatments.

Figure 6.26: Aurora anchor, Cape Evans, author’s photo 1993

Figure 6.27: Metal items inside Mawson aircraft hangar, author’s photo 1992 (note the corrosion affects both painted steel and galvanised cables)
Figure 6.28: Tin cans outdoors at Cape Royds, author’s photo 1993

Figure 6.29: Motor wheel, Cape Royds, author’s photo 1993
All the 12 sites observed experience less than six weeks (approx 1,000 hours) when air temperatures exceed 0°C and even shorter periods when the ISO TOW criteria states corrosion can occur (ie T> 0°C simultaneously with RH> 80%).

This could imply:

i. corrosion occurs during very short periods when ISO criteria for corrosion are met; or

ii. that salts play an exceptional role in corrosion in polar conditions; or

iii. ISO criteria underestimate conditions where corrosion can occur; or

iv. corrosion is occurring under ice layers as proposed by Rosales.

Field observations alone are insufficient to determine which of the scenario is correct, emphasising the need for measurement of corrosion rates and quantification of conditions in which corrosion can occur.

Evidence of corrosion below 0°C from corrosion measurements

Low corrosivity rates measured in inland Antarctica

An obvious conclusion drawn from Table 6.2 is that corrosion rates in inland Antarctica are exceptionally low, as expected from the severe low temperatures and distance from the sea. According to ISO 9223 corrosivity for all these inland sites should be zero, since temperature is never above 0°C, but there is a clear relationship between measured corrosivity and climate, distance from the sea and altitude indicating corrosion rates are not an artefact and they are clearly not zero, so cold alone does not stop corrosion. Potential sources of error relating to blank measurements and precautions taken to prevent corrosion before and after exposure are addressed in Appendix D.

Unexpectedly high corrosivity at coastal Antarctic sites

Table 6.5 collates corrosivity, TOW and salt data where available from all known Antarctic corrosion research. As expected, corrosivity rates are generally highest in the warmer, more humid conditions (and hence high TOW hours) in the Antarctic Peninsula and lower at
Mawson and locations with lower temperatures and katabatic winds. It is not possible to plot corrosivity versus TOW from this table since different test metals were used.

**Table 6.5: Corrosivity measurements cited in the literature**

<table>
<thead>
<tr>
<th>Author &amp; date</th>
<th>Measurement location</th>
<th>Metals tested.</th>
<th>1-year Corrosivity (µm/year)</th>
<th>TOW, salt deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>King et al (1988)</td>
<td>Cape Evans (coastal) and Lake Vanda (Dry Valleys)</td>
<td>BISRA low alloy copper steel</td>
<td>10.87 0.87</td>
<td>Not recorded.</td>
</tr>
<tr>
<td>Fahy (1990)</td>
<td>Arrival Heights near Scott Base</td>
<td>Aluminium BS 1476 HE 9</td>
<td>Weight change given in gms for varying anodised thickness.</td>
<td>Not recorded.</td>
</tr>
<tr>
<td>Mikhailov et al (1993)</td>
<td>Mirny (66°33'S)</td>
<td>Steel (St3), Cu, Cd, Al (D-16)</td>
<td>7.7 (steel); 3.1 Cu; 0.3 Cd; 1.3 Al.</td>
<td>ISO TOW= 93 hrs/yr.</td>
</tr>
<tr>
<td>Rivero et al (1996)</td>
<td>Artigas (62° 10'S)</td>
<td>Low alloy steel</td>
<td>66 (1 year exposure) 40 (2nd year) 40 (3rd year)</td>
<td>ISO TOW = 8919 hrs/yr (total for 3 years). Negligible SO$_2$, Cl$^-$ deposition 180.1 mg m$^{-2}$ day$^{-1}$.</td>
</tr>
<tr>
<td>Rosales &amp; Fernandez (2001)</td>
<td>Jubany</td>
<td>Steel (St 3) zinc, copper, aluminium (D16).</td>
<td>36-41 (steel) 1.22-2.48 (Zn) 1.97-2.10 (Cu) 1.07-1.50 (Al)</td>
<td>ISO TOW =2453 hrs/yr (one year); SO$_2$ negligible, Cl$^-$6-30 mg m$^{-2}$ day$^{-1}$.</td>
</tr>
<tr>
<td>Hughes, King and O’Brien (1996)</td>
<td>Signy</td>
<td>BISRA low alloy copper steel.</td>
<td>36.4</td>
<td>ISO TOW not estimated</td>
</tr>
<tr>
<td>Hughes, King and O’Brien (1996)</td>
<td>Rothera</td>
<td>BISRA low alloy copper steel.</td>
<td>27.1</td>
<td>ISO TOW not estimated</td>
</tr>
<tr>
<td>Hughes, King and O’Brien (1996)</td>
<td>Mawson</td>
<td>BISRA low alloy copper steel.</td>
<td>3.35</td>
<td>ISO TOW not estimated</td>
</tr>
<tr>
<td>Hughes King and Ganther (2001)</td>
<td>Davis</td>
<td>BISRA low alloy copper steel.</td>
<td>8.7</td>
<td>ISO TOW not estimated</td>
</tr>
<tr>
<td>Hughes, King and Ganther (2002) and Ganther et al (2002)</td>
<td>Cape Denison</td>
<td>BISRA low alloy copper steel.</td>
<td>12.2 (average of 3 coupon measurements)</td>
<td>ISO TOW = 175 hrs/yr ‘King’s’ TOW = 2,628 hrs/yr $^{18}$</td>
</tr>
<tr>
<td>King et al (2001)</td>
<td>Terra Nova Bay (Enigma Lake) 74° 43’S</td>
<td>Unalloyed steel, Copper bearing steel, zinc.</td>
<td>9.3 (unalloyed steel) 8.1 (copper-bearing steel, 3.2 (Zn). (note: these are one-year rates calculated from a shorter exposure period of 34 days)</td>
<td>ISO TOW = 0 hrs/yr TOW measured by sensor = 28.4 hrs/yr ‘King’s’ TOW = 29.9 hrs/yr</td>
</tr>
</tbody>
</table>

$^{18}$ During the AAE, Cape Denison temperatures were only above freezing for 29 days during February to December 1912 and 32 days during 1 January to December 14 in 1913 (Madigan 1929: Table VIII), thus the
Comparisons of Antarctic, Arctic and temperate corrosivity

TOW in Arctic Scandinavia, Russia and Canada are typically 1000-4000 hours (see literature survey in this chapter) with corrosivity typically between 0.43 and 32 µm/yr. TOW at Antarctic Peninsula sites were also high: Rivero et al measured ISO TOW totalling 8919 hours during three years at Artigas, which averages 2973 in one year. Rosales and Fernandez (1996) measured 2500 hours/year at Jubany. Coastal sites elsewhere in Antarctica were significantly lower (eg 93 hours at Mirny).

Again it is unfortunately not possible to compare corrosivity against TOW due to different metals and methodologies and the incomplete salt deposition data. However, corrosivity measured at Cape Evans (King et al 1988) is equivalent to corrosivity in outer urban Melbourne, Australia, which has a temperate climate (King et al 1982) where TOW is close to 50% or 4,380 hours.

Corrosivity for coastal locations according to climatic type

Annex B of ISO 9223 tabulates climate zones with calculated ISO TOW. For ‘extremely cold’ climates, with temperatures ranging between -65° to +32°C, calculated TOW using criteria T>0°C and RH>80% are 0-100 hours/year. For ‘cold’ climates, with temperatures ranging between -50° to +32°C, ISO TOW varies from 150-2,500 hours/year.

At Cape Evans the ISO TOW is zero yet corrosivity is 10.87 µm/year, whereas Mirny has ISO TOW of 93 hours/year but lower corrosivity, 7µm/year. Corrosivity measured at Cape Evans is also higher than Mawson (3.35µm/y), although Mawson temperatures are much colder.

ISO TOW calculated from temperature and RH monitoring data measured at Cape Denison in 1999 (Ganther et al 2002: 3, Table 1) was 2% of the year (or ~175 hours). This is inconsistent with measured corrosion rate (12.2 µm/yr).

maximum possible ISO TOW is 32 x 24 = 768 hours, and probably much less since exterior RH is frequently below 80%.

Comparison is possible in this case since the same method and coupon composition were used.
This implies temperature is not the dominant rate-determining factor for corrosion in Antarctica so other temperature and RH criteria, and salt deposition, may have significant effects.

**Corrosion within sites and inside buildings**

The field observations found very significant corrosion damage at locations that are:
- very close to the shore;
- exposed to offshore winds; or
- subjected to periodic meltwater or saltwater inundation.

For example, the aircraft hangar at Mawson is within 30 metres of Horseshoe Harbour and has severe delamination of structural components and extensive visible salt deposits on the ground (figure 5.9) and inside the building. Artefacts in the meltzone at Cape Denison are often completed corroded through (figure 6.1).

It would be desirable to measure corrosivity inside buildings to quantify corrosion risks affecting artefacts on display. Careful selection of locations for measurements is necessary to avoid unrepresentative microclimates, loss and interference. Corrosivity inside a building is commonly estimated to be approximately 1/80 of the exterior corrosivity at temperate sites (George King, personal communication). This ratio may be different at sites where katabatic winds cause greater salt penetration. Mason (1999) reported indoor chloride deposition at Cape Evans was one third of the external deposition rate, discussed in Chapter 5.5.3. High RH occurring inside many of the buildings increases corrosion risks, as does water ingress at Cape Denison.

**Effects of duration of coupon exposure**

In temperate climates the corrosion rate of steel generally slows down with time as the corrosion products that are formed provide protection to the steel substrate. Exposures of copper-steel coupons at Cape Evans (King, Dougherty, Dalzell and Dawson 1988) showed a reduction in the corrosion rate from 10.83 µm/year in one year of exposure to 4.42 µm/year over nearly three years. Rosales and Fernandez (2001) and Rivero et al (2001) measured decreases in corrosivity in multi-year exposures at Antarctic Peninsula sites (Table 6.4).
Effects of multi-year exposures and comparisons with single-year exposures are discussed in detail in Hughes, King and O’Brien (1996) giving comparisons with large corrosivity surveys throughout Australia and New Zealand.

Multi-year exposures at a larger range of locations in Antarctica with different climatic characteristics are needed before sufficient data exists to make conclusions about the protective abilities of the thin layer of corrosion product on the surface of steel. This has some practical significance for long term conservation management since it would help to measure long term corrosion rates and in turn help to estimate effective lifespans of historic metal items (eg nails, ridgecapping, hinges, etc) that cannot effectively be treated on site in Antarctica and where progressive replacement is going to be necessary at some stage.

Data limitations and accuracy

A major limitation in corrosion research is that the meteorological data available from weather stations in Antarctica are not in a form that makes it easily possible to calculate ISO TOW. Meteorological data are mainly synoptic observations at 9am and 3pm of wet and dry bulb temperatures (from which relative humidity is calculated) and air pressure measurements. These are used by meteorologists because they provide more accurate longterm climatic data than the electronic sensors used to record continuous temperature and RH in Automatic Weather Stations, which have accuracy limits of about ±3% that are insufficiently accurate for climatology.

Blanks were included in the coupon cleaning process to take account of uncorroded steel that may be dissolved as the corrosion products are removed. The blanks are included with the corrosion specimens from the beginning of the cleaning process and since uncorroded steel would not be attacked until most of the rust is removed the blank loss figures over-estimate the true situation. For specimens from coastal sites the blank losses are very small compared to the specimen mass losses, but for some of the inland sites they are most significant.

6.5.2 Effect of temperature and RH on surface wetness (Research Question 2)

Factors other than air temperature may influence the actual ‘time of wetness’ of metal surfaces in Antarctica, allowing corrosion to occur at lower temperatures. The long hours of
sunlight in the Antarctic summer can cause the surface of dark objects, such as corroded metal, to reach considerably higher temperatures than surrounding air temperature. There is considerably less cloud cover in Antarctica than in the Arctic, which is frequently affected by ‘Arctic haze’.

Thus solar gain in Antarctica is more effective and may raise surface temperatures sufficiently for corrosion to occur, but conversely warming could also reduce RH next to surface (King, GA, Duncan & Ballance 1998) to below the level at which corrosion can occur. To resolve this ambiguity the Terra Nova Bay (TNB) experiment was devised to measure temperature and RH conditions at which surface wetness occurred in Antarctic field conditions.

The TNB experiment found ISO TOW was zero but Figure 6 in King et al (bound as Appendix I of this thesis) shows that surface wetness occurred when RH was above 50%. Figure 8 (ibid) shows that wetness occurs at temperatures as low as -10°C combined with RH down to 50%.

Applying these criteria (called ‘King’s TOW criteria’) to the 1999 Cape Denison temperature and RH monitoring data, TOW was calculated to be 30% (2,628 hours), rather than 175 hours, which is sufficient for significant corrosion to occur.

The experiment conducted at Cape Denison (see Appendix L), a warmer coastal site, found that King’s TOW (31.8% of the 14 day exposure time) over-estimated the gold grid measurement of TOW (13.2%) but was much greater than ISO TOW (2%). This indicates further investigation is required\textsuperscript{20}. The presence of salts would increase the period for which liquid is present via depression of freezing point, discussed in 6.5.8, but the gold grid sensor should account for this so it is unlikely to be the source of the discrepancy.

\textit{Effect of timing of initial exposure}

Due to the complexities of Antarctic logistics it was not possible to arrange for all exposures at different sites in Antarctica to start at the same date. It is also possible that the season when

\textsuperscript{20} As discussed in Appendix I, “wetness events have almost completely occurred within air temperatures of zero to -10°C and RH of about 48 to 83%”.\textsuperscript{20}
the exposure commences may affect corrosivity since corrosion is less likely in winter but may occur in summer. Once exposure occurs, corrosion products begin to form on the surface and may tend to protect the underlying metal.

The thickness of the corrosion product will depend on the length of exposure as well as other complex factors such as salt exposure. In addition, windborne particles could strip off protective corrosion layers, as occurs at Davis (figure 6.24), which would increase corrosivity rates.

For logistical reasons most exposures inevitably commence in summer but there could be differences between exposures commencing early or late in the season, particularly since day length varies considerably in polar regions. To overcome potential variations from different starting dates any future coupon exposures should commence on midsummer’s day.

**ZINCORR measurements**

These measurements (Table 6.3) were commenced in the Antarctic summer and provide an indication of corrosion rate just for the warmer part of the year. Comparison with standard ZINCORR indexes for Australian climates shows that “summer” nylon indices for Cape Denison falls in the lower range of typical Australian sites, the iron and copper index as low pollution in mild season classification (Ganter, Cole & King 1999). Thus it can be concluded that the measured corrosion indexes indicate that corrosion measured outside Mawson’s hut is comparable to measurements in temperate Australian environments.  

**6.5.3 Formation of corrosion products under ice layers (Research Question 3)**

Rosales and Fernandez (2001) propose another mechanism by which corrosion could occur at temperatures below 0°C: via liquid layers that form underneath ice due to the presence of salts. This raises potential questions for conservators about the extent to which metals covered by ice are protected against corrosion. While this is seemingly at odds with Harrowfield’s observations of photographs of artefacts freshly excavated from ice at Scott’s

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21 Most of southern Australia experiences summer maxima that are rarely above 40°C and winter minima rarely below -5°C.
hut in the early 1960s which showed they were not corroded\textsuperscript{22} this may be due to the apparent rapid ingress of ice which occurred before salts had penetrated inside the building.

Rosales and Fernandez (2001: 5) state that “non nulle current densities were measured during anodic and cathodic polarisation of metals at temperatures down to -6°C to -8°C”. Also, that “liquid monolayers that could exist under the ice deposits would have a much higher salt concentration than those corresponding to rain” and they would produce practically 100% TOW for long periods due to the covering effect of the ice layer. Ice cover would reduce oxygen diffusion into the anodic sites of the corrosion cell. Essentially, the criteria for corrosion to occur based on measurements at Jubany are temperature above -8°C and RH above 80% (ie ‘Jubany’ criteria are $T > -8°C$ plus $RH > 80\%$).

While the ‘Jubany’ TOW criteria differ from ISO TOW only regarding temperature\textsuperscript{23} and were derived using a different method and in a warmer, cloudier saline climate so the differences between King’s criteria and the Jubany criteria may relate to these differences in environmental conditions. For example, Jubany has a cloudy climate so solar gain may not be as significant as at TNB. Jubany experiences high salt deposition and long periods of high RH so a moisture film is more likely to form than at TNB.

The difficulties of field measurement indicated that it may be preferable to resolve which criteria best apply in Antarctic conditions using a climate controlled chamber with salt spray/fog facilities to measure temperature, RH and salt deposition and compare with gold grid TOW measurements and coupon corrosivity. Visual observation of ice formation could be undertaken in real time and be recorded photographically and to further investigate the presence of salts under ice. This data would be helpful in revising ISO 9223 to produce more accurate corrosion criteria (and hence estimate corrosion risks) for cold climates.

\textsuperscript{22} Dr Harrowfield (comments to author on draft thesis, 2009) compared photographs of biscuit tins after excavation from ice (early 1960s, exhibiting minimal corrosion) and some years later at Canterbury Museum after they had been exposed inside the hut and were significantly corroded. Similar observations of artefacts excavated from ice in the Cape Adare stores hut revealed freshly excavated metals were unaffected by corrosion.

\textsuperscript{23} Both ISO and ‘Jubany’ require RH>80\%, but ISO requires $T > 0$, whereas Jubany temperature criterion is $T > -8°C$. 


6.5.4 Effects of air temperature and surface temperature on corrosivity (Research Question 4)

Figure 9 in Appendix I shows wetness as a function of surface temperature ($T_s$) and air RH during the TNB experiment. This shows that the majority of wetness events occur when surface temperatures are between -12°C and +3°C. Surface temperatures were found to be on average 1.4°C higher than the air temperature ($T_a$). $T_s$ exceeds 0°C for only 6.3% of the exposure time. The difference between $T_a$ and $T_s$ was divided into classes and shown as a histogram in Figure 7 of Appendix I. This shows that for a majority of the exposure time there is heating of the plate by solar gain of up to 5°C and short periods of up to 23°C solar gain.

Higher surface temperatures could theoretically allow corrosion to occur, although the actual wetness occurrences indicate that temperatures above 0°C are not necessary for corrosion to occur.

The ‘non-zero’ corrosivity measured at inland Antarctic sites (Hughes, King and O’Brien 1996) could also possibly occur during short periods when surface temperatures exceed -10°C due to solar warming, which could even occur at Vostok where monthly (air) maxima in January are between -25 and -30°C, [http://www.aari.aq/data/data.asp?lang=0&station=6#tmax.txt](http://www.aari.aq/data/data.asp?lang=0&station=6#tmax.txt).

6.5.5 Can temperature and RH data and TOW measurement be used to predict corrosion risks for a site? (research question 5)

The TNB experiment and the Cape Denison experiment demonstrate that ISO TOW provides a poor estimation of the conditions in which a film of moisture is present on a gold grid sensor, which simulates a typical metal surface. ISO TOW criteria therefore significantly underestimate corrosion risks in Antarctica. Current practice for the design and maintenance of contemporary station infrastructure is based on the use of standards such as ISO 9223 with its false presumption of low risk, whereas risks are similar to moderate conditions in temperate climates such as Melbourne. All the evidence suggests ISO 9223 requires revision and that infrastructure management practices should be updated to address the higher risks because of the potentially serious consequences.
The TOW measured by the gold grid sensor at Terra Nova Bay (28.4 hrs/year) is close to the TOW estimated from TNB wetness criteria (29.9 hrs/year). However, corrosivity measured by the steel coupon at TNB (9.3 µm/year) appears inconsistent with the Cape Denison measurements where the TOW calculated using TNB criteria is nearly 100 times higher (2,628 hrs/yr), but the steel coupon corrosivity measured at Cape Denison is only slightly higher (12.2 µm/year)). The short duration of both exposures will overestimate the annual corrosivity rate.

While there is still ambiguity about use of temperature and RH data to correlate with coupon measurements of corrosivity, gold grid sensors may be useful to estimate relative corrosion risks within a building, particularly for inaccessible locations where critical structural elements may be at risk.

Three alternatives have been proposed to ISO TOW criteria for cold climate corrosion, each based on a different methodology, developed by three independent research teams (Table 6.6).

**Table 6.6: Temperature and RH criteria for corrosion devised by various researchers**

<table>
<thead>
<tr>
<th>Proponents</th>
<th>Test location</th>
<th>TOW T &amp; RH criteria</th>
<th>Site characteristics</th>
<th>Measurement method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rosales and Fernandez (2001)</td>
<td>Jubany, Antarctic Peninsula</td>
<td>T&gt;-8°C, RH&gt; 80%</td>
<td>Annual mean temp -2.0°C, consistently high RH (mean RH= 83.8%); high salt deposition, low pollutant</td>
<td>Electrochemical method to measure current flow using 0.1M Na₂SO₄ soln with controlled temperatures</td>
</tr>
<tr>
<td>King <em>et al</em> (2001)</td>
<td>Terra Nova Bay, Ross Dependency</td>
<td>T&gt;-10°C, RH&gt; 50%</td>
<td>Temperature consistently &lt;0°C (annual mean Mean RH Low Cl- )</td>
<td>Coupon with attached gold grid sensor to electrically measure presence of moisture with T &amp; RH conditions</td>
</tr>
<tr>
<td>Henriksen and Mikhailov (2001)</td>
<td>Various locations in a valley between northern Norway and Kola Peninsula, Russia</td>
<td>T&gt; -4°C RH not considered</td>
<td>Variable temperatures (summers warmer than Antarctica, winter monthly mean -10°C) Variable RH Varied Cl- deposition Variable SO2 pollution, locally high.</td>
<td>Statistical regression analysis of climate conditions with corrosivity measurement.</td>
</tr>
</tbody>
</table>
The TNB experiment deliberately chose a location with very cold conditions and minimal salt deposition to elucidate criteria for corrosion where air temperature is rarely if ever above 0°C. By comparison, the Jubany measurements and those by Henriksen and Mikhailov were in locations with relatively warm conditions with much higher RH and salt/pollution deposition. It is possible that the use of temperature and RH criteria alone are insufficient to predict TOW and that the effects of salts and pollutants and of drying factors such as wind have particularly significant effects on surface wetness in Antarctica. The strongly drying effects of wind at Cape Denison, with intermittent periods of salt deposition could explain the relatively low grid sensor wetness (13.2 % of exposure) compared with just the temperature and RH criteria determined from the TNB experiment.

6.5.6 Impact of ice removal on corrosion risks for interior of AAE hut (Research question 6)

The removal of ice since 1997 could increase long term corrosion risks in any of the following ways:
- Increased temperatures may result from decreasing temperature stability inside the hut and/or;
- Exposure of previously covered metals to high RH; which will also
- Increase oxygen and salt access to the metal surface.

Regular and repeated condition surveys of metal artefacts and building elements are required to monitor these risks.

As mentioned in Chapter 4, the Conservation Management Plan (DEWHA 208) for the site does not evaluate these risks to metals. It is extremely difficult to protect metals from corrosion in high RH and the evidence presented previously is that low temperatures will not significantly reduce corrosion rates. Items that are potentially at risk following ice removal inside the AAE main hut include:
- Nails, bolts and hinges particularly those inside the wall spaces where moisture penetrates but is slow to dry out, and where salts may percolate through the roof;
- Some tin cans and artefacts including staples in books; and
6. Corrosion and other damage to metals

- Artefacts on the floor and in the Dark Room which appear to be periodically affected by meltwater.

The acetylene equipment appears less likely to corrode (although this was largely covered by ice during the author’s visit) since it appears to be galvanised.

6.5.7 Effects of salts on corrosivity (Research question 7)

Salts other than sodium chloride must be considered here because the calcium content of seawater makes it less corrosive by allowing precipitation of calcium carbonate films on cathodic locations (Evans 1981: 164-165). Other authors cited by Evans consider magnesium salts may be even more important in reducing corrosion caused in seawater.

The influence of the sea

The influence of sea ice on marine salt deposition, and thence on corrosivity, is potentially significant in Antarctica but difficult to correlate with corrosivity due to the difficulty in reliably distinguishing sea ice from pack ice (ie broken sea ice) via satellite images. Sea ice persists for up to ten months at the Ross Island sites, and around seven months at Signy and the other Antarctic Peninsula locations. Strong katabatic winds at Cape Denison and near Dumont d’Urville are known to cause polynya (areas of open water in winter) evident in satellite photos (Adolphs & Wendler 1995).

Mason (1991: 22) anticipated sea ice would minimise salt deposition (and thus corrosion) since aerosol salt particles can form above open leads. Winds can cause sea ice to break into pack ice, and sea winds increase deposition rates. However recent research has shown that much sea-salt aerosol around the coast of Antarctica is generated not from open water, but from the surface of newly formed sea ice (Curran et al 2006).

Topography influences salt deposition through wind speed and direction and exposure to sea winds. Vortex behaviour observed by Mawson at Cape Denison the (see Figure 5.10) that affects the whole of the headland (Jacka & Jacka 1988: 94) could result in salts being carried

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24 Described by Gerd Wendler in research summaries at [http://antarctica.gi.alaska.edu/index.html](http://antarctica.gi.alaska.edu/index.html)
inland further than would be expected with a katabatic wind regime. While katabatic winds generally reduce corrosion risks, local topography and its effect on salt deposition may produce local anomalies. The cross arm of the Memorial Cross has been blown off several times and is severely affected by katabatic winds. Metal bands on the cross arm are severely affected by corrosion with severe delamination and weeping of the corrosion products, indicative of high salt deposition.

At Davis, wind direction strongly influences corrosion of the metal panels of the Old Donga Line\(^{25}\) due to the association of corrosion and corrision together (figure 6.24). Winds pick up particles (mostly approximately 2mm-8mm diameter) which have corroded the original protection and strip off corrosion products allowing fresh surfaces to be exposed. While the winds are not strong they are directional, predominantly ESE, and the combined effects of corrision and corrosion has been sufficient to completely cut through the metal layer (figure 6.24) and expose the polystyrene insulation within.

*Influence of wind direction*

Katabatic winds, which dominate coastal areas such as Cape Denison and Mawson produce low temperatures since they blow from the cold polar plateau. Katabatic winds occur during periods of high air pressure, which in turn produces low relative humidity. Thus a region with katabatic winds predominating should have lower corrosivity than an equivalent location with a milder wind classification.

This was confirmed by the measurement for Mawson Station (67° 36'S), which experiences predominantly offshore katabatic winds has an average corrosivity of 3.3 µm/year while Rothera (67°34') has onshore winds predominantly from the north which frequently blow over open water producing higher corrosivity (27.1 µm/year). Cape Evans (77° 38'S) is much further south and experiences colder temperatures but no katabatic winds and has a corrosivity of 10.83 µm/year (King *et al* 1988).

\(^{25}\)Expeditioner accommodation.
In most of Antarctica salt deposition is a particular concern since rain is very rare\textsuperscript{26} so salt deposits are rarely washed off surfaces and snow appears less effective in removing salts. As discussed in Chapter 5, it is common to see profuse marine salt deposits on the ground at many coastal locations in Antarctica although the visibility of these salt deposits may be fleeting since they deliquesce in high humidity and may merely appear as wet films on the surface where they are deposited.

Despite its strongly katabatic wind regime outdoor salt deposition measured at Cape Denison was 5.5 mg/m\textsuperscript{2}/day\textsuperscript{27} (Hughes, King and Ganther 2002: 867). This is however much lower than at Cape Evans (45.5 and 34.2 mg/m\textsuperscript{2}/day and at Jubany (6-30 mg/m\textsuperscript{2}/day) and Artigas (180.1 mg/m\textsuperscript{2}/day).

Detailed EDAX and XRD analyses of corrosion products have been published for metals exposed at Antarctic Peninsula sites (Rivero \textit{et al} 2001, Rosales & Fernandez 2001, Morcillo \textit{et al} 2004). These found corrosion products on steel consistent with marine conditions but the profile of the corrosion layers were more deeply fissured and the surface morphology was honeycomb-like. The South American researchers provide similar studies of zinc, copper and aluminium for four-year exposures including SEM micrographs of surfaces and cross sections. Their collaborative work concluded that the flattened surface of copper corrosion is from the effect of an ice layer over the metal and that freezing in metal interstices produces micro-cracking of steel that increase its corrosion rate. Low atmospheric sulphur pollution was recorded although sulphur products of marine origin were present. They account for the high corrosion rate of aluminium via the hypothesised formation of a saline layer beneath ice layers covering the metal.

Maxwell and Viduka (2004:493) examined corrosion products scraped from corroded artefacts inside the Ross Island huts and found these were “generally free of chloride ions” but do not mention whether other salts may be present that could cause corrosion as their testing used “semi-micro qualitative wet chemical methods”. The evidence presented in

\textsuperscript{26} Excepting the Antarctic Peninsula, as previously discussed.
\textsuperscript{27} Daily rate measured over 14 days.
Chapter 5 and in the research of Otieno-Alego et al (2000) shows the importance of identifying other ions present, particularly sulphates.

Contrary to the results of Maxwell and Viduka, Otieno-Alego et al (2000) found high concentrations of chloride and sulphur compounds in corrosion products scraped from corrosivity coupons exposed at Mawson, Davis and Rothera (Otieno-Alego et al 2000, Appendix H, Table II). The analyses using XRF and inductive couple plasma–mass spectrometry and Raman microspectrometry identified mainly goethite and lepidocrocite. The chloride and sulphur contents of corrosion products were approximately three times as high at Mawson, Davis and Rothera compared to an industrial site in Australia (Newcastle). Sulphur compounds of marine origin predominate at Davis and Rothera. These are derived from the decomposition of plankton and a complex variety of sulphur compounds are produced. Low rates of leaching due to lack of rain result in retention of salts in the corrosion profile, which can form concentrated solutions of pollutants during high RH.

6.5.8 Implications for preservation (Research question 8)

Application of TOW criteria and corrosivity measurements for risk management

The evidence of Rosales and Fernandez and that of King et al 2001 from the Terra Nova Bay study is that corrosion can occur at temperatures significantly lower than 0°C. At dry, non-marine TNB the critical RH was 50%, whereas Rosales and Fernandez’ method does not specify an alternate critical RH to the ISO TOW. At Jubany RH exceeds 80% for many months of the year and salt deposition was high.

Regardless of which temperature and RH criteria are ‘correct’ in which environments, TOW using either Jubany or King’s TOW criteria are moderate at early historic sites at Cape Denison, Cape Adare and Ross Island but are high for Antarctic Peninsula sites. Moisture events that allow corrosion to occur happen are expected mainly in summer which is when high RH occurs inside most of the historic buildings. Salt deposition is high at many sites and salts are retained in corrosion products due to lack of leaching by rain. Corrosion prevention and treatment must take account of these conditions.
6. Corrosion and other damage to metals

Effectiveness of conservation treatments

Artefact treatments

Metals conservation treatments and strategies that have been used at Antarctic historic sites include:

- relocation of artefacts offsite or inside buildings to reduce exposure to damage (eg Ross Island sites);
- some use of tannic acid with various inhibitor to treat ferrous alloy items indoors, with application of a wax coating;
- replacement of corroded nails with new fasteners (often cross-headed screws);
- trials of various coatings and re-treatments of artefacts (Maxwell and Viduka 2004) and
- vacuuming/wiping to remove dust and deposits on indoor artefacts in the Ross Island huts as preventive maintenance and various treatments of tin cans (Bickersteth, Clayton and Tennant 2008)\(^\text{28}\), similar operations at Cape Denison (Berry 2010).

Maxwell and Viduka (2004) conducted outdoor exposures for three-year and one-year periods and on-site treatment assessments focussing on treatment of artefacts on display rather than building elements. The coatings included various proprietary lacquers as well as several waxes and greases that are used by conservators for indoor protection of treated metals (eg microcrystalline wax). The approach is evidently a broad-based trial and the rationale for selection of the coatings is not given. Trial re-treatments were conducted on ten ferrous alloy artefacts that had been previously treated with tannic acid and a chromate inhibitor and a wax coating.

The re-treatment consisted of washing “for redevelopment of any corrosion products” followed by application of the same selected conservation and commercial coatings as used in the outdoor trial. They reported that “all the wax coatings… broke down” and that “only those coupons coated with lacquers did not fail and start corroding” and cite evidence about the success of various current and previous treatments since 1987. Without further details of the corrosive environment it is difficult to evaluate the evidence presented. The authors stated that “none of these objects were relocated to a high risk microenvironment” (ibid: 497).

\(^{28}\) Available at http://www.heritage-antarctica.org/content/library/Conserving_and_Interpreting_Historic_Huts_2008.pdf
high success rate of previous treatments was reported especially with a new commercial coating (ARI) whose mode of action is said to be to contract and produce a denser corrosion layer. Difficulties in carrying out on-site treatments are discussed detailing issues such as flash rusting and the need for heat lamps to dry surfaces before coatings are applied.

It was concluded (ibid: 498) that “reducing the RH within the [Ross Island] huts [during summer] should result in a significant reduction in general corrosion rates”. However, the evidence of the TNB experiment suggests that RH would have to be reduced below 50% to prevent moisture films forming. To produce such conditions would appear to be in practice impossible given the low temperatures that determine RH inside the huts. Further removal of ice under the huts may reduce sublimation problems identified by Mason (see discussion in Chapter 4) but is unlikely to reduce RH in summer to levels sufficient to reduce corrosion risks.

Maxwell and Viduka (ibid: 498) conclude that “results from sampling and analysis show that the presence of chloride ions is far from universal within the inside artefact assemblages” but did not identify other corrosive ions present. Similarly, Mason (1991:78) presumed that because chlorides were relatively low there were low corrosion risks. Bickersteth, Clayton and Tennant (2008: 2) also presume that the salt problems at Ross Island sites are primarily chlorides. However, salt deposition data (Otieno-Alego et al 2000) shows sulphate deposition is significant in Antarctica and is selectively retained in corrosion products. Unfortunately aerosol salt deposition data is not widely collected and is not available for Ross Island. Samples collected from inside the huts (see Chapter 5) identify high amounts of sulphates, however, their corrosion impacts are more difficult to assess because of the diversity of sulphur compounds occur and their differing solubilities and chemical interactions. It cannot be presumed that lack of chlorides means a lack of salt risks.

More recently, conservation treatments have been carried out at Ross Island sites using a laboratory at Scott Base staffed over winter. Bickersteth, Clayton and Tennant (2008: 6) report there are about 5,000 artefacts at Cape Royds, about 8,000 at Cape Evans, 500 at Cape Adare and 350 at Hut Point requiring a treatment program lasting until 2013. Tin cans are a significant proportion of artefacts requiring attention and approximately 100 cans were treated in the 2006 winter season. The treatments reported (ibid: 4) are time-consuming but are stated to be effective with generally little re-treatment required although the conditions to
which re-treated artefacts are returned will have a significant impact and this is not evaluated in the published project reports. Treatments are very similar to those developed by Fox (1979) in Canada who identified risks from toxic bacteria and risks of pin-hole corrosion.

Removal of the can contents is carried out for leaking cans and samples are retained. Few non-aqueous techniques appear to have been developed for the painted/labelled tin-plate. Mason (1991: 26-27) observed the need for treatment of filiform corrosion, which requires particular conservation techniques to arrest the tunnelling front of the corrosion under the enamel/paint layer but no further details have been published in recent reports although this is an interesting and significant phenomenon at some Antarctic sites.

Treatments of artefacts at the AAE site are currently being undertaken (Berry 2009) using a similar approach to that at the Ross Dependency huts with laboratory treatments typical of museum conservation in temperate conditions and artefacts mostly treated and returned to their original locations. This approach involves significant resources due to logistics costs.

**Building elements**

Experimental data from sites around the world have shown that atmospheric corrosivity greater than 40µm/year makes effective protection of metals with most types of coatings very difficult. To protect items that are embedded or that cannot be completely coated such as nails or hinges is particularly difficult because various corrosion effects (eg differential aeration) are likely to concentrate corrosion damage where the coatings are discontinuous. In addition, many coatings are unlikely to meet the durability, environmental and ethical29 criteria required in historic metals in Antarctica, discussed below.

Removal of the nails for treatment is not generally feasible, nor desirable. Replacement with modern nails is intrusive and difficult to carry out without risking further damage so prevention is still the best prospect for treatment. Treatment of the exposed nail heads with corrosion conversion treatments and application of an elastomeric polymer coating on top may be worthy of field testing in Antarctica. However, the effectiveness of any treatment may

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29 The key ethical requirement is reversibility but aesthetic qualities are also important.
be compromised where atmospheric salt deposition is high or where the risk of corrosion of the treated surface is significant, especially at Cape Adare.

Replication of shelf brackets is being used at Cape Evans and is proposed at Cape Denison\(^{30}\), although the metal alloy proposed is not currently specified. There are some significant incorrect notions about suitability of conservation methods that require comment. A frequently suggestion is that ferrous metal building elements at risk of structural failure should be replaced by stainless steel. Unless the stainless steel can be hidden, its appearance is often inappropriate. Stainless steel in proximity to other metals and in contact with moisture formation will cause galvanic corrosion, accelerating corrosion of the other metal if it is electrochemically less stable. The common ‘18/8’ grade is not durable in marine conditions\(^{31}\) and some other grades are unsuitable where crevice corrosion is likely.

Lack of understanding of the scientific context of some historic buildings led to some initially unsuitable suggestions for treatment of the Magnetograph House and Absolute Magnetic huts at Cape Denison. Copper nails were specified by the AAE for these buildings since ferrous metals interfere with geomagnetic measurements. In 1997 ferrous metals were proposed for repairs, and when the geomagnetic concerns were raised the advice was changed to galvanised nails, not understanding that these are zinc coated steel, risking the same problem! Finally, use of copper replacement nails was agreed.

**Ethical issues**

The Burra Charter of Australia-ICOMOS (International Commission on Monuments and Sites), produced in 1979 and in its subsequent revisions, implies that conservation treatments consider possible long term effects to avoid those that might ultimately cause more harm than good. The Australian Institute for the Conservation of Cultural Material Code of Practice (AICCM 1999) requires that:

\(^{30}\) The brackets must be able to bear the weight of the shelf contents. However, this still raises fundamental questions about the conservation approach that expends significant resources to treat metal artefacts and return them to conditions where corrosion risks are high, long term efficacy of the treatments is unknown and reliance on ice removal to reduce RH risks is arguably misplaced.

\(^{31}\) Stainless steel used at Cape Adare has corroded (David Harrowfield, personal communication, Canberra, 2009).
“The advantages of the materials and methods chosen must be balanced against their potential adverse effects on future examination, scientific investigation, treatment, function and ageing” (AICCM 1999: 13).

In the severe climatic conditions of Antarctica it is obviously important to ensure proposed treatments can withstand the climatic conditions. It is important to determine whether the treatment will cause any unforeseen damage to the original material. Since Antarctic climatic conditions are so extreme and unfamiliar it is more likely that unforeseen problems may arise, increasing the need for caution and testing. Conservators prefer treatments that are ‘reversible’ but in Antarctica this is complicated by environmental and logistical constraints on use of chemicals and the difficulty or impossibility of dismantling and extraction of failed structural repairs.

The impact of any corrosion treatment also needs to consider its potential to impacts on other causes of deterioration, ie all proposed treatments should be considered in terms of their holistic impact. For example, the use of vapour barriers, frequently proposed as a solution for snow ingress, must consider whether this could promote condensation inside the wall space which could increase corrosion of fasteners. Other treatments that could increase corrosion risks are:

- those that could increase thermal absorption, such as use of dark cladding or roofing materials;
- anything (eg membranes) that may change flows of meltwater and thus promote higher RH in proximity to metal items; and
- excavation of artefacts from protective encasement in ice.

Another ethical issue concerns the risks of keeping artefacts in very high relative humidity inside buildings (where RH often exceeds 95%, as discussed in Chapter 4) well above the level where conventional treatments such as protective coatings can be expected to be effective. Thus even if artefacts could be treated to remove corrosion, corrosion is likely to recur if the objects are displayed in their original locations. This is often cited as grounds for relocation or repatriation of artefacts to enable their long term preservation although this should be balanced against the historic reasons for retaining them at the site where they have greatest significance. The excavation of large quantities of metal artefacts from ice in the Ross Dependency huts without timely and effective treatment has led to the significant
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conservation problems at the sites today. In retrospect a slower process of excavation and evaluation would have highlighted the problems at an earlier stage.

**Metal deterioration other than corrosion**

**Physical damage**

Cape Evans and Hut Point were ‘cleaned up’ during the 1960s (Quartermain 1961) and a large number of artefacts may have been physically damaged during the early expeditions were removed. At Cape Denison many original artefacts are extant due to the relatively hurried nature of the AAE departure which meant that their intended removal of ‘rubbish’ could not be completed. Thus there are some artefacts that bear evidence of ‘historical’ physical damage such as crushing and piercing at Cape Denison, whereas this is not so evident at Cape Evans.

At Cape Denison many of the fuel tins have holes (possibly from a pick) or are partially flattened (figure 6.30). Lazer (personal communication 1999) considers this may have been done by the AAE perhaps to allow unused fuel to evaporate rather than leave a potential risk of fire or explosion. Some artefacts in the vicinity of the hut have been crushed but it is difficult to determine whether this occurred during the AAE or from later visitors. Many people visiting or working at the sites walk in this area and most of the year it is covered by snow so they are not aware of the risk of trampling artefacts underneath.

Figure 6.30: Fuel tins, Cape Denison, author’s photo 1985

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32 Dr David Harrowfield observed excavation damage affecting particular items at all of the Ross Dependency huts from the 1960s excavations which he has photographed (personal communication, Canberra 2009) although not seen by the author.
At more recent sites such as Wilkes, many artefacts were long considered not to have any historic significance other than curiosity value and tinned foods are reputed to have been opened and discarded by visitors (Clark & Wishart 1991).

**Tin pest**

A large number of tin-plated artefacts occur at the older sites (Cape Adare, Cape Denison, Cape Evans, Cape Royds and Hut Point), mostly fuel containers and food tins. Tin plate is produced using either electro-plating or dipping of steel sheets into molten tin, producing a layer of high purity tin. Despite the large number of tin plated objects, and their exposure to temperatures at which allotropic change might be expected to occur, no evidence of tin pest was found at any site.

**Detached and wrinkled mirror backing at Cape Evans**

A glass mirror (figure 6.31) approximately 50cm x 40cm hangs in a wooden frame on an inner partition in Scott’s Cape Evans hut. The metallic layer behind the glass was very wrinkled and had separated from the glass. Headland (personal communication at Cape Evans 1993) stated that this was ‘due to freeze-thaw damage’, although neither the glass nor the metal absorbs moisture. The metal is still bright and not significantly oxidised or discoloured, thus it is unlikely to be due to any kind of corrosion process or ‘tin pest’.

A more likely cause is differential thermal movement leading to adhesion failure of the metal layer to the glass. It could not be determined during the brief visit, nor during subsequent enquiries, what type of metal was used to manufacture the mirror backing. Mirrors of this period are typically manufactured by applying a thin layer of silver, aluminium or tin to the back of the glass. Liebig developed a chemical method for coating glass with silver in 1835. Modern manufacturing methods (since the 1920s) use vacuum sputtering of silver or aluminium.

The extreme temperature range inside the hut (Held et al 2005) was +9.4 to -35.1°C measured over a three-year period. Contemporary mirrors observed by the author in unheated railway stations in Harbin, China showed no sign of such damage although it has a much greater
annual temperature range (approximately -30°C to +30°C). The thermal coefficients of expansion of the metals (in units 10^{-6}/°K at 20°C) are 18.9 (Ag); 23 (Al); and 22 (Sn), and 8.5 \times 10^{-6}/°K for the glass. This difference in coefficient of expansion might not be a problem if the same change occurs during both expansion and contraction, but if there is a hysteresis effect this could produce a small permanent change with each expansion cycle that may account for the damage observed.

The metal backing is fairly uniformly affected with the centre of the mirror generally in much the same condition as the edges although there are some random creases which may be due to pressure from the board at the back (inspection was not possible). No records were available to allow comparison of condition over time, but the detached metallic layer does not appear to be in danger of disintegration. The glass provides significant protection from visitor handling. No treatment is feasible, nor required, but to improve visitor understanding of the conservation problems of the site guides should not ascribe the problem to freeze-thaw damage.

Figure 6.31: Wrinkled mirror in Scott’s hut at Cape Evans, author’s photo 1993

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33 Coefficients at other temperatures could not be found.
6.5.9 Risk management

Identification of conservation treatment priorities using corrosion data

Standard conservation practice for determining priorities for any historic site requires:

- preparing a condition report;
- identifying treatment and maintenance requirements in a conservation management plan;
- carrying out treatments; and
- monitoring outcomes.

This is complicated in Antarctica by the large numbers of artefacts involved, the lack of effective treatments for outdoor metal artefacts, high logistics costs and concerns about long term conditions for display of treated artefacts.

Table 6.3 presents the author’s categorisation of risks and potential treatments. Risk number four covers building elements and artefacts in environmental conditions inside buildings where they are not covered by ice which results in a high risk priority based on consequence rankings of 2 (minor) to 4 (major). Risk number five covers those that are covered by ice and thus not exposed to air and salts which results in a low risk priority given the evidence that objects that remain enclosed in stable ice formations do not suffer any significant deterioration. Table 6.3 also identifies the major treatment types applied. While evidence from studies such as Maxwell and Viduka (2004) and Bickersteth, Clayton and Tennant (2008) suggest corrosion can be controlled by intensive treatment in an offsite laboratory, the long term risks have only been qualitatively assessed against environmental conditions and probably represent the ‘best case’ scenario.

Corrosivity and TOW data can assist in providing a quantitative basis for estimating corrosion risks incorporating factors such as TOW, salts and pollutants. Several conservators have already applied corrosivity measurements for estimating risks to historic buildings and artefacts in cold climates (see Appendices J, L; Croome 2004). Corrosivity measurements using the ISO 9226 methodology are particularly relevant since these represent the rate of atmospheric corrosion at an unsheltered location at the site providing a basic estimate of corrosion risk compared to hundreds of other sites around the world. The results can be applied to estimate relative risks using a holistic model for corrosion developed by Cole,
Paterson and Ganther (2003) to estimate variations within small local areas of rural, marine, urban and industrial landscapes due to variations in factors such as climate, topography, sheltering and precipitation.

Corrosivity measurements showed the rates at Cape Evans (10.87 µm/yr) and Cape Denison (12.2 µm/yr) are comparable to outer urban Melbourne, while Mawson (3.35 µm/yr) has an overall lower corrosivity, which is still sufficient to result in significant damage, even inside buildings. It is more difficult to estimate risks inside buildings since no standardised coupon measurements have been undertaken although this would be useful particularly where it can be correlated with TOW measurements from gold grid sensors and from temperature and RH measurements.

In addition to corrosivity, further detailed risk factors should be assessed for individual items:

- Is there a significant risk of structural failure, *eg* stress cracks in fittings, necking of nails?
- Does the context of the artefact (*ie* the fact that it is *in situ*) outweigh removal for treatment and storage?
- Will returning the treated object to its original location result in further problems?
- Is treatment even possible, *eg* if the metal is part of an inseparable assembly (*eg* nails rusted into wood, etc)?
- Can the cause of corrosion be treated effectively (*eg* can salt deposition be excluded or high RH be controlled)?

Principles for classification and triage of Cape Denison artefacts according to their historical significance were developed and published in Hayman, Lazer and Hughes (1998).34

*Management of artefacts*

The risk matrix in Table 6.3 indicates the difficulty caused by a lack of effective conservation techniques for metal artefacts apart from those published by Bickersteth, Clayton and Tennant (2008). The effectiveness of preventive techniques such as vacuuming has not been

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34 These include evaluating the collections of material repatriated to Australia immediately after the AAE and BANZARE expeditions since these include many artefacts returned from Antarctica then stored in museum conditions, consequently having fewer conservation problems.
quantitatively assessed although given significant resources this maintenance requires it would be useful to do so. Development of methods to remove concentrations of salts from inside the roof and wall spaces, not just the artefact arrays, or to exclude salt penetration may improve efficiency.

### 6.5.10 Recommendations for further research

Two main areas require further investigation:
1. Improved correlation of TOW criteria with corrosivity rates; and
2. Development and evaluation of effective ‘on site’ treatments for outdoor and indoor artefacts.

**Corrosion science studies**

Cold climate corrosion researchers from Argentina (Rosales), Australia (Hughes and King), Norway (Henriksen) and the US (Perrigo) developed a research strategy for ongoing investigation of the climatic conditions that allow wetness to form, although this has not progressed due to lack of funding. The proposal envisaged exposing standardised metal coupons of steel, copper, zinc, and aluminium with instruments (especially improved platinum grid transducers for TOW measurements) at a range of Arctic and Antarctic locations. The research proposed to examine factors including angle of exposure of the coupons, the times of initial exposure and more detailed analysis of corrosion products for salt factorisation (Hughes, King and Ganther 2002: 869). Refinements of methodology proposed include commencement of exposure at the equinox to address seasonality issues and both one-year and multi-year exposures.

In contemporary Antarctic buildings, condensation can occur inside wall spaces from heated humidified air which condenses at vapour barriers. TOW sensors can measure conditions inside wall spaces and roofs of both contemporary and historic buildings, where corrosion risks are high. Data from these studies would improve materials specification to reduce maintenance requirements and costs, which would also minimise adverse environmental impacts from repair work such as repainting. Currently personnel at Antarctic bases consider
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corrosion risks to be low so few and better communication of appropriate practices is required to improve building practice.

**Corrosion under ice layers**

Investigation of the occurrence of corrosion under ice layers as proposed by Rosales and Fernandez could not be undertaken in this thesis. However, the Terra Nova Bay experimental apparatus could be utilised inside a climate-controlled chamber to measure corrosion currents under ice layers as it is too difficult in Antarctica to control the large number of variables involved.

**Climate chamber studies**

A climate chamber could also be used to measure corrosion currents over a range of temperature and humidity conditions, with varying salt deposition rates using salt spray (fog) apparatus to simulate particle deposition. The climate chamber would enable greater control of variables compared with field exposures and would help elucidate the role of other factors (eg solar warming, wind and evaporation).

**Multi-year exposures**

Research by Rosales *et al* (2001) and Rivero *et al* (1996) suggest the need for further studies to determine temporal corrosion rate variation in Antarctica and whether corrosivity varies according to the thickness of the corrosion products. It is expected that corrosion may be linear in low corrosivity areas since corrosion layers are thin and do not protect the surface from further corrosion. For high corrosivity locations the corrosion rate may be expected to decrease with time since thicker corrosion layers may be protective against further corrosion although cracking may reduce protection. This research would enable more accurate long term prediction of corrosion risks from climate data.

**Research to improve conservation practices**

Many opportunities exist to utilise corrosion science to improve conservation practice at Antarctic historic sites, as discussed in Appendices J, L and M. These include providing
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Guides for identification of corrosion phenomena and factors (including salts), application of standard test methods for measuring corrosion factors and exposure testing of coatings and use of electronic sensors.

**Protective coatings**

The coating, even in indoor conditions must be durable in low temperatures and must be effective in conditions of almost continuous saturation RH in summer and with relatively high salt deposition at Ross Island sites. Given the scarcity of research funding and the high cost of logistics testing numerous coatings in the hope of finding one that will provide satisfactory performance is difficult.

However, one irreversible coating may be worth considering for indoor use if other coatings prove ineffective: ‘Parylene’ was studied by the Canadian Conservation Institute for preservation of partially fossilised plant material from the Arctic (Grattan & Bilz 1991). This Union Carbide process applies thin films of poly-para-xylylene slowly deposited as monomer, molecule by molecule, to form a completely even and transparent film over all surfaces, including internal ones, with little adverse effect on appearance. Consideration of the ethical issues and extensive testing are essential preliminaries, but this might be useful to treat the more severely corroded tin cans with rusted on paper labels at the Ross Island sites (where there are multiple examples of each type) in less favourable locations indoors where otherwise few viable options can be envisaged.

**Reburial**

Reburial in ice, similar to the approach used at Dealy Island (Janes 1982) may be a useful strategy where large numbers of small artefacts cannot be immediately treated, and where regular access to the artefacts is not required. This would require resolution of the potential occurrence of corrosion under ice layers, although this risk could be addressed by ensuring artefacts are dried and sealed in impermeable metallised plastic packaging before burial.

Suitable reburial sites include permanent drifts that are not liable to ablation on the southern and leeward sides outside buildings, or inside buildings that remain filled with ice. Variations of this technique could combine reburial with passive radiators (discussed in Chapter 4).
where large numbers of artefacts need be stabilised to prevent environmental contamination (eg at Wilkes).

*Cathodic protection*

Cathodic protection has been used for *in situ* conservation of historic structures in other climates (for example, Look and Spennemann 2009) using both impressed current and sacrificial anodes. This could enable *in-situ* conservation of the *Aurora* anchors at Cape Evans if measurement of corrosion rates confirms it is required and if direct current could be provided on site.\(^{35}\)

*Vapour phase inhibitors*

Vapour phase inhibitors (VPIs) can be used for on-site storage where artefacts are not required for display and can be sealed in containers. This could be used for artefacts at high risk of loss or damage if they remain at their present location but where removal offsite is not appropriate for ethical, logistical and/or cost reasons. This would be particularly useful for mixed-material artefacts where desalination is difficult.

Low-toxicity VPIs are available that could meet strict Antarctic environmental protection requirements although few have been tested for effectiveness at low temperatures. Low temperatures may prevent volatilisation which is essential for temporary bonding of the VPI to the metal surface. VPIs are not generally effective where extensive corrosion has already occurred and where salts are present but could be useful for on-site storage of treated artefacts.

**6.6 CONCLUSIONS**

- Metal artefacts and building elements at all coastal Antarctic historic sites are affected by corrosion ranging from minor to severe despite the temperature and RH criteria of ISO 9223 (T>0°C plus RH>80%) which imply corrosion will not occur.

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- Corrosivity measured at Antarctic historic sites using the ISO 9226 coupon method ranged from 3.35 µm/yr at Mawson to 12.2 µm/yr at Cape Denison and 27.1 µm/yr at Rothera, comparable to rates in temperate climates.

- ISO TOW significantly underestimates corrosivity in Antarctica as surface temperature, salt deposition and orientation have much more significant effects than in temperate climates.

- Application of new corrosion criteria developed from experimental data measured at Enigma Lake (Terra Nova Bay) is difficult at coastal locations. However, but this and other research in polar conditions indicates corrosion risks for Antarctic historic buildings are higher than inferred from ISO TOW. Treatment of metal exposed from ice in high RH is difficult to achieve with conventional treatments such as corrosion removal and coatings.

- Salt deposition and salt retention in corrosion products (particularly sulphates) significantly affect corrosion rates in Antarctica.

- Corrosion science methodologies such as measurement of TOW and salt deposition parameters, particularly inside wall spaces, could improve conservation practice through better understanding of corrosion risks.

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