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ss Great Britain: teamwork as a platform for innovative conservation

Abstract

Brunel's 1843 ss Great Britain was a technological milestone of world importance. It now rests in its original dry dock in Bristol. Research established the significance of the ship; identified its inherent instability and reviewed conservation options to support a successful 8.5 million pound Heritage Lottery Fund bid. The complex preservation project involved innovative use of desiccation to preserve the hull, along with a large scale conservation programme for the fabric of the ship and dockyard structures. The input of architects, engineers, conservators, corrosion scientists, historians and many other specialists was managed directly by the executive director and a qualified project manager who maintained timetables and co-ordination. Research into the effect of relative humidity on the corrosion of chloride infested iron provided data for use in a design that changed the dry dock into a climatically controlled envelope around the unstable hull.

Keywords

Brunel, ship, iron, corrosion, conservation, project-management

Iron ships comprise a range of differing and inherently unstable alloys, which have been subjected to an aggressive marine environment throughout their working lives. Size and resource implications normally result in their continued exposure to aggressive open air environments in museum contexts (Birkholtz 1997). The limited finance available to underpin large cost-hungry ships like the ss Great Britain condemns them, either to a lingering 'death' or incremental transformation to replicas, as corroded parts are slowly replaced with modern metals or materials. Curators generally struggle to preserve their ship in a climate of limited financial support from visitors, benefactors, trust funds, local authorities and small grant applications (Ashley 1997, Robinson 1997). Preservation normally relies upon a fire-fighting approach dictated by the uneven supply of money and resources. A long-term executable conservation plan often only exists in broad terms, if at all, and is unlikely to be supported by the necessary research and specialist input.

This paper describes how the ss Great Britain Trust challenged this gloomy overview of the plight of large industrial objects, to develop an innovative conservation plan for the preservation of a large chloride infested and highly unstable iron ship. Emphasis is on the management structure that made this possible and the reasoning behind the course of action taken. The need to address a broad range of historical, cultural and commercial issues to justify and support the conservation plan in the successful pursuit of funding, are also highlighted. The paper finishes by offering a brief resume of the underpinning science is also offered.

Historical

The ss Great Britain was the brainchild of the remarkable engineer Isambard Kingdom Brunel (Corlett 1990). Launched in 1842 as the first ocean going liner



Fig 1 ss Great Britain at her launch in 1843.

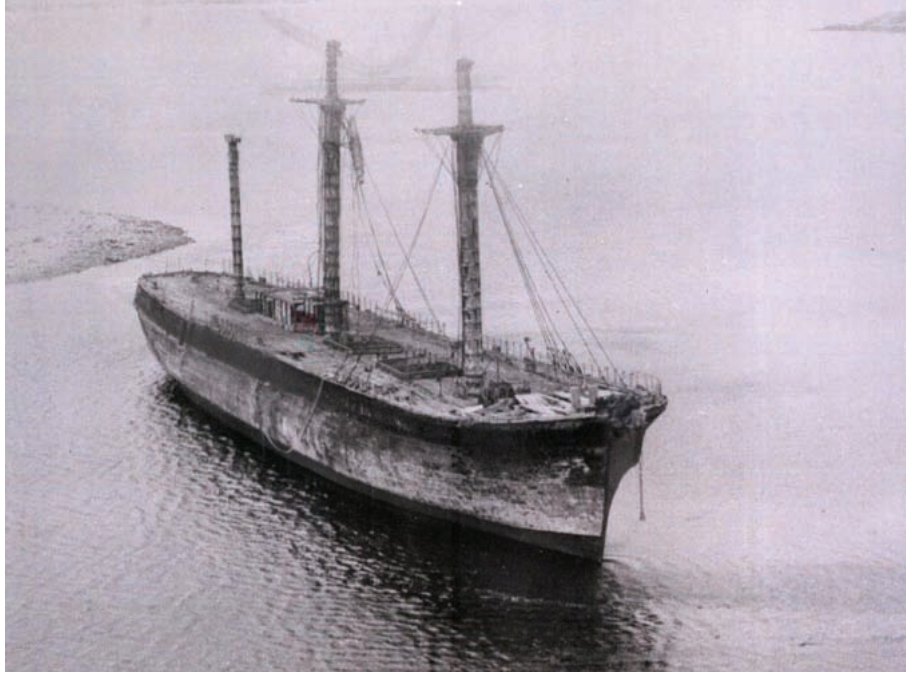


Figure 2 ss Great Britain sitting in Sparrow Cove.

with a wrought iron hull and screw propulsion, she was then the biggest ship in the world at 322 feet long (see figure 1).

After a short transatlantic career she was engaged in taking emigrants to Australia and in later life she was converted to a sailing ship, but after suffering damage rounding Cape Horn the ship was purchased by the Falkland Islands Company to serve as a floating warehouse (1887–1933). In 1937, once she became too old for this job she was towed to Sparrow Cove and holed to enable her to sit on the shallow bottom, where she was left to rot (see figure 2).

This flooding submerged the inner and outer sides of the lower hull, reducing oxygen access to the metal and increasing its chloride content, as compared to the upper reaches of the hull. These were oxygenated and subject to sea spray, strong wind and rainwater, which could respectively wash out chloride and dry the hull rapidly. Corrosion at the wet but highly oxygenated waterline would be severe. Any paint on the hull will have offered some protection to corrosion while it remained intact.

Salvage

The ss Great Britain Project was created in 1968 to salvage the ship and in 1970 she was towed across the Atlantic on a pontoon barge. The large size of this barge required the ship to be floated the final few miles up the River Avon (see figure 3) to her resting place in the original dry dock in which she had been constructed (see figure 4). This fortuitous union of ship and dry dock, with the surrounding workshops and offices that had supported its construction, created a large heritage site of world importance. Both the importance of this combination and its potential symbiotic relationship for visitors was not recognised and developed until a much later date.

The original aims of the ss Great Britain Project Ltd., which is an independent registered museum and charitable company set up in 1971, were stated in the Memorandum of Association:

to acquire, transport, rebuild, restore and fit out the *ss Great Britain* and to preserve the same for all time and for the benefit of the public as a ship of historic interest and to place the same upon public display in whole or in part as a museum of general industrial and marine archaeology

The lack of a co-ordinated conservation plan and a long-term budget influenced the early preservation of the ship. This was an ad-hoc procedure with no incremental conservation programme or final goal. Although some work was



Figure 3 ss Great Britain travelling up the River Avon.



Figure 4 ss Great Britain in the dry dock in which she was built.

undertaken by professionals, enthusiasts and volunteers also contributed. Interested groups and Trustees included engineers and those interested in shipbuilding, which influenced the nature of the preservation and restoration work carried out on the ship. The mud and debris within in the hull was cleaned out. The hull was subjected to standard shipyard maintenance practices of aqueous pressure wash and flame gun treatment followed by painting. This did not prevent ongoing corrosion, as the deep seated chlorides in the metal surface were not removed and poorly maintained paint layers are never totally effective barriers for either moisture or oxygen.

During this first 25 years of the life in dry dock parts of the upper regions of the hull were replaced or rebuilt and a steel weather deck was added. Mild steel was used for repairs and, in places that did not require structural integrity, glass reinforced plastic repairs were used on the hull. There was also an incomplete attempt to insert replica engines into the ship and the first class saloon was reconstructed to provide an eating area, which is used for functions to earn money for the ship. These actions involved changes to the ship's fabric.

Without a conservation strategy that takes into account the corrosion mechanisms and the options for either preventing or controlling them in the long-term, the ship was heading towards becoming an unviable structure. An iconic element of Britain's industrial heritage would be lost and an opportunity to create a major visitor attraction in Bristol, by preserving both ship and dockyard complex would be lost. Against this backdrop of ongoing corrosion and an absence of a researched conservation plan was a need for major new initiatives in management, which would result in a preservation plan, improved funding and action.

The appointment of a professional curator in 1997 led to a halt in interventive processes on the hull, the introduction of a new philosophy of minimum intervention and a revised mission statement in (1998) that focuses on conservation and interpretation (*ss Great Britain Project 1998*):

To preserve the ship, *ss Great Britain*, and it's building dock for all time for the public benefit of all, and to place the same upon public display as a museum for the enhancement of public understanding and appreciation of her social, commercial, scientific and technological context and significance.

Importantly the new mission statement recognises the heritage of the site within

any preservation plan, as well as the ship and its life. It retains the concept of perpetuity, but this must be set against the instability of iron and it may be an unrealistic view. The decision from the ss Great Britain Trust, “to conserve fully to the highest standards the extant fabric of the ss Great Britain (1843–1970) and its building dock” defined the preservation programme as a conservation task, rather than a restoration programme.

Other objectives in the long-term Development Plan centre on broader issues, which must be seen as an integral part of any conservation plan as they will influence its design and provide parameters for developing funding bids:

- To enhance public understanding and appreciation of the social, commercial, scientific, and technological context and significance of the ship Great Britain, of the manner and construction, of the other ships, Great Western and Great Eastern, and of I K Brunel (and his Collaborators) in his maritime related ventures.
- To enhance the quality of the visitor experience and visit value (by improving and completing the interpretation of the ship, dock, and site.)
- To provide education and outreach services of consistently high quality and innovation.
- To achieve full registration as a museum with Museums and Galleries Commission, and compliance with all appropriate regional and international standards.
- To improve access to the ship for all visitor types, and an increase in overall number of visits per annum.
- To ensure financial viability and ethical integrity of ss Great Britain Project Ltd. in order to achieve the above objectives.

These goals generate the question, “how can a 322 feet long chloride ridden wrought iron hull be prevented from corroding in the atmosphere?” In simple terms, devising conservation procedures and managing their execution encompasses academic research and transfer of theory into practice, taking account of time, finance and resources. Conservation can be reduced to a simple formula:

- identifying problems;
- investigating them using materials science;
- utilising these results to research conservation options;
- linking conservation options to ethics and finance;
- adopting a pragmatic approach throughout.

Large objects require extensive management input, as conservation may take several years and involve both a wide range and large number of staff. Appropriate management structures and good planning facilitates controlled, measured and reasoned action that is the cornerstone upon which professional conservation rests.

New opportunities for conservation

The Heritage Lottery Fund (HLF) has the potential to provide very large amounts of money for selected heritage projects recognised as being of great national importance (Robinson 1997). Large items such as ships and industrial complexes can move away from piecemeal conservation to a holistic preservation strategy in their attempt to gain finance from HLF, which has strict criteria and priorities that successful funding applications have to meet.

They also consider:

- whether there is need or demand for a project;
- viability of the project, its quality of work and its longer-term role;
- management of the project during implementation and after completion;
- measurement criteria for success in meeting project goals;
- financial accuracy and overall value for money.

Funding applications are rigorously assessed by specialists and peer groups to ensure public accountability. Success requires professionalism and the in-depth research this entails comes at a financial cost, which may prevent the birth of a conservation plan. For the ss Great Britain finance was provided by HLF, as part

of stage one in applying for further funds. Recognition of the importance of the ship had preceded the awarding of this grant.

Plans should provide both preservation options and mechanisms for achieving them, set within financial viability. This immediately elevates the importance of management. Initially management must deal with a multi-task problem and provide inclusive consultation to produce a strategic plan. The implementation of this will require a different form of management that provides focus on action, timetables, standards and finance. The initial two volume conservation plan for the ss Great Britain was overseen by the Executive director and produced by two main consultants. It took the form of assessment of options, justification of goals and identification of viable routes, which were underpinned by a range of specialist reports.

Managing the development of the project design

Guiding the specialist research into a viable conservation plan required a simple decision making structure. The Trustees entrusted management to an Executive Director, who was answerable to them. While it is clear that no single person can generate an entire conservation design, it was felt that one individual should make the decisions that would formulate it. Ultimately, the Executive Director decided the validity, importance and quality of expert reports in relation to the conservation plan and its goals. This “apparent” totalitarian approach deliberately avoided decision making by committee, but required extensive partnership and team working that utilised the outcomes of meetings between individuals and bodies commissioned to provide an opinion. It allows for strong leadership that is properly empowered by and answerable to the governing body, which meets as a committee monthly, and whose chair meets with the executive director weekly.

The Executive Director also has a dedicated specialist in-house team, project manager and lead consulting conservator reporting directly to him. This system of management offers a mechanism for ensuring the core goals are delivered across a large and complex project, where any element can either cut across or contradict another. The Executive Director’s role is to balance competing forces such as; interpretation versus conservation; engineering versus visual aesthetic and mechanical and engineering plant versus visitor experience.

Avoiding extensive committee structures for decision making was a conscious decision. While democratic consensus has a large number of merits, which include pooling thought processes and collective responsibility, committees comprising individuals from widely differing professional backgrounds offer scope for divergent views, slow decision making, wasted resources, timetable slippage and personality clashes. At its worst it can produce inertia. If the architects, structural engineers, mechanical engineers, material scientists, conservation specialists and the other professionals involved in the conservation plan for the ss Great Britain, offered anything more than data and advice, there was scope for a ponderous decision making structure. Without a clear management structure to co-ordinate specialist input, a project is in danger of unchecked growth, reduced impetus and losing adherence to the core vision and its goals.

Implementing the conservation design: Project management

Managing the implementation of the strategic conservation plan differs from managing its design. Management of site work, quality, costs and timetables demand a different range of expertise to those used in strategic development. The conservation plan offers a working design and a document via which HLF can assess conservation viability. Implementation of this involves dozens of contractors, who are required to work to benchmarks and standards within a tight timetable. Controlling this is the remit of a project manager.

The project manager at ss Great Britain rapidly familiarized himself with the conservation design and the professionals implementing it. Maintaining deadlines is essential, as the work of one group of specialists can influence that

of another. Engineering calculations and architectural designs could be delayed by late results from corrosion research. Consultants involved in ongoing work attend design team meetings once per week and monthly Progress Meetings ensure snags are identified and timetables are ratified or adjusted. Not only does this progress the conservation, but it offers accountability for HLF, who also appoint specialists to examine data, monitor progress, approve the quality and assess viability.

Volume 1: Conservation plan for Great Western Steamship Company Dockyard and the ss Great Britain

Justifying preservation is essential for working objects that were conceived as having an end life that occurred either when the cost of repair exceeded the cost of replacement or when the original mission no longer existed (Ashley 1997). Volume 1 of the *ss Great Britain* Conservation Plan examines the historical significance of the Great Western Steamship Company Dockyard and the *ss Great Britain* (Cox and Tanner 1999). The site and its context are discussed and their importance verified with advice on topics such as sustainability, accessibility, the Bristol Local Development Plan and other factors relating to statutory and non-statutory controls of the site. The conservation plan follows Australian Rules – description of heritage assets; analysis of cultural significance; development of policy to preserve this significance and condition report to deliver mechanisms for preservation of the significance identified (Kerr 1996).

Demolition and alteration of existing buildings according to their historical significance is discussed in recognition of visitor requirements and numbers, access routes and health and safety. Planning this involves architects, engineers and historical researchers. These projections influence calculations on long-term financial viability and the income required for staff, plant and conservation needs. This holistic view avoided the limited view of conservation sometimes offered by conservators who become too closely engaged with ‘their’ object (Drysedale 1987). Avoiding focus solely on the ship offers a better chance of funding success, as the ship is the jewel in the crown rather than the single aim of the project.

Volume 2: Condition report and recommendations for the ss Great Britain

This volume was produced by Eura Conservation Ltd in conjunction with the Executive Director and his deputy (Turner et al 1999). Arguably the ship presents the most complex aspect of the whole scheme and the goal is to preserve it... “for all time”. To aid this it is important to determine its rate of corrosion and then control this in a semi-quantitative manner.

Specialist reports formed the basis of a condition report for the hull. This broadly identified it as being considerably mineralised, physically weak and generally chloride infested, as well as being housed within a damp aggressive environment (table 1) (Turner et al 1999). Paradoxically these assessments reflect both the teamwork central to this project and the importance of central management to match data to conservation goals. Time was important as current thickness measurements of hull plates indicated corrosion to the point of instability within 25 years. Retention of mineralised areas on the lower reaches of the hull support the goal of conservation, rather than restoration (Turner et al 1999).

Corrosion model

The results of environmental differences following holing and beaching in Sparrow Cove were evident in damp and oxygenated atmosphere in the dry dock. In July 1999 daily maximum relative humidity within the dry dock was 90% and the minimum was 48%, with maxima and minima of 70% and 40% inside the forward bulkhead (Tanner et al 1998). In comparison to the upper reaches of the hull, both the inside and outside lower regions of the hull were particularly unstable in the atmosphere, due to their long-term total immersion in seawater infusing them with chloride, which can provide a strong electrolyte.

Assessment	Assessor	Outcome
Acoustic and visual assessment of the hull condition	Eura Conservation Ltd. 1998	Categorisation of hull condition from 1–4 (good to very poor)
Mechanical testing – hull, dock caisson, load bearing wooden support struts	Sandberg consulting, inspecting and testing engineers 1998	Ultimate tensile stress measurements and metallographic data
Chloride content of corrosion products Shane Casey – ss Great Britain employee 1999	Shane Casey – ss Great Britain employee 1999	Chloride content of corrosion from selected parts of the hull – not of chloride in the metal
Structural appraisal of ship	Morton Partnership Ltd 1998	Provisional strengthening proposals
Overall structure of the ship and its means of support	Alan Baxter Associates consulting engineers 1998	Identified the effect of early alterations on the structural integrity of the ship
Wrought iron of ss Great Britain	Dr JE Morgan 1996	Properties of wrought iron in design and renovation allows questioning of any repair by conventional welding due to iron-slag mix in wrought iron
Preliminary survey of Great Western dry dock and other masonry	Holden Conservation Ltd. 1998	Essentially and assessment of the environment around the ship.

Table 1 Condition surveys of the ship.

Ferric oxyhydroxides (FeOOH), including Goethite (αFeOOH) and the chloride bearing Akaganeite (βFeOOH), were identified as corrosion products on the hull (Watkinson and Lewis 2004). Magnetite (Fe_3O_4) occurred at the less aerated metal/paint layer interface. Spalling of the corrosion layers revealed the metallic iron and a fresh $\text{FeOOH} / \text{Fe}_3\text{O}_4$ corrosion product mixture, often with weeping (see figure 5).

The corrosion model for chloride infested wrought iron in the atmosphere involves two corrosion reactions; the oxidation of anodically produced Fe^{2+} ions (equation 1) (Turgoose 1982) and acid dissolution of metal at the anode (equation 2) (Selwyn et al 1999). The formation of various FeOOH polymorphs occur and Fe_3O_4 in the reduced oxygen environments beneath paint and corrosion layers (Chandler and Stanners 1966, Jones 1992, Knight 1992,).

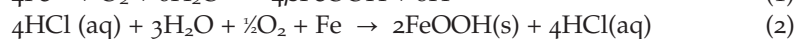
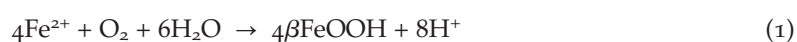


Figure 5 Corrosion at metallic anode sites and spalling of the corrosion product/paint layer.

Treatment	Comment on treatment within context of ss Great Britain conservation plan
Aqueous wash	Inefficient and unpredictable level of chloride extraction; aerated environments provide lower chloride extraction than deaerated (Selwyn and Logan 1993, Scott and Seeley 1987, Watkinson 1982 and 1996).
Alkaline sulphite	Better aqueous chloride extraction due to alkali and deaerated environment, but normally less than 90% chloride removed; caustic solution; impractical on scale required (Gilberg and Seeley 1982, Knight 1997, North and Pearson 1975, Rinuy and Schweizer 1982, Selwyn and Logan 1993, Turgoose 1985, Watkinson 1996).
Sodium hydroxide	Between 55% and 80% chloride removed in aerated environments; caustic solution; impractical scale (North and Pearson 1978, Watkinson 1982, 1983 and 1996).
Alkali wash	Sodium Carbonate wash; used with Holland 1 submarine; efficiency as chloride remover unknown; practical application problems with very corroded structures; disposal of treatment solution (Barker <i>et al</i> 1997, Knight 1997).
Electrolysis	Varying reports on efficiency and stability; disposal of electrolyte is a problem; challenging on a large scale; better with substantial metal cores; hull is extensively mineralised in places (Knight 1997, Selwyn and Logan 1993, Selwyn <i>et al</i> 2001).
Hydrogen reduction	Effective chloride removal; reactive pyrophoric iron produced; ethically questionable; impractical on scale required (Barker <i>et al</i> 1982, Birchenall and Meussner 1977, Tylecote and Black 1980).
Inhibitors	Inhibitor action is unpredictable on heavily corroded iron surfaces that are contaminated with chloride; toxicity limits choice (Argryropoulos <i>et al</i> 1997, Skerry 1985, Turgoose 1985).
Cathodic protection	Hull lacks metallic continuity due to areas of total mineralisation that are being retained as part of the conservation rationale.
Desiccation	Removal of water from the corrosion mechanism prevents electrolytic corrosion.

Table 2 Treatment options for the ss Great Britain (after Watkinson and Lewis 2004)

Conservation options

Corrosion in a damp oxygenated atmosphere relies upon the presence of anodes and cathodes, with solid phase electrical contact between these and in an electrolyte that is replenished by atmospheric oxygen. To stop corrosion at least one agency of decay must be removed or negated. There are a range of options for achieving this (see table 2).

Removing the electrolyte ions from corroded iron is a challenge that no conservation technique has managed to solve for chloride ions (Keene 1994, Knight 1997, Turgoose 1985, Watkinson 1996). The size of the ship offers both practical and health and safety problems for many treatments, especially those aqueous wash systems aiming for 'chloride removal'. They require de-oxygenation and alkaline environments for best results (North and Pearson 1978, Turgoose 1985). Controlled disposal of millions of gallons of alkali wash would present cost and safety limitations. Additionally the chloride extraction efficiency of such treatments is not predictable, although on a small scale some systems have been shown to have good efficiency on wrought iron archaeological samples as determined by sample digestion (Watkinson 1996). Pulsating electrolytic desalination methods have shown good chloride extraction efficiency of small wafer thin artificially chlorinated cast iron samples in laboratory conditions (residual chloride determined by sample digestion), but remains untested with large wrought iron objects (Dalard *et al* 2002). Reports of chloride removal from large cast iron objects using electrolysis focus on the residual instability of the object (McCarthy 2000). Application difficulties arise for all electrolytic methods on the ss Great Britain, due to her size and severe corrosion of the hull producing electrical discontinuity.

Whether chloride removal is attempted or not, post-treatment environmental

control is essential to prevent corrosion, as is the case for the Holland 1 submarine. This was washed to remove chloride, yet remains stored in a controlled relative humidity (Barker et al 1997). The unpredictability, cost and impractical nature of employing interventive conservation methods designed to remove chloride, convinced the Executive Director and Eura Conservation Ltd. that controlling the damaging influence of chloride in the hull by environmental methods, was the most cost effective and predictable preservation option.

Controlled storage that eliminated oxygen would prevent the oxidation of iron, but this is costly and also impractical if visitor needs are taken into consideration. Object size is crucial in any such instance where an enclosed display case is necessary (Mardikian et al 2004). An alternative control method used extensively in conservation is to remove water in order to prevent electrolyte formation. Even on a small scale attaining and maintaining low relative humidity offers challenges. Before initiating desiccated storage, it is necessary to experimentally examine iron corrosion and to establish what corrosion reactions could occur as chloride infested iron is dried, then determine the effect of moisture on these reactions. The resulting data will reveal how dry the ambient environment should be to prevent the corrosion reactions examined. This information can be of use to those designing the storage environment for the ship.

Underpinning research for corrosion control

The Executive Director recognised the importance of reproducible laboratory testing to support his ideas on preserving the ship by desiccation. The Conservation Department at Cardiff University was commissioned to research a corrosion model for chloride infested iron. The goal of this work was to determine no-corrosion relative humidity values for reactions involving chloride bearing compounds in contact with iron and to examine how corrosion rate related to changing relative humidity. Resulting data on no-corrosion points and corrosion rate provides an opportunity for management to make value judgements on design and operating conditions for the moisture controlled storage space around the hull. Initial design and running costs will vary according to relative humidity - the drier the environment the higher the cost.

Modelling drying of the hull reveals that chloride bearing β -FeOOH will form as drying concentrates chloride and corrodes the iron. β -FeOOH will also be present from earlier corrosion. As chloride concentrates and pH drops at the metal surface, it is thermodynamically possible for solid ferrous chloride to form (Turgoose 1982b). Iron corrodes when mixed with $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ at 20% relative humidity, but it does not corrode when the relative humidity is 15%, where $\text{FeCl}_2 \cdot 2\text{H}_2\text{O}$ is the stable hydrate form (Turgoose 1982b). The water in $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ is thought to support electrolytic corrosion, whereas $\text{FeCl}_2 \cdot 2\text{H}_2\text{O}$ does not.

β -FeOOH is reported to corrode iron that is in contact with it, due to its hygroscopicity and the mobility of the significant amount of surface adsorbed chloride that it carries (Ishikawa *et al* 1988, Turgoose 1982a, Watkinson and Lewis 2004 and 2005a). The surface adsorbed chloride of long-standing rain washed β -FeOOH on the hull may have been removed rendering it incapable of corroding iron in contact with it at low humidity (Watkinson and Lewis 2005a). β -FeOOH will retain surface adsorbed chloride in areas of the ship that are not rain-washed and it can corrode iron in contact with it, provided the storage relative humidity supports the β -FeOOH/iron corrosion reaction. The reported 25 year metastability of β -FeOOH (Gilberg and Seeley 1981) has not been detected by the authors of this paper (Watkinson and Lewis 2005a). This means that chloride bound up in the crystal structure of β -FeOOH will not necessarily be released by transformation to α -FeOOH.

Based on the corrosion model involving β -FeOOH and ferrous chloride, experiments were carried out to link relative humidity to corrosion of chloride infested iron in low humidity environments by examining the effect of β -FeOOH, $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ and $\text{FeCl}_2 \cdot 2\text{H}_2\text{O}$ on iron powder at differing relative humidities (Watkinson and Lewis 2004). Results were used by the ss Great Britain Trust to

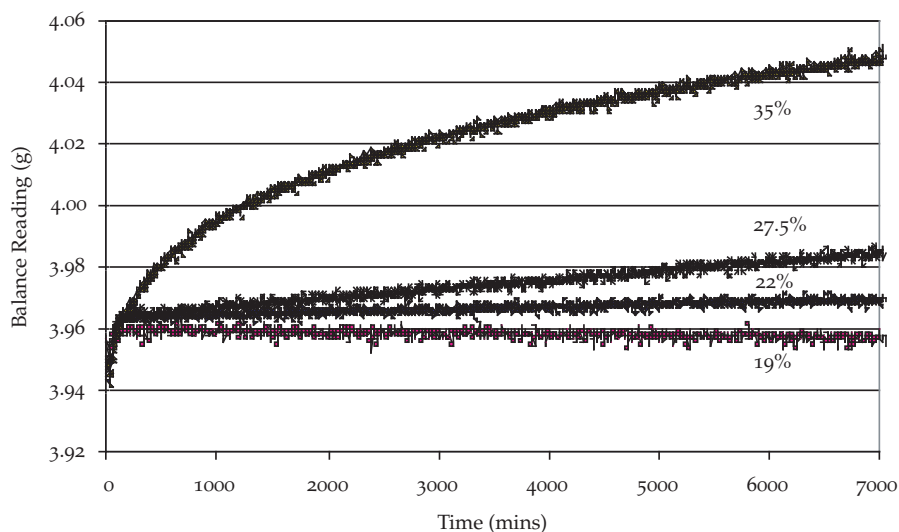


Figure 6 Weight change versus time for 2g iron powder and 2g ferrous chloride at selected relative humidities (Watkinson and Lewis 2004). $\text{FeCl}_2 \cdot 2\text{H}_2\text{O}$ at 19% and $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ at other relative humidities.

design their storage environment.

Extensive testing of the hygroscopicity of βFeOOH and ferrous chloride and their ability to corrode iron has been reported elsewhere (Watkinson and Lewis 2004, 2005a and 2005b). In summary, Analar grade $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ and synthesised βFeOOH , which was assayed as 99% pure (Watkinson and Lewis 2004) were used in corrosion tests with pure iron powder in a climatic chamber that controlled relative humidity to $\pm 1\%$ (established by test calibrations) and $\pm 0.5^\circ\text{C}$. Test samples were placed on a calibrated balance (accuracy 0.0001g) in the chamber. All tests were run at fixed humidity and 20°C to allow for calculations in specific humidity, as well as relative humidity. Weight changes that may be due to iron corrosion, oxidation of corrosion product, desiccation or hydration, were dynamically monitored to file every 5 minutes. These values were used to determine whether corrosion of iron had occurred, along with visual inspection, XRD and FT-IR of the sample.

Results

$\text{FeCl}_2 \cdot 2\text{H}_2\text{O}$ was stable at 19% relative humidity and iron powder mixed with it did not corrode (see figure 6). In contrast $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ was the stable hydrate at 22% relative humidity, where corrosion of iron powder occurred and became faster with increasing relative humidity (see figure 6).

For mixtures of unwashed βFeOOH and iron powder exposed to various fixed relative humidity values, corrosion continued down to 15% relative humidity and was not measurable at 12% (see figure 7). Initial weight loss at low relative humidity is due to desiccation of the βFeOOH exceeding any weight gain due to corrosion. Later weight gain from corrosion exceeds any loss from desiccation.

Corrosion significantly increases as 30% relative humidity is approached for both $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ and βFeOOH . Desiccation below 19% relative humidity will prevent corrosion of iron involving $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ and the corrosion contribution of βFeOOH is slight. Corrosion of chloride infested iron can be prevented below 15% relative humidity. This data is being used by engineers and architects to design climate control plant and the tolerances of the dock and hull seals that would create the controlled storage space around the ss Great Britain Hull. The results reported here endorse the principle of desiccation as a means to preserve the iron hull of the ss Great Britain.

Discussion

The semi-quantitative data from testing also offers an opportunity for the management team to adopt a pragmatic approach to preservation of the hull. Cost effectiveness often promotes compromises. Stopping iron corrosion costs a great deal of money (below 15% relative humidity). Until 21% relative humidity

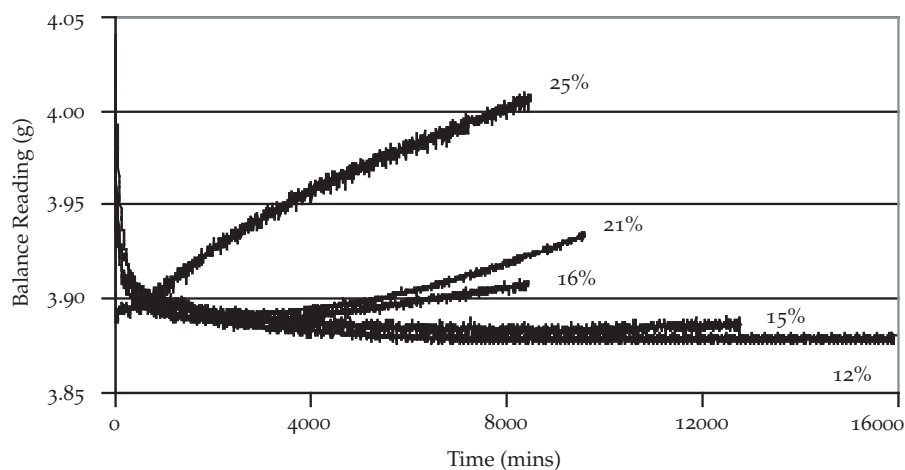


Figure 7 Weight change versus time for 2g iron powder and 2g beta-FeOOH at selected relative humidities (Watkinson and Lewis 2004). Initial weight drop is due to water loss from beta-FeOOH.

is reached only β FeOOH contributes to corrosion of iron and the rate of corrosion is very slow. This offers a cheaper storage option with a limited corrosion rate. Above 21% relative humidity both $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ and β FeOOH will contribute towards corrosion and rate of corrosion increases with rising relative humidity. Above 25% relative humidity corrosion becomes more rapid and is significant at 30% relative humidity. Keeping the ship below 25% relative humidity is much more beneficial for its survival than keeping it at 30%, where corrosion rates are about six times greater overall (see figures 6 and 7). If low relative humidity storage is chosen fluctuations to relative humidity values below 25% will produce limited corrosion, but rises to 30% relative humidity will cause significant increases in corrosion rate.

Overall this research has not only offered data useful for designing a controlled storage space, but also a tool for understanding and predicting the increase in corrosion rates expected with rises in humidity. The results that it produced must be interpreted in relation to their laboratory modelling. On the ship the iron is flat plate and there are overlying corrosion layers. This morphology may influence corrosion rates and loss of metal.

The conservation design

Cost and aesthetic considerations dictate the design of the controlled space around the hull. Similar criteria had influenced other designs for enclosing historic ships, where a national competition was used to find a design for the building to house the wooden warship *Wasa* (Hafors 1997). A structure to encase the whole of the ss *Great Britain* was rejected on the grounds of cost, major engineering issues and the aesthetic transformation of the heritage dock area. The solution adopted offers a visual concept of a floating ship with visitors able to explore below the waterline while inside the dry dock (figure 8). A glass water-covered horizontal plate constructed from the dockside to the side of the hull would enclose the chloride ridden lower section of the hull.

Within this space local drying of the hull will occur by dehydrated air channelled over its surface. Engineers and architects are responsible for designing plant and the new structure, taking into account operational parameters such as air leakage, solar gain, turbulence and temperature and moisture variation within the enclosed space. The interior of the ship is being refitted to represent various periods in the history of the vessel. The entire hull interior will form part of the controlled environment and will be sealed against the atmosphere. In this way science has been used to address the chemistry of corrosion and architects and engineers translate this into a control solution by overcoming the practicalities of environmental control.

It is energy differences that lead to the establishment of corrosion cells. It might be thought that making the lower region of the hull passive could establish a huge galvanic cell with the upper region of the hull. A number of factors mitigate against this. Mineralization, corrosion between overlapping riveted



Figure 8 Artists impression of the controlled space around the lower hull of the ss Great Britain.

plates and sections of hull replaced with epoxy resin offer electrical discontinuity and there is a range of metal compositions in the upper hull, which has a recent steel deck and assorted modern steel supports. There will also be an absence of electrolyte. No structural steel additions are added to the wrought iron by welding. Also the exterior of the hull is protected from the elements by a quality controlled protective coating system devised by Robert Turner of Eura Conservation Ltd. Solid areas of the upper hull have been totally stripped of corrosion by hydroblasting at up to 2500 bar and taken down to the metal. This is then coated with a two pack zinc rich wet application epoxy primer (Leigh L111) applied to a dry film thickness of 50 microns. The mid coat is a two pack epoxy (Leigh L653) applied to a dry film thickness of 125 microns, which is then top coated with two pack conservation grade urethane sheen finish (Leigh C237). The good chemical resistance of epoxy resins is combined with the good UV resistance of poly urethanes. Fragile areas of the topside are cleaned at low pressure of 8 bar using a Vacublast and Australian Garnet Powder. Thin surfaces are cleaned to SA2.5 and allowed to flash rust before being cleaned immediately prior to adding the Leigh's M111, which is tolerant of gaps between coating times. This coating regime allows for excellent weather resistance and offers a degree of protection against possible galvanic corrosion by limiting water and oxygen access.

No system is fail safe in its operation. The target relative humidity may not be constantly attained. It may fluctuate or operate above the specified level. To understand how such fluctuations would influence the rate of iron corrosion, Cardiff University is modelling the effect of high humidities and fluctuating humidity on the corrosion process, with long and short lived dwell times above the target relative humidity. This allows for predictions on possible damage to the iron hull if the plant controlling relative humidity failed. It also offers options to run plant more cheaply at values slightly above optimum relative humidity levels, in the knowledge that it is known what affect this has on the corrosion process and its rate. In this instance research offers opportunity for informed operational flexibility. Beyond this lies the task of designing a monitoring system to ensure that the desired operational parameters are met in practice and to aid their modification if this is necessary.

Conclusion

Devising a conservation plan for the ship required input from a very wide range of experts capable of solving specified problems. Their solutions were co-ordinated into a conservation design and action plan by an Executive Director, with extensive knowledge of the ship and the principles of heritage management and conservation planning. Implementation is overseen by a project manager, who ensures the various parts of the plan are delivered on time and to appropriate standards. A further tier of quality control was ensured via HLF accountability requirements. While the desiccation model tested and used for the *ss Great Britain* conservation design is simple, the project size and the technical challenge posed when instituting desiccation required a focussed centralised decision making process, backed by strong project management. This management successfully led and co-ordinated specialised input from hundreds of professionals from the private sector, through university researchers to heritage consultants, to support a single goal – the preservation of the *ss Great Britain* within the key parameters set.

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