Conservation Plan

for the

Great Western Steamship Company Dockyard

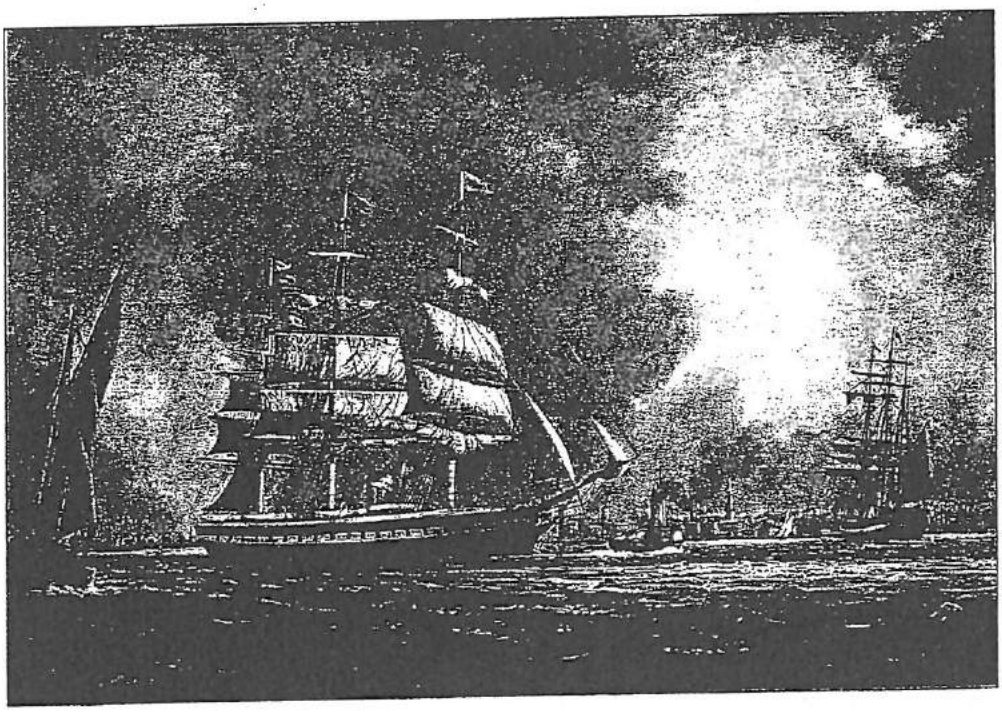
and the

ss Great Britain

Volume 2 - Condition Report and Recommendations for the ss Great Britain

Prepared by Eura Conservation Ltd
and the ss Great Britain Project

December 1999



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SS GREAT BRITAIN CONDITION REPORT

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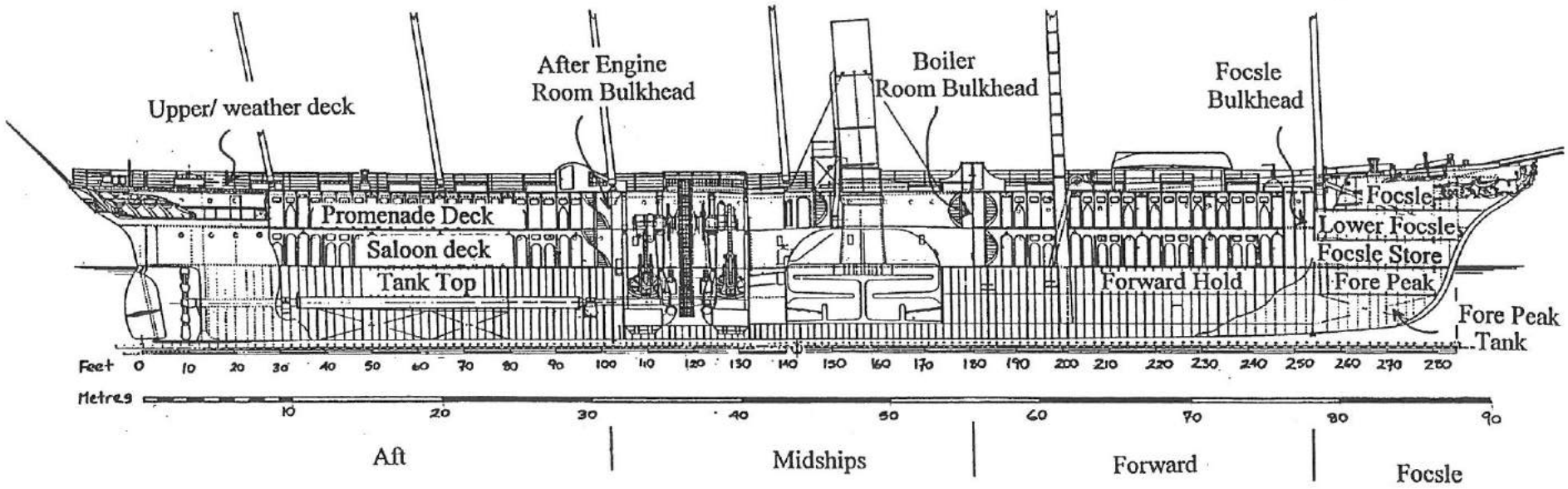

Figure 1 Inboard Profile of the ship, in her 1844 configuration

ss Great Britain Particulars

Length on keel	289 ft	(88 metres)
Length overall	322 ft	(98.1 metres)
Breadth Extreme	50 ft 6 inches	(15.4 metres)
Load Draught	18 ft	(5.48 metres)
Crew	130	
Passengers	252	

EXECUTIVE SUMMARY

1. This report describes the present condition of the historic fabric of the *ss Great Britain.* It assesses the condition in terms of any risks to the ship and presents options for treatment of the iron and for dealing with the ship's structure. These options are evaluated in terms of their ability to preserve the maximum amount of original material from the ship's working life, using the minimum intervention, and ensuring that any treatment is as far as possible reversible. Recommendations for the preferred approach are given.

2. The over-riding conclusion of the Report is that the hull is corroding at an accelerated rate, due to chloride contamination within the iron plating and frames. The Report finds there to be a marked contrast between the condition of the topsides (above the waterline), and the area below. The topsides show signs of the unexceptional electro-chemical corrosion to which all metals are subject, but the lower hull and the interior show signs of accelerated chloride corrosion, probably resulting from the ship's immersion in salt water for 120 years. In these areas the corrosion product are highly friable, and are spalling in large sheets of scale.

3. Conventional shipyard cleaning practices, such as grit-blasting, have been ineffective at removing these chlorides, and deleterious to the existing ironwork. A comprehensive survey of the hull interior and exterior has shown that since the ship was last cleaned a further 17% of the existing metal has corroded so badly that it would not survive these cleaning practices again, and that 43% would suffer major damage.

4. The Report considers it likely that, given current corrosion rates, major intervention to preserve the ship must occur within 3 to 5 years. If this does not occur, there is an ever increasing risk of partial structural collapse and loss of substantial portions of the vessel's original wrought iron fabric.

5. Threats to the ship from fire and explosion, as well as inundation should the caisson be breached, are also assessed as considerable.

6. The report shows that many of the treatments which are offered as options are ineffective at halting the effects of chloride accelerated corrosion, and thus will not deliver long term preservation of the ship. Of the remaining options which do deliver longevity of the metal, a number fail to do so in an achievable, cost effective, reversible manner. The Report recommends that the only way this can be done is through preservation in a controlled environment, with relative humidity kept at or below 20%, being the level at which electro-chemical corrosion will stop.

7. It is recommended that this environment be created by establishing a seal between the ship and the side of the dry dock, to allow dehumidification of the ship below the waterline, and by sealing the weather deck to allow dehumidification of the interior of the ship. This option will present the vessel in a manner that leaves her fully accessible to the public, and which aids visitor comprehension and interpretation.

SUMMARY RECOMMENDATIONS FOR CONSERVING THE SHIP'S IRONWORK

1. Pre-treatment documentation and survey

	Recommendation	Responsibility
1.1	Survey and document all pre-1970s material before, during and after the conservation process.	Curator & Conservator
1.2	Remove all extraneous, non historic material from the ship.	Curator

2. Monitoring of the ship and her environment

2.1	Expand current continuous monitoring regime of the ship's environment.	Curator & Conservator
2.2	Institute a complementary monitoring regime, measuring ship movement and the weights imposed on the ship's shores and keel.	Curator & Conservator
2.3	Replace the timber shores with purpose-designed, adjustable steel shores and supports, with attached load sensors. Link these to the environmental monitoring system.	Curator & Conservator
2.4	Institute a regular programme of vessel maintenance and cleaning	Curator

3. Dehumidification

3.1	Protect the ship from chloride-accelerated corrosion by removing moisture from the hull of the ship, and then maintaining the ship in a museum style controlled environment, at a stable relative humidity level at or below 20%.	Architect
3.2	Construct a seal between the ship and the side of the dry dock, to allow dehumidification of the ship below the waterline.	Architect
3.3	Construct the seal in the form of a glass roof, to give the overall impression to the visitor that the ship is afloat.	Architect
3.4	Extend the steel weather deck over the wooden bulwarks, and connect it to the ship's hull to form a seal, to allow dehumidification inside the ship.	Conservator
3.5	Support the glass roof independently from the ship, to ensure that the ship and the dock can move independently and that neither is restrained from seasonal or progressive movement and to reduce the load on the ship.	Architect

3.6	Dehumidify any room within the ship that is not in direct contact with the hull iron to a lesser degree than those in contact.	Architect
3.7	Dismantle all the outermost panelling of the accommodation and move it inboard, by at least ¾ metre, to provide a gap large enough for maintenance and a free flow of dehumidified air.	Architect
3.8	Place any machinery or ducting as unobtrusively as possible, and so as not to hamper other conservation treatment or research work.	Architect

4. The need for controlled humidity decrease

4.1	Regulate temperature or dewpoint within the dry dock and hull to prevent condensation on the hull.	Architect
4.2	Guard against galvanic corrosion of the area between the dehumidified metal of the waterline and the 'humidified' area above in the topsides	Architect, Curator, Conservator

5. Conservation treatment of the hull

5.1	Leave the vessel's topsides exposed to the environment, above the glass plane, to improve the quality of interpretation for visitors.	Architect
5.2	Clean the hull surface, consolidate areas of loose scale, and apply appropriate paint coatings.	Conservator
5.3	Clean the topsides to SA2 or SA2 ½, and remove and replace failing GRP.	Conservator
5.4	Remove the dome headed bolts on the hull exterior, if possible, and treat the resultant holes.	Conservator

6. Drainage and moisture control

6.1	Redesign drainage system within and from the ship	Architect
6.2	Reconnect the original lead scuppers to the hull.	Architect
6.3	Reduce the outlets from the hull to a minimum and pipe them directly to the dock waste water disposal system.	Architect
6.4	Consider provision of cloakrooms to reduce moisture, and encourage their use.	Architect

7. Improvements to services

7.1	Control the general use of gas and heat on the ship, and avoid it where possible. If no alternative, undertake risk assessment and control hot works. No heat is to be generated at least four hours before ceasing work, and all gas equipment will be removed from the ship and environs at the end of each working period.	Curator
7.2	Reduce risk of explosion and fire, and water vapour in the ship by siting the galley on the dockside, if the caterers cannot manage without gas-fired equipment. If the galley cannot be re-sited, it should be made all electric.	Architect
7.3	Remove the heating system from the after tank top hold and site it in a new plant room. Duct hot and/or conditioned air into the ship as required.	Architect
7.4	Place dehumidification equipment off the ship, if possible. The irregular offset to the port side of the dry dock might provide an appropriate place for such equipment.	Architect
7.5	Re-wire the electrical system of the ship and the surrounding buildings to reduce the risk of fire, increase safety and make the system more easily understood.	Architect
7.6	Strip out existing services rather than modify or adapt them. All new services should be appropriate to requirements and modern standards.	Architect
7.7	Fit a new, purpose designed automatic fire fighting system. This should be permanently active, fully accessible to all members of staff at all times, and not require coupling before use.	Architect
7.8	As an interim measure, permanently attach the three-inch fire main currently in use to a water supply.	Curator
7.9	Modernise, rationalise and, where possible, centralise the ship's services. Create a new plant room to accommodate main electrical distribution & control equipment, heating equipment, dehumidification equipment, pump controls and fire-fighting controls.	Architect

8. Structure of the Ship

8.1	Build a compound armature within the ship which relies on keel, bulkheads, stringers and frames to strengthen the ship's pre 1970's iron, and which allows public access, interpretation, and treatment of the ship.	Architect
8.2	Provide individual foundations for special concentrations of load.	Architect

8.3	The attachment method will have regard to the agreed hierarchy of intervention	Curator
8.4	Remove any modern concrete in the hull that is considered to be deleterious to the iron's chemical stability.	Curator, Architect

9. The dry-dock

9.1	Improve drainage into the sumps and ensure a higher standard of water-tight integrity of the dry dock entrance, walls and floor.	Architect
9.2.	Investigate the under-wall and floor structures to ensure the ship's support structures are adequate and that drainage is unimpeded.	Architect
9.3	Analyse the dock structure and condition, including taking photogrammetric survey and photography, and non-invasive survey.	Architect
9.4	Clean the dry-dock to enable a more comprehensive survey, remove all organic matter & litter, rake out joints, re-point using an appropriate mortar and re-set loose stones & bricks.	Architect
9.5	Establish a regime of maintenance cleaning and repairs.	Curator
9.6	Institute full, safe public access to the dock	Architect

10. The Caisson

10.1	Inspect and treat the caisson.	Architect
10.2	Construct a sheet piling dam across the entrance to the dock, to act as a physical barrier and protect against catastrophic failure of the caisson;	Architect
10.3	Pump out the water between the new barrier and the caisson to allow inspection and maintenance of the caisson.	Architect
10.4	Lift the caisson out of position, treat it and the dock seals and surrounding masonry	Architect
10.5	Use the sheet piling dam to form an anchor for a new pontoon allowing pedestrians to pass along the towpath across the dock entrance.	Architect
10.6	In the absence of a sheet piling dam, fit a boom or very strong and firmly anchored chain across the entrance to the dry dock.	Curator

SS GREAT BRITAIN CONDITION REPORT

1. INTRODUCTION

1.1. This report has been commissioned by the trustees of the ss Great Britain Project with the support of the Heritage Lottery Fund. The Project Monitors are Arnold Root (English Heritage) and Sam Hunt (South West Museums Council). It has been carried out over a period of 12 months from summer 1998 to summer 1999 by Eura Conservation Ltd, in close consultation with the curator and staff of the ss Great Britain Project, and with the kind assistance of a number of consultants, advisers and sub-contractors. These contributors are kindly acknowledged at Appendix A. The brief to Eura is attached at Appendix B

1.2. The purpose of the report is two-fold:

1.2.1. Firstly, to describe the condition of the historic fabric of the ship, *ss Great Britain*, as she stands today in terms of the materials from which she is constructed, the dry-dock environment in which she sits, and the purpose to which she is now put.

1.2.2. Secondly, to make recommendations or give suggestions for future conservation treatments and/or palliatives to address any issues identified in the survey of the ship's condition. These recommendations are based on preserving the maximum amount of original material from the ship's working life, using the minimum intervention, and ensuring that any treatment is as far as possible reversible.

1.3. The report serves as an adjunct to the research and conclusions of the full Conservation Plan[1] completed in 1998 and also supported by the Heritage Lottery Fund. The Conservation Plan has clearly established the significance of the *ss Great Britain* and her importance to British maritime and industrial heritage. Therefore, this report has considered the options available to the ss Great Britain Project trustees charged with responsibility for an object of this importance.

1.4. The main premise is that the original fabric of the ship up to her return from the Falkland Islands is of fundamental value, and the preservation of this fabric is the first priority of the ss Great Britain Project.[2] It is this fabric that provides the tangible link with her past and it is this fabric that the Project now wishes to preserve in perpetuity for the enjoyment and education of future generations.

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[1] Dr Joe Cox, January 1999, Conservation Plan for the Great Western Steamship Company Dockyard and the *ss Great Britain*, Vol 1

[2] Ibid, p110

1.5. Comment on the fabric of the ship is limited to pre-1970's elements, unless later materials pose a potential danger to those elements.

1.6. It should be recognised that the display of old, marine-exposed wrought iron in an exterior environment, is not at all straightforward and that the detailed specification of treatment will require ongoing research and discussion between the curator, trustees and the professional conservation team advising them.

2. PARAMETERS AND METHODOLOGY

2.1. The ship's condition was physically examined in detail by two professional metals conservators with extensive experience in the conservation, cleaning and preservation of exterior metal structures. Further, a detailed examination was made of the ship's internal support structure and external shoring by two separate firms of structural engineers. Investigation of other aspects of the ship's condition was undertaken by a variety of consultants and by staff of the ss Great Britain Project (see Appendix A).

2.2. The ship's condition was assessed from the following perspectives, which were thought to be crucial to understanding the present structure of the vessel and to presenting a unified strategy for assuring the vessel's future:

2.2.1. The condition of the **weather deck,** (see Figures 1 and 2) and particularly the extent to which it is capable of providing a water and weatherproof seal to the hull;

2.2.2. The condition of the ship's **visual appearance** internally and externally, and the condition of her paintwork;

2.2.3. The estimated level of frailty or **mechanical strength** of the ship's plates. This was accomplished with a visual and acoustic survey, in which 5254 separate points on the hull were tested lightly with a ball pein hammer.

Each point surveyed was referenced according to its constituent material (iron, steel, fibreglass etc), its location internally or externally, its frame location, numbered from the stern, and was given a condition rating.

It had been intended that ultra-sonic thickness measurement of the plates would provide information to give an absolute indication of the state of the plates, in comparison with a similar survey undertaken in 1968. In the event, no such similar ultra sonic measurements could be taken in 1998, as the hammering techniques used in 1968 to prepare the ship's corroded surface for ultra-sonic measurement were deemed by the consultant

conservator to be too destructive of the original iron-work.[3] Further tests were undertaken in November 1999 using repeat-wave ultra sonic equipment, which is capable of disregarding paint layers. These proved to be completely incapable of reading the wrought iron, with its slag inclusions, air voids and crystalline structure. Ultrasonic thickness measurements were taken of the steel in the topsides;

2.2.4. The extent to which the hull is contaminated with free or soluble **chlorides**, and what implications this has for corrosion and conservation treatment;

2.2.5. The condition of the ship's internal **structure** and external structural supports;

2.2.6. The nature of **physical risks** to the ship, and whether fire detection and control is adequate; and

2.2.7. The condition of the **dry dock** and the physical protection afforded by the **caisson** were also assessed, given their pertinence for ensuring the continued preservation of the ship.

3. DOCUMENTATION

3.1. An academic literature search on the subject of iron conservation, particularly in relation to a marine or high chloride environment, was carried out. The resultant bibliography is attached at the end of this Report.

3.2. The extant records of work upon the ship since her rescue in 1970 held by the ss Great Britain Project were examined, and discussions carried out with participants in the different stages of treatment that the ship has received since that time.

3.3. All survey work upon the ship has been documented by Eura Conservation using a grid reference system based upon the existing frames[4] and strakes.[5] Every fifth frame from aft has been visibly numbered at each deck level, and references to locations are made by frame number coupled with either strake number up from the keel, or measurement above internal decks.

3.4. Survey work and identified features were recorded by photography, and reports from advisers are included within or attached to this report as Appendices.

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[3] In one instance, the preparation of the iron plate for ultrasound testing actually pierced the plate..
[4] The ship has 163 wrought iron ribs or 'frames' spaced between 17 and 21 inches apart.
[5] The ship's outer hull is formed from plates butted together into 20 fore and aft runs of planking or 'strakes'. Each strake extends the length of the vessel from stem to stern, laps over its adjacent strake, and is double riveted to it.

4. THE WEATHER DECK

4.1. From a conservation point of view, the weather deck is probably the most important addition to have been made to the ship since she returned to Bristol. It provides a contribution to the structural stability of the ship, and acts as a roof to all internal elements.

4.2. The weather deck has two main elements: a mild steel plate deck and an overlying wooden deck separated by an air gap.

The steel deck

4.3. The steel deck, which was partially funded by the National Heritage Memorial Fund, was laid down in 1995. The deck is 8 mm thick,[6] and is welded onto short sections of steel angle-iron which are themselves welded to the ship's weather-deck beams. The steel deck is covered with a bituminous coating, and has a slight camber, designed to allow it to shed water from the centreline of the ship towards the beams.

4.4. The steel deck was designed to replace a failed traditional deck system, and while it provided an excellent step forward in generally protecting the ship's interior from weather and water ingress, it provides such protection around the edge of the deck only partially. This is because an attempt has been made in a number of places to retain the timber pieces of the bulwarks by butting the steel to the inside of the wooden bulwark. The join cannot be completely watertight, and during periods of rainfall, water drips into and around the wooden bulwarks, leaving large parts of the ship's interior sides (and particularly the focsle) wet. A diagram showing the beam-ways extent of this deck is provided at Figure 2. The bulwarks themselves are in some danger from the effects of wet rot, as noted in the survey of the Ship's timber elements.[7]

4.5. The steel deck directly above the bow end of the focsle deck is covered merely with a layer of concrete. This concrete acts as a water collector and may also be contributing to a build-up of condensation on the under-surface of the steel deck at this point.

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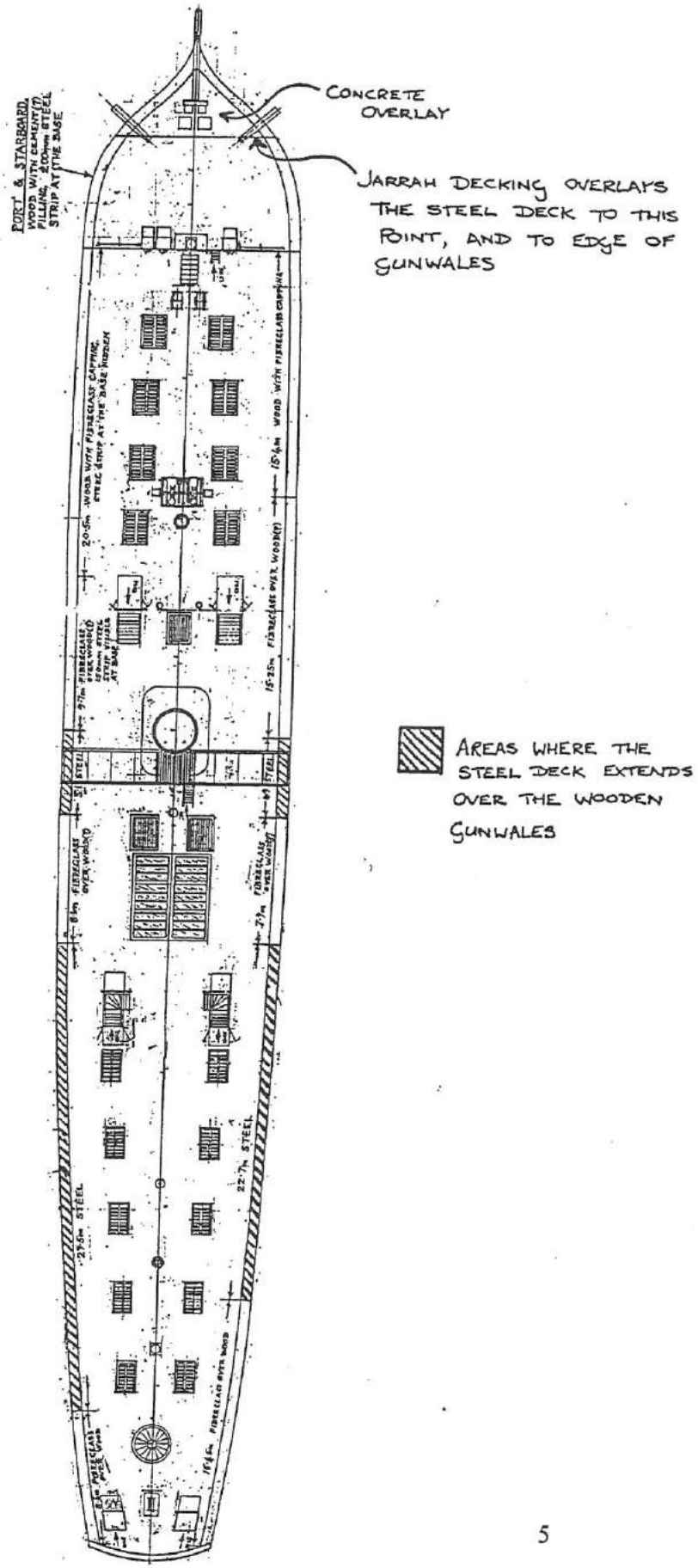
[6] This dimension has been confirmed through ultra-sonic thickness testing performed in November 1999.

[7] Dr Derek Sinclair, March 1999, Condition survey of timber elements of the steam ship *Great Britain*. Scottish Institute of Wood Technology.

Figure 2 Plan view of the ship showing the extent of the 'new' steel deck



The wooden deck

4.6. Overlying the steel deck other than in the area above the bow end of the focsle deck is a wood plank deck, consisting of planks of Jarrah hardwood 4.5 cm thick, 12 cm wide, and averaging 360 cm long. Between the wooden deck and the steel deck is an air gap of 3 cm on the focsle deck, and 5 cm on the rest of the deck. This gap is designed to allow ventilation and more rapid drying of both wood and steel decks. The wooden deck is caulked with a modern two-part poly-sulphide compound. This caulking is in generally good repair. There are, however, 52 runs of seam where the caulking has visibly separated slightly from one or both sides of its adjoining timber planking. From the focsle to engine skylight, there are only 4 such separations of caulking. From amidships to the stern however, about one in 20 caulked seams is separating from its adjoining planking in lengths of up to 1.5 metres. It is uncertain whether this is allowing rainwater to seep through to the steel deck underlying it, as the inter-plank gap narrows considerably below the level of the caulking, with a gap of only 3 mm.[8] The steel deck is in any case able to accommodate such rainwater.

Drainage from and within the ship

4.7. Water running off the wooden deck or collected by the metal deck underneath flows into a steel channel integral with the metal deck, running just in-board from the bulwarks along the full length of the ship. Into this channel are drilled thirteen drains which connect into a system of metal piping on the interior of the ship. The piping leads to some of the 8 holes drilled into the starboard of the ship and 9 into the port, all of which drain directly onto the dock floor. Most of the drain holes have external runs of piping or tubing leading out through the hull, which allow draining water to clear the hull. Others merely allow the water to dribble down the hull.[9]

4.8. The piping system, installed in the mid 1970's, has not been fully married with the new steel/wood weather deck, and leaks are apparent both in the forward hold, and aft on the promenade deck. Some runs of pipe-work have not been completed. On the port side of the hull are 4 original lead-lined scuppers,[10] and on the starboard side 2, which also form part of the water drainage system. These were all disconnected during the building of the metal deck and only one (starboard amidships) was reconnected. If the scuppers were to function correctly, they would run out through the ship's side and discharge either directly onto the floor of the dock, or in the amidships part of the hull, onto the side of the ship thence the dock.[11]

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[8]Captain Chris Young, RN, 1999, Personal Communication,

[9] Maurice Ball, 1998, Report on scuppers and on-ship drainage see Appendix G

[10] These are shallow lead-lined openings (about 6 inches wide) cut through the waterways and bulwarks of the ship, to carry water off the deck into the sea.

[11] Maurice Ball, 1988, op cit

4.9 Apart from the drainage problems mentioned above, there are a considerable number of leaks from each of the 19 wood framed sky lights, the 62 hull side scuttles or portholes, from corrosion holes in the upper face of the hull side, and in the deck around the foremast and bowsprit bitts and the nightheads.[12] These leaks are listed in Appendix H These are causing disfiguring stains and contributing to high levels of humidity and to corrosion.

5. EXTERNAL PAINTWORK

5.1. The uneven quality of the ship's external painted finish is obvious. It ranges from a complete covering of paint in the best preserved areas, to a complete covering of products of corrosion in the worst preserved areas. The surface often has a superficially good appearance disguising considerable corrosion underneath. This is due to the strength of the paint film and the nature of the products of corrosion, which have the ability to form strong plates of scale underneath.

5.2. The hull is covered with a variety of paint types or schemes. Discussion with Commander Joe Blake, the first Director of the ss Great Britain Project, and reference to the minutes of the Project's Dock/Ship Committee show that there were three main schemes:

5.2.1. Initial treatment of the rescued hull with 10,000 psi water blasting followed by gas flame cleaning/drying. Lead paint was applied to the resultant surface while the metal remained warm.[13]

5.2.2. A second phase beginning in 1980 included the application of phosphoric acid and lead paint.

5.2.3. A third phase cleaned parts of the hull with needle guns to remove easily detachable corrosion products, and followed with application of a rust conversion treatment (Fertan), red lead primer, plus a conventional ship undercoat and top coat. This system was designed to give a life of approximately 5 years, after which time the complete coating was to be removed and the treatment reapplied.

5.3. The most recent scheme, together with other restoration work, was halted in 1997 by the Curator for thorough review and a reconsideration of all the ship's conservation management and her presentation to the public. This Condition Report is part of that review.

5.4. The major factor determining the current state of the paintwork is probably the amount of time that has elapsed since it was applied. The effects of ultra-violet degradation, the effects of pollution, erosion from wind and rain, and

[12] These are stout timber uprights near the stem of the vessel on each side of the bowsprit

[13] Dr Ewan Corlett, 1990, The Iron Ship The story of Brunel's ss Great Britain, Conway London p177

the corrosive, unstable nature of the metal surface which the paint overlies, combine and grow progressively worse with time.

5.5. The paint film itself may in some circumstances be contributing to the iron's corrosion. Where the bond between the paint film and the iron becomes broken, moisture, oxygen and chlorides can become entrapped close to uncorroded ironwork. Where this happens, the paint film is contributing to the corrosion process, but also allows it to remain unseen for a considerable period of time. Only when the products of corrosion expand so as to physically rupture the paint film does the true extent of the damage become easily apparent.

6. WROUGHT IRON HULL PLATES AND FRAMING

General description of plating

6.1. The ship's hull is constructed of wrought iron plates, each one around 1.8 metres long and varying between 0.4 and 1.2 metres in width. These are shown in Figure 3. On average they are about 0.75 metres in width. When first built, the plates varied between initially 12 mm and 21 mm thick. Moving up the hull from the garboard strake (nearest the keel) to strake 5, each plate's topmost edge laps over the outside of its upper neighbour. This changes at Strake 6, which overlaps strake 5 on the inside, in the manner with which a conventional lapstrake or clinker boat is fastened.[14] This system continues up to strake 16 just below the white band around the ship's hull.[15] Strakes 17 and 18 are butted flush to one another, and strake 19 overlaps strake 18 as before.

6.2. Each plate is fastened to its neighbours above and below with a double line of flush rivets. Each plate butts onto to its lengthwise neighbours with a single line of rivets, which pass through butt straps on the interior of the ship. The rivets are standing well proud of the surface in areas that have been cleaned back with needle guns. Generally, strakes which had been under the 1882 wooden sheathing (from strake 9 and upward) appear thicker and in a better state of preservation than those below, with the rivet heads appearing flush with the surface

6.3. The hull's external appearance is dominated by vertical rows of dome-headed bolts between strakes 9 and 17. These bolts were fitted in the early 1970s as a cosmetic measure, to fill the holes left by the removal of the 1882 timber hull cladding, but are non-historic and are visually extremely distracting, given that the original rivets are countersunk. However, they may contribute to the fixing of the plates to the frames since most of them pass through frames.

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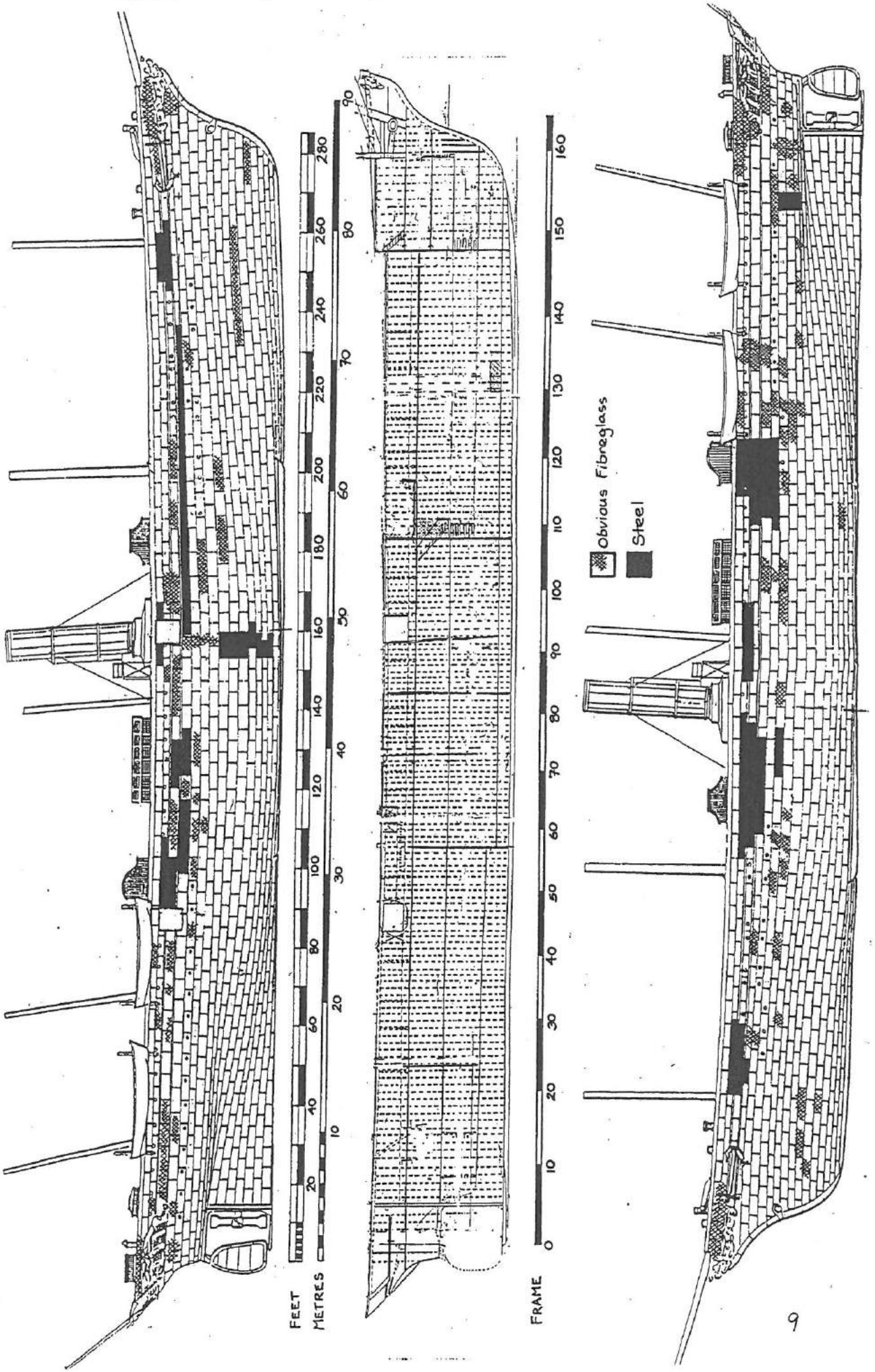
[14] Captain Claxton, 1845 noted that "in pitching or dropping each lap resists a little, and the combined resistance of as many edges as in heavy weather may meet the water would be equal to that of a flat surface of 8 or 9 inches on each side of the bow or quarter." in A description of the Great Britain Steamship built at Bristol for the Proprietors of the Great Western Steam ship Co, Bristol.

[15] Corlett, 1990, The Iron Ship, op cit, p41

Figure 3 Diagram showing relative areas of iron,steel and fibreglass



Extent of visible corrosion

6.4. The hull shows visible corrosion, especially in the areas underneath the docking keels and on the lower starboard side of the hull, from frame 90 to frame 130. The ship's port side has been extensively needle-gunned, as was the starboard side from the bow down to approximately frame 130. Areas not needle gunned are still covered by thick corrosion scale, ranging in thickness from 3 mm to 10 mm.

6.5. In these areas, perforation of the plates is common, with large plates of corrosion product, covered by paint, separating from the surface. These plates range in size from 25 mm diameter and 0.5 mm in thickness to over a metre long, about 200 mm wide and in parts 10 mm thick. The presence of such large pieces of corrosion scale does not necessarily mean that the same thickness of iron has become detached from the ship, however.[16] Rather, this spalling effect is due to the volumetric expansion of existing corrosion products, which cracks the overlying paint coating, allowing oxygen and moisture in and further accelerating the corrosion cycle.

6.6. Because of the volumetric expansion of the corrosion scale, it is both difficult to measure the existing thickness of sound metal, and to make a measured assessment of the rate of loss of iron under the paintwork. However, the large quantities of corrosion that can be seen under some of the paint (and inside the ship) lead to the conclusion that the loss rate per year is considerable, and is probably more likely to be measured in fractions of a millimetre rather than in microns. This is supported by the findings of an 1872 Lloyds survey which showed that the vessel's hull plates were thought to have reduced in thickness by between 15% and 20%, or between 0.5% and 0.7% annually. A further investigation of the hull plating in 1968, found the average hull plate thickness to be in the region of 7 to 9 mm thick, implying a loss of up to 40% of thickness between 1843 and 1968, or 0.3% per annum[17].

6.7. An assessment of the relative frailty of the iron plating as it is now was achieved using the visual and acoustic testing methodology explained in Section 2.2.3. Figure 4 below illustrates the summarised results from this testing, while the full results of the survey are presented at Appendix C in alpha-numerical tabular form.

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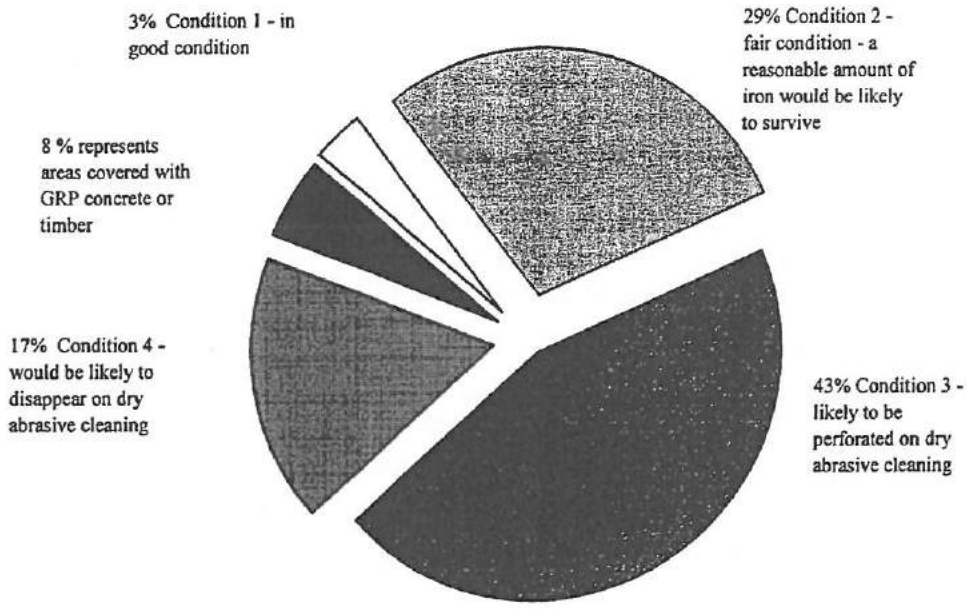
[16] Fullalove, L, & Turgoose, S, 1992, Draft Report on survey of the condition of the ship's hull. (unpublished)

[17] Corlett, 1990 The Iron Ship, op cit p165. Corlett found that the bulk of This compared with. The implication from this is that while the vessel was in operational use, undergoing perhaps more frequent ship-yard cleaning, she may have incurred a more rapid reduction in hull thickness than while she was abandoned.

Figure 4 – Condition of all tested plates



6.8. The survey largely confirmed what was visible externally. It shows that the ironwork below the waterline is generally in poor condition, with spalling, friable corrosion products and exhibiting signs of substantial chloride accelerated corrosion, inside and out. This is particularly bad under the docking keels. It further confirmed that the traditional 'shipyard' cleaning approach to which the ship has been subject over the past 30 years has been largely unsuccessful in stabilising the ship's corrosion. The survey showed that there had been considerable deterioration in the hull fabric over that time.

6.9. The survey results in particular show that:

6.9.1. Of the hull plates examined, about 17% are graded as 'condition 4', displaying very severe corrosion, with parts missing. This plating is likely to become lace-like or non existent if it is dry-blasted at a pressure sufficient to remove the corrosive products, or if it is cleaned with abrasive methods;

6.9.2. A further 43% are graded as 'condition 3', displaying severe corrosion, and likely to be perforated and degraded by abrasive cleaning;

6.9.3. In about 28 % of the hull plating examined, there was found to be corrosion, but the plates probably had sufficient iron remaining to withstand dry blast cleaning (condition 2);

6.9.4. Only 3 percent of the hull plating examined was found to be in comparatively good condition with a strong probability of a reasonable amount of material remaining (condition 1).

6.9.5. The condition of the hull, both port and starboard, was roughly comparable in terms of the extent and nature of the corrosion product, with no discernable patterns emerging

6.9.6. About 77 % of the testing was performed on iron plates - the rest of the testing was done on areas of steel or glass reinforced plastic. These areas were generally in the topsides, above the waterline.

6.10. Visual inspection demonstrates that corrosion products in the area below the waterline is substantially different from the products seen in the topsides above the waterline, where there is virtually no spalling to be seen. In the upper areas, the effects of corrosion are seen in the form of rust streaks and patches, with the appearance actually worse than the underlying condition. This can be seen, for instance in the three strakes below the gunwale. There are two suggested explanations for the differences in corrosion product between the two areas.

6.10.1. First, that there is a quantity of modern steel and fibreglass in this area, as seen in Figure 3. As steel produces less voluminous scale for a given conversion of metal to oxide than does wrought iron, there is correspondingly little scale to be seen. Ultra sonic testing of the thickness of the steel in the upper works revealed average plate thickness of between 6.2 mm and 6.4 mm, virtually the same as the 6 mm inch plate installed in the early 1970s.

6.10.2. Second, that the corrosion product on the wrought iron is indicative of the different environments to which the above and below waterline areas were exposed during the vessel's working life. During that period the ship's topsides and her areas near the bow wave waterline and in the wake of the propeller were exposed to heavily oxygenated water, salt spray, and alternate wetting and drying cycles. They were consequently at great risk from corrosion. As found by the ss Great Britain Project, on the ship's return from the Falkland Islands they were found to be in a poor state of repair.

6.11. This may explain why parts of the topsides had to be replaced with modern materials, and also why strakes 7 and 8 near the bow wave became so perforated. On the port side, strake 8 is perforated from frame 129 to frame 140. Strake 7 is perforated from frame 132 to the bow. Strake 6 is perforated in a minor way, around frame 135. On the starboard side, Strake 7 is perforated from frame 150 to the bow, and Strakes 7 and 8 are also perforated between frames 140 to 146, and 79 to 86. These areas of perforation have been covered on both port and starboard with fibreglass patches.

6.12. The lower hull, meanwhile, was usually underwater, had little exposure to free oxygen, and was relatively protected from the effects of corrosion. However, it become thoroughly contaminated with chlorides from the sea water. On return from the Falkland Islands, this part of the hull was exposed to the open air, where chloride enhanced corrosion rapidly began to take effect. This may explain why so much of this part of the hull was clean and well defined when first refloated in the Falkland Islands, and why it is now spalling so badly.

6.13. On the port side, this spalling is most apparent on strakes 1, 2, and 3, with the whole area between frames 64 and 115 (basically the area under and around the docking keels) showing much corrosion.

6.14. The corrosion appears far worse on the starboard side however. There is heavy spalling of strakes 1 to 8 from amidships forward to frame 138. Needle-gunning appears to have been undertaken from the bow aft to frame 138. From frame 91 (near the crack) to frame 107 on strakes 1 to 7 there is heavy corrosion spalling, ranging between 5 and 10 mm thick, in large continuous bands up to a metre wide. There is intermittent spalling of starboard strakes 1 and 2 all the way to the stern of the ship. Where this spalling overlies bands of riveting, it gives the deceptive appearance that the whole plate has popped its rivets. The modern steel plates covering the crack (see below) have decayed badly, with the steel around the attachment bolts having in some cases completely decayed.

6.15. Most areas that were needle-gunned are presently paint coated, with the underlying structure not available for inspection. When small uncoated areas were examined in 1992, they revealed that the needle-gunning had removed all but a thin layer of hard black magnetite corrosion from the surface. However, the surface profile was such that chlorides could be expected in widespread corrosion pits.[18]

6.16. On the port side of the hull, strakes 10, 11, 12, and 13 from frames 83 to frames 112 appear not to have been needle-gunned. These areas have an obviously more degraded paint covering, with a line of exposed metal visible on strake 10. Paint is peeling off strake 13 in small 'blisters' however. The corrosion product is not forming in large plates as is happening in the lower parts of the hull.

[18] Fullalove & Turgoose, op cit p2

Damage, stress corrosion, and man-made holes

6.17. At frame 10 on strake 10 on the port side, a small crack (no more than 1 mm in width) is visible in the paint covering the butt join between the two plates. While alone this would give no cause for concern, it is matched by an area of blistering paint and corrosion product on the same frame at strakes 11, 12, 13, and 14. This might be indicative of stress corrosion.

6.18. On both sides of the hull between frames 115 and 126, what appears to have been a 19th century repair to the hull has been made, with four plates applied to strakes 9 and three plates on strake 8. The original repairers made no attempt to hide their work. It is in good condition on the port side, but on the starboard side the lower riveted surfaces have sprung, and the butts between plates are highly visible.

6.19. On the port side, at strakes 3,4, and 5 at frame 139, there are signs of impact damage, with plates depressed inwards, and a large hole visible at stake 5 and stress corrosion visible at strake 4. This damage may have been the result of storm damage from the ship's last working run to Port Stanley in 1886, or from the vessel striking an object at some other time. The hole at strake 5 has been patched with GRP.

6.20. On the starboard side, between frames 90 and 93, a large crack is visible in the hull, extending from the from the sill of the forward entry port to the docking keel. When the ship was scuttled at Sparrow Cove in the Falkland Islands, wave action under the hull produced a deep scour on the Starboard side, which led to the ship hogging and splitting down the hull[19]. The crack was covered by steel plates which have now heavily corroded.

6.21. At frame 137 on the starboard side, there appears to be a line of corrosion from strakes 4 to 12. One of the starboard side's scuppers is in direct line with this corrosion, possibly indicating that the corrosion was caused by water flowing from this feature.

6.22. Since 1970 75 holes of varying size have been cut into the hull of the ship, including the "drawbridge exit" door cut out at the aft end of the dining saloon and 14 regularly spaced holes through the hull on the starboard side of the hull between frames 59 and 74 (under the docking keel) on strake 4. Included also are large rectangular air vents cut into the port side for the heating system at the locations shown below in Table 1.

6.23. There are also a considerable number of holes generated by the iron corrosion. These are particularly evident on the starboard of the hull, near strakes 7 and 8, centred around frame 125. These holes allow moisture and pigeons into the hull, are visually distracting, a source of corrosion and a potential cause of local weakness.

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[19] Corlett, 1990, The Iron Ship, p 165

Table 1 – Port side Air vent aperture locations and dimensions

Frame No	Strake number, measured from keel up	Width of opening (m)	Height of opening (m)
15	5/6	0.5	0.5
48	8/9	0.5	0.5
60	11	0.5	0.25
83	8	0.5	0.25
104-106	8/9	1	1

Glass Reinforced Plastic

6.24. Glass reinforced plastic (GRP) has been used extensively for patching holes in the hull. Originally, epoxy resins were used below the water line and polyester above. All polyester patches have been subsequently replaced with epoxy resin.[20]

6.25. GRP is an excellent material for the cosmetic patching of holes in wrought iron, being light in weight, waterproof, and easily sculpted, textured and painted. However, as with paint, it is prone to becoming detached where the bond between it and the metal to which it is attached breaks down, leading to corrosive micro-environments and the increasingly rapid corrosion of the underlying iron.

6.26. This damage appears to have occurred in some areas of the hull, with the GRP patches easily visible and obviously detaching. This can be seen on the port aft quarter, at the junction between strake 19 and the gunwale. Generally, although the fibreglass can be differentiated visually from the iron because of its surface texture, it appears to have adhered quite well to its surrounding metal. (Figure 3 shows the areas of visible fibreglass). However, some areas appear to have been extensively covered with GRP, with only products of corrosion below. This is particularly the case with strakes 8 and 9, near the bow and stern, which were subjected to highly oxygenated water during the ship's life. It is not known if these are areas of corrosion that were consolidated or reinforced with GRP, or areas of original iron that have oxidised since the application of the patches.

6.27. GRP in a wet environment is also prone to osmosis and wicking. This can lead to an accelerated weakening of the GRP with increased corrosion of the underlying iron. This may play a part in accelerating localised corrosion of the ship around such patches.

[20] Captain Chris Young, RN, Personal Communication, July 1999.

Hull interior

6.28. The condition of the inside of the hull is extremely varied. Following the ship's return from the Falkland Islands, the whole interior was pressure washed, and some areas of the forward hold were coated with chlorinated rubber.[21] Public areas such as the after promenade deck have been regularly painted in the same manner as for the exterior, and show no apparent signs of major corrosion or staining, giving the impression that the ironwork is in good condition.

6.29. Other areas of the hull, such as on the saloon and midships promenade decks, are given over to accommodation of various kinds, including the galley, much of which is built close to the hull and so prevents examination of the adjacent internal ironwork. This militates against day-to-day inspection and maintenance because of the seriously disruptive work involved in opening up these areas. Ultimately, this will work to the detriment of the ship. Access to the hull sides is generally easier in those areas of the ship that are not open to the public and have not been refurbished.

6.30. There is corrosion obvious in those parts of the ship that are not regularly painted, such as the forward hold, the boiler room, and the after tank top. This corrosion takes the form of the same plate-like encrustations of scale visible underneath the docking keels on the hull exterior. The underlying cause of this corrosion is probably the influx of salt water which flooded the ship when she was beached in the Falkland Islands. By the beginning of 1999, scale delaminating from the plates in the boiler room had built up at the juncture between tank top and hull to form mounds 30 cm in depth. These mounds were themselves found to be harbouring moisture, and exacerbating the corrosion process. In this area, and in areas not open to the public, such as the rear tank top, the overall impression is one of serious corrosion. The rate of loss of material appears to be of the same magnitude as the spalling on the outside of the hull in the midships area

6.31. There are considerable amounts of equipment, spare parts, rust scale and rubbish stored in the upper focsle, the engine room, boiler room and the after tank top. These increase the load on the ship, hold moisture and restrict the free flow of air. These factors do not contribute to the conservation of the ship's iron. A programme to clear these areas is underway.

Chloride contamination in the wrought iron

6.32. The differing nature of the corrosion products seen on the exterior of the hull above and below the waterline may be explained by the variations in environment to which these parts were exposed during the ship's working life - namely that the areas below the waterline were protected while the hull was immersed, while the topsides were under constant threat from spray and wet

[21] Fullalove & Turgoose, op cit.

and dry cycles, and from aerated water action.[22] Once the hull had been brought back to the relatively humid air conditions of the Great Western dry-dock, chloride-accelerated corrosion began in earnest on the lower hull.

6.33. In the presence of moisture and oxygen, these chloride compounds accelerate the ordinary electro-chemical corrosion process to which iron is subject, and they also combine with the chemical constituents of water, oxygen and iron to produce further corrosive compounds.[23]

6.34. A program of testing was designed to determine whether such chloride contamination exists, and if so, to determine if there was any consistency in its quantity and distribution.

6.35. To this end, a Soxhlet extraction system was selected as the best means of achieving these objectives. Although it does not remove all soluble chlorides from a given sample, it was considered to be safer, easier and more cost effective than other methods such as alkaline sulphite extraction, high-temperature high-pressure washing, or repeated aqueous boiling.[24] It was also considered to be more reliable in revealing the presence of chlorides than the use of Potassium Hexacyanoferrate papers.[25] The Soxhlet system removes some free or soluble chloride components from solid corrosion samples by subjecting the samples to repeated flushing with heated de-ionised water solvent. The solvent is then tested for chloride levels using reagent tablets.

6.36. This method and the sampling techniques were similar to those used by Hampshire Museums Service in their work on conservation of the Monitor M33, and in their testing of samples from Cutty Sark and HMS Belfast. A full description of the test method, apparatus used, and the results recorded for the *ss Great Britain* are at Appendix I.

6.37. The test results showed that free or soluble chlorides **are** present in elevated quantities within the hull metal (see Figure 5). Levels of up to 180 parts per million (ppm) were recorded internally, and 300 externally. Most levels internally were between 30 to 80 ppm (Bristol tap water measured using the same reagent tablets exhibited a level of 30 ppm, whereas standard de-ionised water exhibited 5-8 ppm.)

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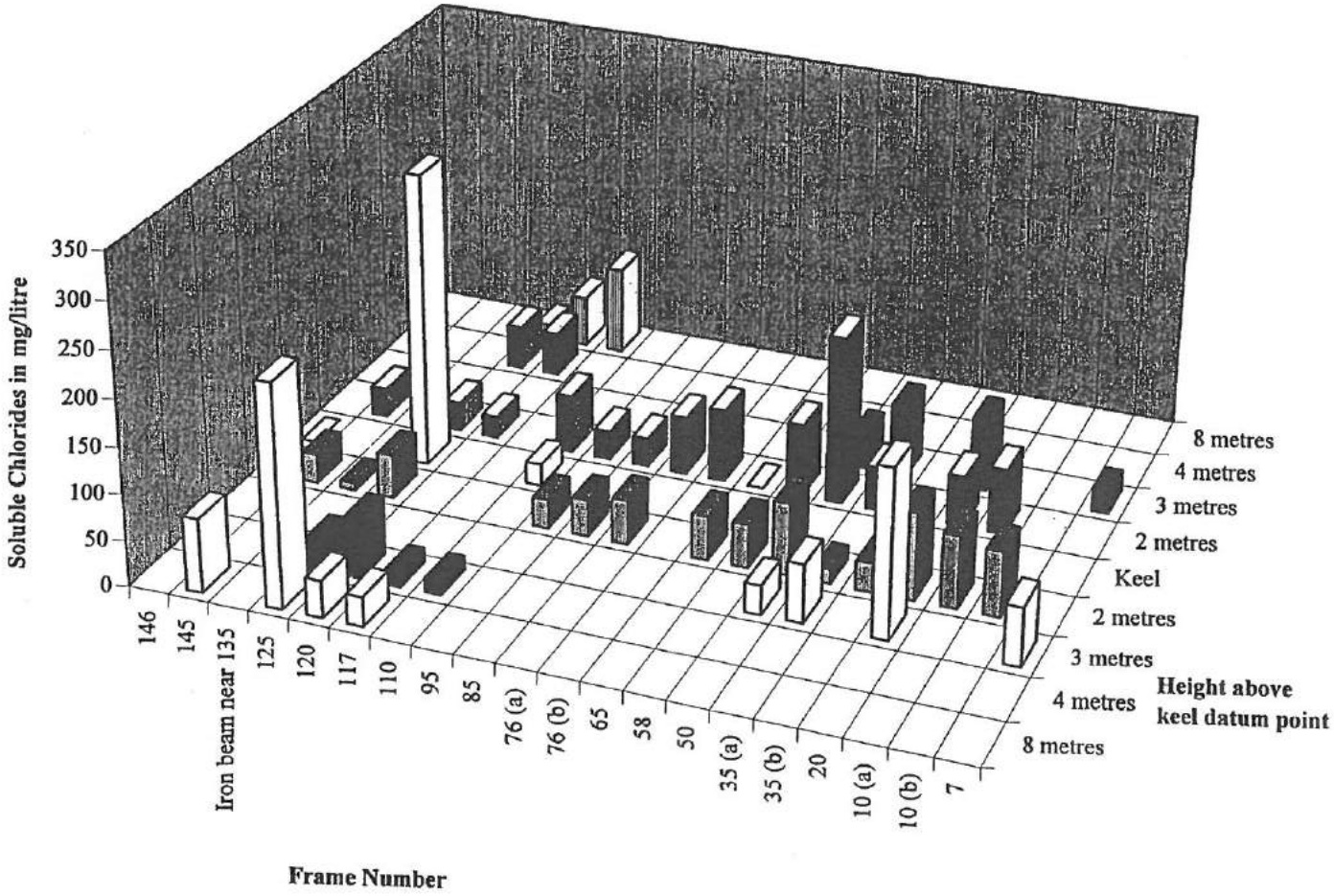
[22] Corlett E, The Iron Ship, op cit p166 notes that the crew of HMS Endurance found in 1968 that the bow wave area could be penetrated by repeated hammering, but that this was quite localised.

[23] For a discussion of this process, see for example North, N, and MacLeod I, 1987, 'Corrosion of Metals' in Pearson ed, Conservation of Marine Archaeological Objects, Butterworth

[24] Watkinson, D, 1996, discusses the relative efficiency of the various methods in Chloride extraction from archaeological iron: comparative treatment efficiencies, in Archaeological conservation and its consequences, International Institute for Conservation of Historic and artistic works. London

[25] K Blackney, and B Martin describe the use of such papers in Development and long term testing of methods to clean and coat architectural wrought ironwork located in a marine environment. English Heritage Research Transactions Vol 1 There they noted that the papers had in some instances failed to detect chlorides, due to the salts being harboured within the fibrous wrought iron, and thus not coming into contact with the paper. (p114)

Figure 5 - Soluble Chloride Contamination



Soluble chloride levels are being measured on 2, 3, 4, 6, and 8 metre waterline intervals throughout the hull, measured from a datum on the keel near the mainmast. Where the same frame is shown as (a) and (b), two independent tests were made.

6.38 Internally the distribution of chlorides showed little consistency longitudinally or in waterline heights. It is present from stem to stern, and keel to 10 metre level, with high and low readings almost side by side. No trends were apparent. The whole interior of the vessel is contaminated to various degrees.

6.39 Some of the highest chloride levels were recorded in samples from within the iron box girder at the 8 metre level. This reading was probably due to the fact that these areas acted as dams or water traps, and may never have been adequately flushed with fresh water as was the rest of the hull.

7. CONDITION OF THE TOPSIDES

7.1. Corrosion samples could not be taken on the interior of the hull on the promenade deck aft or amidships nor on the saloon deck aft. Most of these areas are covered with well-adhering paint, and there was little obvious active corrosion evident. Nor could samples be taken on the hull exterior above the waterline. The latter difficulty demonstrates a clear difference in the condition of the exposed upper works in contrast to the under body of the hull.

7.2. The lack of corrosion may be due to a number of factors :

7.2.1. First, as noted earlier, her topsides were less contaminated with chlorides because they were never submerged in salt water, but only exposed to the effects of spray and wave action

7.2.2. Second, it can be presumed that during her working career, her topsides were more regularly painted and kept rust-free than the area under the waterline. Since the 1970's additional heavy layers of paint have protected this area from moisture and/or oxygen

7.2.3. Third, for at least the past thirty years, the vessel's topsides have been subjected to the effects of repeated rinsing with rainwater, which have diffusing the soluble chlorides out of the metal and into solution. This conclusion is supported by earlier analysis by Sandberg Consulting Engineers,[26] who conducted tests on four corrosion samples, taken from separate pieces which had been in the open air and rain for many years. They concluded that the low chloride levels in those samples were due to the samples having been subject to regular rain washing. This effect would have been pronounced on areas of tumblehome,[27] where the hull plates presented a flatter surface to falling rain than, for instance, areas at the bow or stern. Water diffusion is an accepted and valid

[26] Sandberg Consulting Engineers, Report 17499/M/01 Testing of structural materials ss Great Britain. 2 October 1998.

[27] Part of the hull above the maximum beam where the ships sides curve gently inwards, and is thus exposed to vertical rain fall.

conservation treatment for removing soluble salts,[28] but as it requires such a lengthy treatment process, and the extraction rates are so slow, it is generally not used.[29] In the case of the *Great Britain*, however, she is lucky to have had the benefits of 30 years worth of such treatment on one part of the hull.

7.3. Although the effects of water diffusion may have been beneficial to the topsides, this may not have been the case in the lower part of her hull, where chloride levels of up to 300 ppm were recorded externally. It is conjectured that some of the soluble chlorides which diffused from the upper hull were simply re-deposited lower down. The fact that this part of the hull has unusual 'reverse lap' strakes may have aided this deposition, by providing a ledge or settling area on the top edge of each strake.

7.4. In conclusion, therefore, the testing regime confirmed the presence of high chloride levels within the *ss Great Britain*'s iron fabric. Such high chloride levels may explain why the lower hull is deteriorating at a higher and more visible rate than the topsides.

8. ENVIRONMENTAL MONITORING

8.1. Until 1997, no environmental monitoring had been undertaken, within or around the ship. Since then, temperature and relative humidity inside the ship has been monitored continuously through a radio data logging system downloading to a computer in the curator's office. There are five battery powered sensors in addition to an exterior environment sensor. The computer is running with Meaco Museum Monitoring software.

8.2. This monitoring system was purchased in 1997 with financial assistance from the South West Museums Council. This system provides continual records of humidity and temperature in most of the major compartments of the ship: the focsle, forward hold, forward promenade deck, dining saloon, and aft tank top.

8.3. The monitoring has shown there to be generally high levels of relative humidity inside the vessel. Fluctuations in both temperature and relative humidity were experienced on a diurnal and seasonal basis in all areas monitored, and variations were seen between one part of the ship and another, within the same time frame. There is evidence of a minor buffering effect in relative humidity between the exterior and interior. The graph below is representative of typical data for relative humidity and temperature in the forward hold and externally. over several days

8.4. Given that corrosion of iron slows only when relative humidity drops below 40% and stops completely only when a relative humidity level of 20% or

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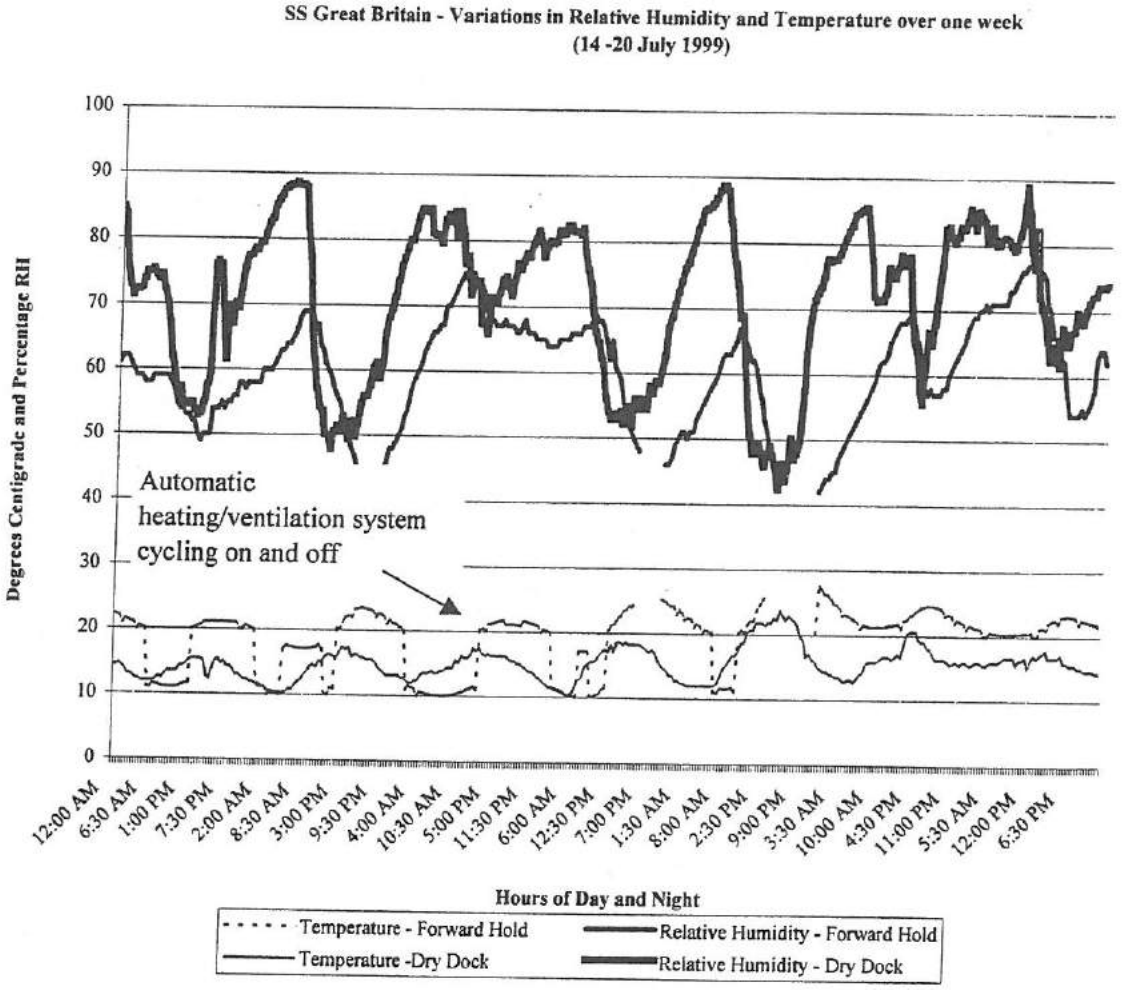
[28] Thompson, J, ed, 1992, Manual of Curatorship. A guide to Museum Practice. 2nd edition. Butterworth, Oxford p359

[29] MacLeod I North N, 1982, Conservation of a composite cannon, Batavia (1629), International Journal Of Nautical Archaeology 11.3, 213-219, & Hamilton 1999

below is achieved,[30] this environment is clearly extremely deleterious to the life of the ship's hull. In the case of the *ss Great Britain*'s hull, however, the added presence of chloride ions in the metal's fabric accelerates the corrosive effects of the high humidity environment,[31] and will adversely affect the ship's longevity and visitor safety if no remedial action is taken.

Figure 6



8.5. There is currently no continuous program of monitoring of movement within the ship's structure, or within the dry-dock. Such changes could be manifest in the form of longitudinal sagging or hogging along the ship's keel, bulging in some areas of the hull plating, or downwards or outwards movement of the hull plating. Some form of movement is likely for the following reasons:

8.5.1. the hull is progressively weakening through corrosion;

[30] Briggs, J R, 1984, Museums and Galleries, p767, quoted in Cassar M, Environmental Management 1999, op cit p 20, and Turgoose S, 1982, Post-excavation changes in iron antiquities Studies in conservation 27, 97-101

[31] Cronyn J, 1990, 'Agents of deterioration and preservation' in The elements of archaeological conservation, Routledge, London p23

8.5.2. the hull was designed as a compression structure, supported by its surrounding water, but no longer has that support,[32]

8.5.3. additional static stresses are being imposed on the hull through the weight of interior fittings such as the engine, the heating system and reconstructed areas such as the dining saloon;

8.5.4. dynamic stresses are being continually imposed on the ship through the weight of visitors - in the case of tour groups this weight can be concentrated in fairly small areas;

8.5.5. load testing in July 1998 of 6 of the shores which support the ship indicates that although they were all supporting equal loads when they were first fitted, they now support varying loads,[33] and

8.5.6. it is certain that the ship's metal expands and contracts to some degree in response to changes in temperature. It is not known how this movement translates into changing loads and stresses;

8.6. In addition, the dry-dock floor on which the ship rests is known to have been subject to movement in the past[34] and in a least one portion of the floor, on the port side just forward of the docking keel, visibly moved between June and October 1999 to such an extent that a cast concrete beam set into the floor was cracked and displaced laterally by about 10 cms.

8.7. A load-monitoring system could identify factors causing inappropriate or unstable conditions, give an early warning of conditions likely to cause deterioration, and allow control measures to be taken based on long term knowledge.[35]

9. STRUCTURAL SUPPORT

General arrangement of Interior

9.1. The ship is divided vertically by bulkheads, forming the aft, midships, forward and focsle sections. The midships sections contained the boilers and pumps used to power the steam ship. Horizontally the ship is split into a number of decks denoted as weather deck, promenade deck, saloon deck, and tank top. The levels vary slightly in some sections.

9.2. Externally the hull of the ship is strutted by a series of substantial timbers within the dry dock which provide local support to sections of the hull.

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[32] This is explained further in the section evaluating the ship's structure

[33] Sandberg Consulting Engineers, October 1998, Test Certificate 17499/M/13

[34] Letter, Brunel to Claxton October 22 1839, quoted in Keystone, 1999, Conservation Plan op cit p15

[35] Cassar, M, 1998, Environmental Management. Guidelines for Museums and Galleries. Museums and Galleries Commission. Routledge London p.53

9.3. The general structure of the ship consists of wrought iron angles forming frames extending up around the hull. These are predominantly 15 cm x 9 cm but with some within the focsle reducing to 10 cm x 10 cm.

9.4. At the base of the hull a tank is formed by a series of longitudinal girders running over the top of the frames and plated on the top face. The girders commence at the focsle bulkhead with a pair, with additional girders added as the cross section of the ship widens up. In the widest part of the ship, there are 10 such longitudinal girders. The girders are attached to one another and stiffened by the addition of transverse plates between adjoining girders. This tank forms an extremely stiff platform for the structure of the ship, being approximately 99 cm deep at the centre line of the hull at amidships.

9.5. The flat keel of the ship is formed directly on the underside of the tank with two docking keels situated either side.

9.6. From the longitudinal girders a series of cast iron stanchions rise up and provide support to the deck beams which span across the width of the ship. These in turn provide support to the various decks. The beams are in some places interrupted by trimming beams which were used to form the access openings to the cargo holds. The lower deck beams would have acted as struts to the hull when the ship was at sea whilst in dry dock they act as ties to the hull, preventing it from 'falling' outwards. The timber props externally also provide support, as well as assisting in providing overall stability.

9.7. The iron stanchions repeat at each level, although sometimes offset from those below, and provide support to beams at higher deck levels in turn. Some of the deck beams have diagonal racking struts at the ends of their spans which provide additional stiffness to the hull.

Focsle

9.8. Limited inspection was possible to the fore peak tank structure. The frames, from frame 154 back to the focsle bulkhead, are tied at two positions in their height by tie bars. The deck to the fore peak level is of plate construction bearing on angle irons spanning across the width of the hull and also tying each frame. The fore mast rising up through the focsle is supported at tank level on two iron stanchions extending down to the keel.

9.9. Along the centre line at fore peak level three timber stanchions rise to support the timber spine beam. One of these is decayed at its head so that it no longer connects to the beam. Two cast iron stanchions appear to have been added to supplement the timber stanchions. These all rest onto the tank plate with no support provided below, although due to the short span this provides satisfactory support.

9.10. At frame 154 a small bulkhead has been formed which has been filled with concrete to the bow.

9.11. The deck to the Focsle Store is constructed of 9.5 cm deep timber boards spanning across the width of the ship and supported to the hull via longitudinal plates. These are themselves supported at every other frame position by a diagonal raking strut. The decking also takes support from the central spine beam described previously. A timber stringer runs along the hull over the deck boards.

9.12. The structural layout of the Fore Peak levels repeats in the Focsle Store, with timber and cast iron stanchions situated directly over those below, with the exception of an additional timber stanchions towards the bow. These support a central timber spine beam extending the length of the focsle and supported off the mast at the rear.

9.13. The deck to the lower focsle is of 7.5 cm deep boarding. This runs longitudinally over 8.5 cm x 8.5 cm angle irons spanning across the ship at each frame position. This takes support from the timber spine beam and raking struts on the ends, except at the two frames at the bow where the span is short.

9.14. A timber stringer, as before, runs around the hull at this deck level. The central timber spine beam, for the deck above, is supported off two timber and two cast iron stanchions positioned directly over those below and runs back to the mast. However the spine beam does not extend to the bow, leaving the area from frame 155 clear.

9.15. The decking to the focsle also spans lengthways over 7.5 cm x 7.5 cm angle irons extending form the hull frames to the spine beam. These, as with the deck below, have raking iron struts to the sides, but also with the addition of approximately 3.5 cm diameter stanchions which are positioned over the tops of the raking struts below.

Forward hold

9.16. The focsle bulkhead has been supplemented by the addition of a solid frame. This is free-standing for much of its height but is welded to the bulkhead above promenade level at three positions. Much of the forward section is free from its deck coverings although the structure of stanchions and deck beams generally survives.

9.17. Almost no tank plating survives, thus exposing the longitudinal girders and web stiffeners between. At the bulkhead position there are two such girders, increasing in number to eight at the forward engine room bulkhead where the ship is significantly wider.

9.18. The girders are formed of vertical plates with two 7.5 cm x 7.5 cm angles riveted top and bottom forming an 'I'-beam section. The depth of this varies along the length of the ship from 48 cm at the focsle bulkhead to 99 cms at the deepest. The girders rest directly on the keel section, or onto the frames with connecting angle cleats.

9.19. Between frames 131 and 135 there are the remains of an earlier mast step with the timber housings bearing onto four of the longitudinal girders Between frames 117 and 121 the base of the modern steel main-mast extends up with stiffeners at the base welded to a base plate supported off the longitudinal girders and intermediate stiffeners.

9.20. Two rows of iron stanchions (approximately 5 cm in diameter) extend back from frame 136, rising up from the two central girders to support the deck beams over, and at varying centres. Forward of this single stanchions exist as the width of the ship decreases. From frame 139 back a further pair of stanchions is introduced, supported off the third set of girders, although in places they bear directly on the frames (frames 135 and 139). These also are at varying centres but generally every fourth frame position.

9.21. The two central stanchions support 7.5 cm x 7.5 cm angles running down the length of the ship. These in turn support 9 cm x 9 cm angles spanning across the width of the ship tying the frames. These ties take further support off the second set of cast iron stanchions.

9.22. Directly over the second set of stanchions, a further set of 9 cm diameter cast iron stanchions extend up to deck beams supporting the main deck. There are nine pairs of stanchions running the length of the forward section.

9.23. At approximately mid-height of this deck there is a horizontal plate running around the hull, extending out approximately 85 cm and supported off raking struts to the frames below. Some stiffening plates have been added over.

9.24. The main deck structure as viewed from below consists of bulb ended deck beams spanning across and tying the frames at frames 108, 120, 123, 127, 131, 135, 139 and 143 respectively. Between frames 108 and 120 secondary deck beams span at right angles over the iron stanchions to the main beams, presumably forming access for cargo etc.

9.25. The deck beams increase in depth at the junction with the frames, forming a deep web for additional stiffness of the joint. The beams are spliced along their length at the positions of the support stanchions below.

9.26. This structural pattern repeats on the upper levels, all the way to the underside of the weather deck, although detailed inspection was difficult. It is possible at the promenade deck level to inspect the underside of the weather deck and its supporting structure. The box stringer running around the periphery of the hull is also obvious.

9.27. The weather deck has been replaced comparatively recently and the new steel plate decking set slightly above the supporting beams by means of steel plates welded to both elements. This gives the advantage of allowing plenty of air to circulate around the iron and steel and thus reduce the likelihood of corrosion occurring.

9.28. To the port side there is quite significant decay to the ends of the deck beams which coincides with wet rot in the deck timber above. The ends of the beams arch down to meet with the frames and plates are incorporated over.

Amidships

9.29. The tank level is generally plated over, making inspection difficult for much of the area. The longitudinal girders continue, with a further pair being introduced, making ten members in total.

9.30. The crack in the starboard hull of the ship between frames 90 and 93 has been covered internally with a layer of concrete, 4 cms thick. The vertical crack extends from the gunwale to the docking keel and has been covered externally by heavily corroded steel plates. The crack appears alternatively in the shell plating and at the butt strap positions in the hull to the starboard side.

9.31. Above the tank top level, the amidships houses the replica engine. It is contained by bulkheads at frames 57 and 83.

9.32. In the forward section of amidships two rows of cast iron stanchions are positioned over the longitudinal girders at frame positions 84, 90, 97, 100 and 103. Three lines of modern steel stanchions have been introduced (12 cm diameter), one centrally and the remaining two to the sides. These are supported on new plates over the girders, whilst the central beam bears directly over a stiffener between the girders. These were inserted to allow part of the deck above to be used as a dance floor (this is the room now known as the Hayward saloon

9.33. Deck beams at main deck level extend from the hull frames at positions 84, 97, 100 and 103 for the full width of the hull. At frames 88 and 93 the deck beams are curtailed. This created an open area presumably to pass cargo but which has now been filled to make the floor for the Hayward saloon

9.34. Between frames 82 and 83 the false boiler bulkhead is positioned which is supported on a frame on the line of frame 84.

9.35. The engine house area is open up to the weather deck level with viewing galleries from both the main and promenade decks. Deck beams exist at main deck level on frames 77 and 80 with cast iron stanchions below, but without any decking. The ends of further deck beams survive either side of the re-constructed engine house. These have been cut short and welded to raking longitudinal plate inserted as part of the recent works.

9.36. These raking plates extend down to bear on top of the longitudinal girders with two shaped plate stiffeners behind running and connected to the frames. These raking plates provide a bearing for the cylinders for the pistons of the engines.

9.37. Above the tank level the viewing galleries either side of the engine are generally supported on deck beams extending out and supported on a longitudinal beam at the position of the open well. The beams to the weather deck structure are visible from the promenade deck.

Aft Tank Top

9.38. At the stern of the ship the structure below the tank decking consists of two longitudinal girders divided along their length by stiffeners. Rather than have cut outs as elsewhere the stiffeners are solid, providing storage for water. The frames extend down to the girders which are generally plated over, making a full inspection difficult.

9.39. From frame 42 onwards the two girders are supplemented by four additional members with a bulkhead being formed on this line.

9.40. The deck beams are supported on cast iron stanchions extending up from the longitudinal girders, or in places from the frames to the hull.

9.41. A series of deck beams span across the width of the ship at frame positions 11, 14, 17, 20, 24, 28, 31, 42, 44, and 52. Between frames 31 and 42 trimmer beams span down the length of the ship from a blocked up opening. Over the beams is a relatively modern decking of steel.

9.42. Much of the structure above the saloon deck level is concealed by offices or interpretation areas. It can be presumed that the structural form follows as elsewhere, with deck beams spanning across the width of the ship with intermediate support provided by stanchions at regular centres. This is confirmed where the structure is visible.

9.43. At Frame 53 a timber beam straddles the tank top from port to starboard. This beam is 35 cm wide and 16 cm deep, and is enclosed fore and aft with iron plating. The timber is exposed on its top surface. This beam was possibly used as a foundation for supports for the propeller shaft.

Analysis of Structure

9.44. The ship clearly is designed as a compression structure, below the water line, to withstand the pressure applied to it from the sea. In the dry dock the ship will never have to withstand these compressive forces but is subject to tensile forces as the dead weight of the hull and parts of the decks attempt to 'bulge outwards'. Therefore, many components are subject to forces that have reversed direction against the original design of the component. This effect is somewhat counterbalanced by the nature of the hull plating itself, which is constructed in such a way as to create a stressed skin structure. However, the corrosion and spalling of material from the hull plating below the waterline, combined with similar wastage of material in the internal framing, means that these areas are now carrying the same load from the upper sections of the hull, where the condition is not as poor, as before, but with a decreased capacity to

do so. This may eventually cause the lower section to start buckling. This would only partly be countered by the ability of the deck beams to cantilever out to support the hull.

9.45. It is clearly evident that much wasting of the internal skeletal structure has occurred, particularly related to the angle irons forming the frames. In some areas, wastage has occurred to such an extent that the support structure no longer exists. This can be seen in the wastage of the box stringer on the promenade deck of both port and starboard sides of the forward hold, and in the metal shelf in the starboard side on the saloon deck around frames 100-110, in the aft section of the forward hold. However, it is also evident that the ship retains considerable longitudinal and transverse strength.

External Structural Supports

9.46. The ship is supported on a series of 73 keel blocks and 33 shores (see Figure 11). The shores are of variable quality and carry varying loads. Some are bent, presumably because of the increase in loads they are carrying and a number have obvious wet rot.

9.47. It is extremely difficult to take sightings along the curves of the hull to determine whether or not any movement has taken place longitudinally or in any of the ship's sections. The most obvious sight line, the angle iron on which the timber cladding was fixed, is itself distorted and non-continuous.

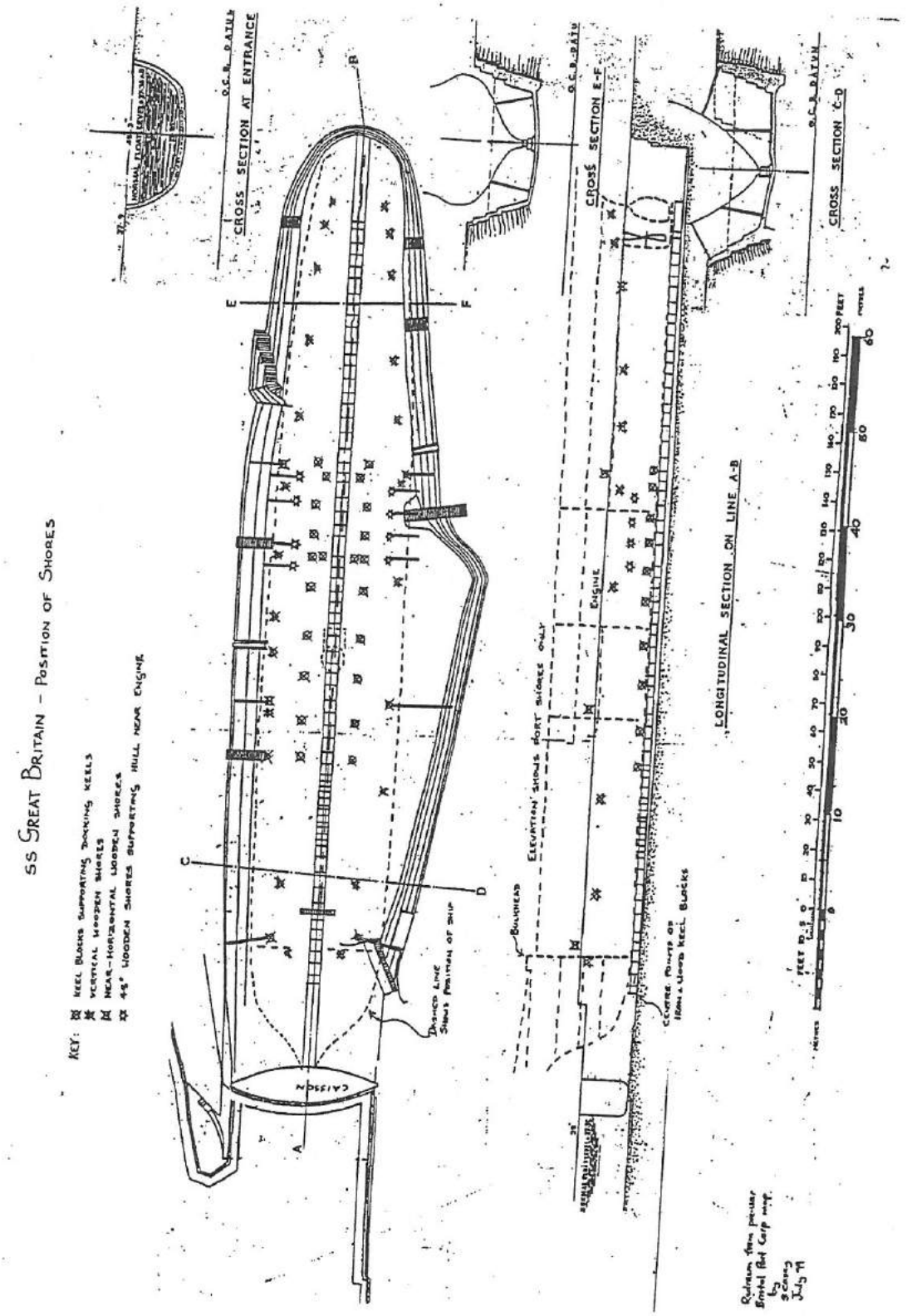
9.48. However, load testing of the timber shores which support the ship showed that movement or 'spread' of the structure may be slowly occurring. Load testing was carried out in late 1998, using a timber strut, a hydraulic jack and a load cell. The timber strut was placed next to the shore under consideration and jacked up until the shore became loose. Often this did not happen because the angle iron on the ship against which the shores are placed began to deform. This was usually at a load of 2500 - 3000 kilograms.[36] The loads measured on a selection of the wooden shores were found to vary widely. As the shores were all supporting equal loads when they were first fitted, the current variance in weights shows that their loads have changed since they were first fitted.

9.49. Some of the shores were put in place as a temporary measure to support the hull during the installation of the replica engine, and were intended to carry light loads only. As some of these in the vicinity of the replica engine now appear to be carrying loads in excess of 3000 kilograms and are fitted into corners of masonry, controlled removal may be difficult.

9.50. The reasons for any change in loading on the shores might include: movement of the dock, movement of the ship, or the transfer of a load or stress through the ship's internal structure onto one or more hull plates, which results in an

[36] Sandberg Consulting Engineers. Report 17499/M/01, op cit

Figure 11 Plan of the Great Western dry dock showing the position of the external ship supports



increased stress on those plates. As discussed in the section on the condition of the dry dock, there are visual clues that the floor of the dry dock heaves and falls. Also, it is certain that the ship's metal expands and contracts to some degree in response to changes in temperature. It is not known how this movement translates into changing loads and stresses. Increased loading due to the installation of the replica engine has been catered for by the installation of concrete beams underneath the engine which transfer loads down to the keel and docking keels. However, it is possible that loads elsewhere within the ship (such as from large parties of visitors) may result in localised loading on some hull plates or frame members.

10. SERVICES

10.1. The current widespread use of gas in providing heating and catering facilities, the haphazard nature of the ship's electricity supplies and fittings, and the limitations to the current fire detection and fighting systems all lead to the inevitable conclusion that one of the major threats to the ship is from fire and explosion. This section explains the nature of that risk.

Gas supply

10.2. Flammable gas is used in many areas of the ship. The hot air heating system is fired by natural gas supplied through a pipe entering the ship's hull on the port side, and the modern kitchen/galley is powered by the same system. A number of portable butane gas heaters are situated around the ship, and the gas bottles are stored on board when not in use.

10.3. Gas supplies for the buildings on the North side of the dock (the café and shop) are routed through piping which enters the ship's starboard side, passes through the ship and exits via piping on the port side.

10.4. The official gas bottle store is a wire cage structure on the dockside. However, its capacity has been exceeded, and a number of bottles are stored outside the cage.

10.5. The maintenance team uses oxyacetylene equipment, and the gas bottles, while stored outside the ship, are kept handy in the bottom of the dry dock.

Electricity supply

10.6. Electrical wiring on board the ship clearly dates from various periods of installation since 1970, and is complex, if not haphazard, with breaker boards widely dispersed around the ship. It appears that the system is working at maximum capacity and can be unreliable. It is doubtful if the wiring would all meet current standards.

10.7. The variable nature of the wiring also makes it very difficult for people not familiar with the system to respond to emergency situations. The project is

heavily reliant on a small number of individuals who have the detailed knowledge of the systems sufficient to be able to respond swiftly to problems.

10.8. The current mains electricity supply on the shore has breakers limiting it to 100 Amps, but is capable of supplying 300 Amps, and should thus cope with any increase in demand resulting from the proposed project.

Fire prevention and fire fighting systems

10.9. The ship's current fire detection and alarm system was fitted in 1990, and at present covers only the Dining Saloon, the Hayward Saloon, and the Galley. Other parts of the ship have no fire alarm. The fitted system, while sounding a standard siren, can be difficult to hear from forward parts of the ship or alongside on the dock.

10.10. Lightning Earthing straps are fitted at the starboard bow and the starboard quarter.

10.11. The current fire-fighting system has three elements:

10.11.1. a three-inch diameter fire main which enters the ship at the bow, and runs the length of the ship. Connected to this fire main are three vertical risers which pierce the weather deck, where they provide hydrant connections for attaching hose. The fire main is coupled to the Floating Harbour by a flexible hose. The pump control for the fire main is housed at the back of the site workshops. However, the fire main is kept uncoupled from the flexible hose in order to avoid the risk of freezing during cold weather, and the workshops are kept locked for significant portions of the day, all weekend, and on public holidays.

The inevitable delay that would ensue between a fire being located and the fire-fighting equipment becoming operable poses an obvious risk to the ship;

10.11.2. a system of stand-alone extinguishers on board ship; and

10.11.3. a one-inch water main running from the shore on the starboard side of the ship through a hole in the ship's side. This is connected to piping which runs the length of the ship, and which is connected to three coiled hoses on the dining room deck level.

11. THE DRY DOCK

11.1. The *ss Great Britain* sits in the Great Western Dry Dock, isolated from the Bristol Floating Harbour by a steel caisson seated in wood-lined slots located on each side of the dock entrance. The dry dock is a grade II* listed structure. A preliminary survey was undertaken in May 1998 of the dry dock and surrounding dock area.[37]

Drainage

11.2. There is significant leakage of water into the dry dock from the dock entrance side slots, and through the walls and floor of the dock masonry. The latter is probably as a result of water ingress across the narrow isthmus between the Harbour and the dock on its north eastern side. The drainage adit leading down to the River Avon, while reportedly sealed up at the river, also appears to leak intermittently. Water entering the dry dock is drained into two centreline sumps, from where it is pumped out to the Floating Harbour by an automatic submersible pump. Drainage into the sumps is far from perfect and the after sump appears to be defective. Sufficient surface water remains to allow vegetation and algae to grow unchecked. Pointing on the dock walls is cracking and falling out in places, and may be responsible for some leakage problems.

11.3. In its historical context, the dry dock would always have been damp, with water seeping in through dock walls and accumulating from rainfall. In its current context, however, the damp conditions engendered by poor water-run-off create three problems:

11.3.1. they create a sub-environment around the lower hull of the ship which is highly conducive to rot in the timber shores,

11.3.2. unrestrained vegetation and root growth is damaging the stone and mortar joints in the dock walls and floor, and,

11.3.3. the dangerously slippery and unstable floor surfaces currently prevent public access to a large part of the dry-dock.

Stability of walls and floor

11.4. The overall stability of the dry dock gives further grounds for concern. Although the dock walls appear to be stable, displaying no signs of significant movement, some movement was observed in the dock floor over the summer of 1999, in the area just below the port side of the forward hold. Possible movement of the dock below the keel blocks and shores could cause serious uneven loading to the ship.

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[37] Holden Conservation, 26 November 1998, Preliminary Survey of the Great Western Dry Dock and other masonry. Ref 418

12. THE CAISSON

12.1. The *ss Great Britain* relies for her primary protection from the waters of the Floating Harbour on the strength and watertight integrity of the steel caisson seated across the dry dock's mouth. This raises two issues of concern: first, whether the caisson and its seals are adequate, and second, whether the caisson is sufficiently protected from accidental damage, as any such damage could flood the dock catastrophically.

12.2. It has been impossible to remove the caisson for repair since 1970, because the dock cannot be allowed to flood with the *ss Great Britain* in it. Despite the lack of repair, visual examination and non-destructive thickness measurements by Sandberg Consulting Engineers,[38] using ultrasonic thickness probes, confirmed that the caisson was in remarkably good condition. However, the caisson cannot remain in situ, untreated, in perpetuity.

12.3. It is conceivable that the dry dock could be suddenly flooded if the caisson was damaged, as might occur if a large vessel in the Floating Harbour rammed the caisson. If this happened the ship would be struck by large volumes of water and perhaps heavy pieces of steel. Further, if the ship refloated, she could damage her hull against the side of the dry dock. Such an accident would be catastrophic to the ship's wrought iron, which has a very poor resistance to impact.[39]

12.4. Two measures have already been taken to prevent such a catastrophe:

- The caisson has had extra concrete and railway iron ballast installed to ensure that it will not float; and
- To prevent the ship from floating in the event of the dry dock suddenly flooding, a small hole has been cut into the ship's plating near the keel in the vicinity of frame 100 to permit the ship to flood. It is not clear, however, that the ship will flood sufficiently quickly to ensure that she does not move. Clearly, this is at best a reactive solution, which seeks to minimise, rather than prevent, damage.

[38] Sandberg Consulting Engineers, op cit.
[39] Dr J E Morgan, 1996, The wrought iron of the ss Great Britain. An overview of properties in design and renovation.

13. CONCLUSIONS

13.1. The condition of the ship below the waterline is very poor, and the threats to her survival are great. The ironwork is generally in extremely poor condition, and exhibits substantial chloride-accelerated corrosion inside and out in the lower parts of the hull. The ship's external topsides, however, do not display the same level of corrosion, as they are relatively uncontaminated by chlorides, and have additionally had the benefit of water diffusion cleaning over the past 30 years.

13.2. Monitoring of the ship's environment has shown there to be high levels of relative humidity, and great fluctuations in those levels on a daily basis. This provides ideal conditions for further chloride-induced corrosion in the lower hull, below the waterline. For as long as the iron in this area is exposed to the air and to moisture in the form of rainwater and excessive humidity, its chloride-contaminated iron will continue corroding at an accelerated rate, weakening her structure, and will eventually be completely oxidised.

13.3. The corrosion process to which the ship is subject is an extremely complex one, in which the various elements present in the atmosphere such as oxygen, water and various pollutants combine with the range of chemicals making up the ship's metals, and also with the soluble chlorides which have infused into the metal. The effects of different oxygen concentrations, temperature, and acidity or alkalinity at the metal surface may also vary the effects of corrosion. The combined effect of this process is to produce a highly variable and somewhat unpredictable range of corrosion products, which may include iron oxides, hydroxides and oxyhydroxides[40], iron chlorides in a range of hydrated states[41] as well as iron sulphides[42].

13.4. If corrosion continues at the same rate as it has up to the present, the life of the vessel will be considerably shortened - the estimate in this report is that the ship has a mere 3 to 5 years left before irretrievable losses to her fabric will occur that will undermine her historical integrity, structural safety and her viability as a visitor attraction.

13.5. The Conservation Plan which this Report supplements stresses the unique nature of the ship, and establishes her international importance. In the light of the conclusions in that Report, and the findings of this Report, it essential that the ship's iron and her artefacts be stabilised to prevent further corrosion and degradation of the ship.

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[40] These might include Ferrous Hydroxide - Fe (OH)2; Iron Oxyhydroxide - FeO(OH); Iron Oxide (Magnetite) Fe3O4; or ferric hydroxide 2Fe2O3 . 3H2O. See Watkinson D, 1999 What is metallic corrosion? Paper presented to the 'Back to basics Conservation conference, Bristol 1999, for a discussion of the range of corrosion products

[41] Ferrous chlorides such as FeCl2; FeCl2 .H2O; or FeCL2.4H2O and ferric chlorides'such as FeCl3; or FeCl3 . H2O

[42] Such as FeSO4 and FE2(SO4)3

14. TREATMENT OPTIONS

14.1. Eleven treatment options have been assessed for their relative ability to meet the ss Great Britain Project's primary aim: the preservation of the ship in perpetuity. Each option was assessed according to its ability to fulfil the following criteria:

14.1.1. Long term retention of original material from the ship's working life;

14.1.2. Reversibility of treatment. The treatment selected should be reversible, so that the treatment could be undone if that should become desirable This requirement recognizes that a conservation treatment may not last indefinitely nor remain superior to all future techniques. If the treatment is reversible, the option to re-treat is always open and the continued preservation of the ship is assured;

14.1.3. Cost. This was assessed in terms of the estimated magnitude of the capital equipment required, the running costs, and the maintenance effort required;

14.1.4. Practicability (ease of actually doing the treatment). Some treatments are theoretically very efficient, but would present severe difficulty in instituting;

14.1.5. Effectiveness of treatment in halting corrosion. Some treatments do not prevent chloride-accelerated corrosion, and thus will, over time, see further accelerated deterioration, irrespective of their initial surface treatment;

14.1.6. Long term accessibility of vessel to public. Some options remove the vessel from the public domain completely, obscure her, or alienate her from its dockyard environment;

14.1.7. Effect of treatment on interpretation. It is important that the selected treatment facilitate and enhance the vessel's interpretation for the visitor, rather than detract from it; and

14.2. The life span of the vessel under differing treatment options is difficult to estimate, but a number of parameters can be set:

14.2.1. While the majority of the iron plates have survived, corrosion has reduced their thickness to about 51% of their original thickness;[43]

[43] This is an extrapolation to 1999 of the 0.3% deterioration in shell thickness observed by Corlett (The Iron Ship p163) to have occurred between 1843 and 1968.

14.2.2. that no conservation treatment is perfect – none will be able to protect every milligram of the ship's metal in perpetuity, as all materials degrade[44] – it will be the conservator's task to slow the rate of decay, but under all cleaning options there will be a gradual reduction in material as the corrosion process continues, with the speed or slowness differing markedly between treatments;

14.2.3. that under some cleaning regimes, there would be a dramatic loss in original material during the treatment;

14.2.4. that there will come a point when there is insufficient metal left in either frames or plating to guarantee the structural integrity of the ship. In this circumstance, the vessel might suffer a total structural failure and collapse. For illustrative purposes, this point is assumed to be when there is only 30% of the original material remaining.

14.3. The different assumptions for each treatment option are listed in Table 2, and Figure 7 shows the point at which 30% of the original material will be reached. Each measure was then assessed in the evaluation matrix in Table 3 and given a rating, which was also equivalent to a score out of 5. The number of years remaining until the thickness of hull plate reached 30% was then divided by 5 (with a 20 year hull life, for instance, earning 4 points) and added to the total. The total score was expressed as a percent of the maximum available score of 55. A discussion of each of the options is also given below.

[44] Cassar M, 1999, p14

Table 2 Assumptions used for life span of wrought iron plating

Option	Length of Treatment (years)	Loss rate of remaining fabric during treatment (% per year)	Loss rate after treatment (% per year)	Period between cleanings (years)	Period until less than 30% of material is left.[1] (years)
Option 1 Do Nothing	No treatment	Not applicable	1% for first 7 years, then progressively more	No cleaning	15-20
Option 2 Ship year style treatment	1	17% [2]	0.3%[3]	10 years[4]	30-35
Option 3 Tannic acid	1	17%	0.3%	15 years[5],	45-50
Option 4 Alkaline sulphite	2	2%	0.23%[6]	10 years	50-55
Option 5 Water diffusion	10	1%	0.26%[7]	10 years	50-55
Option 6 Electrolysis	5	2%[8]	0.2%	10 years	45-50
Option 7 Deposit in dry or anaerobic environment	1	10%	0.02%	N/a	100+
Option 8 Storage under cover	1[9]	17%	0.2%	10 years	45-50
Option 9 Storage in an inert environment	1	N/a	0.01%	N/a	100+

[1] It is likely that, given the poor and variable quality of the wrought iron, its weakness from stress corrosion, accelerated chloride corrosion, and damage from various incidents during the vessel's life, that there is risk of structural collapse of portions of the vessel, once the amount of original fabric drops below 30%.

[2] Based on Eura Conservation's estimate that 17% of areas tested would be completely destroyed if subjected to abrasive cleaning. It is assumed that this amount of corrosion has built up over the past 20 years, and that 8% would therefore be similarly corroded due to accelerated chloride corrosion (and removed in cleaning) every 10 years.

[3] Extrapolation of the amount of wastage between 1843 and 1968 (40%, or 0.3% each year)

[4] 8% of material is lost.

[5] The longer life cycle is given by a longer life of coatings, with 8% lost

[6] This treatment method is assumed to be more effective than water diffusion and less so than electrolysis

[7] This treatment method is assumed to be more effective than shipyard style treatment, but less than electrolysis

[8] Loss from unrestricted evolution of hydrogen bubbles

[9] Subjected to conventional shipyard treatment

Option	Length of Treatment (years)	Loss rate of remaining fabric during treatment (% per year)	Loss rate after treatment (% per year)	Period between cleanings (years)	Period until less than 30% of material is left.[10] (years)
Option 10a Dehumidify in glass cocoon	2	10% in first year, then 5% in second year[11]	0.03 %	N/a	100+
Option 10b Dehumidify under glass roof	1	1%	0.02%	N/a	100+
Option 10c Dehumidify with modified waterline	1	1%	0.07% [12]	N/a	100+

[1010] It is likely that, given the poor and variable quality of the wrought iron, its weakness from stress corrosion, accelerated chloride corrosion, and damage from various incidents during the vessel's life, that there is risk of structural collapse of portions of the vessel, once the amount of original fabric drops below 30%.

[11] Under the other dehumidification proposals, the dehumidification would taken place before treatment, or while treatment was occurring. This could not happen under this proposal. Either the whole hull would have to be consolidated first, and then covered with the shell, or the shell put on first and then dehumidification would start. There would be considerable ongoing loss of material during each procedure.

[12] This is greater than the other dehumidification proposals due to some degradation of material in the topsides.

Figure 7 - Estimated relative loss rates of iron plating from the hull of the ss Great Britain under different treatment scenarios

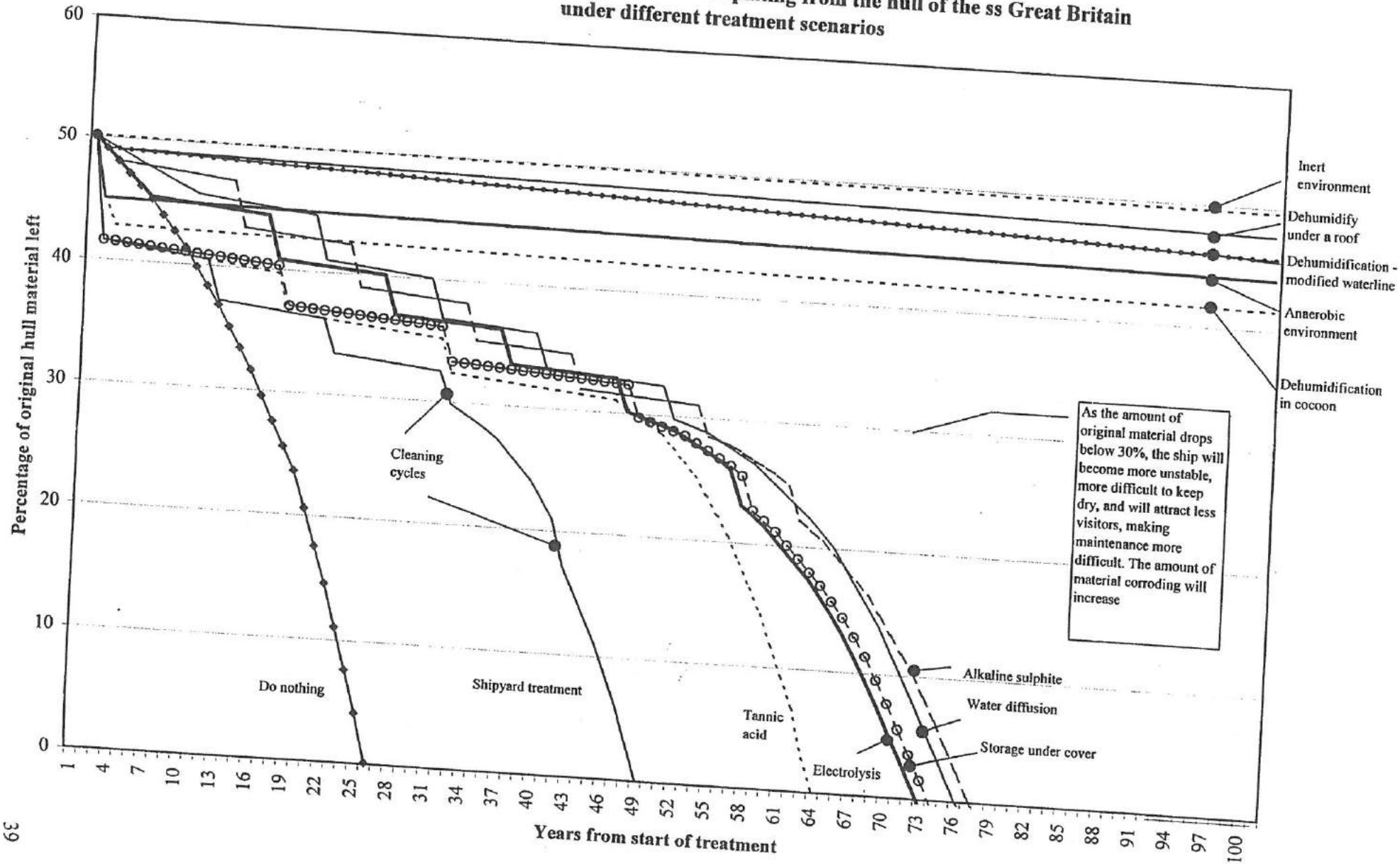

Table 3 Matrix for evaluation of the preferred metal treatment option [a]

Option	Long term retention of original material	Reversibility of treatment [b]	Cost	Practicability (ease of actually doing the treatment)	Effectiveness of treatment in halting corrosion	Long term accessibility of vessel to public	Effect of treatment on interpretation	Period from treatment until 30% of original material is left (years)	Option score (out of 55)	Score as a percent of maximum available score
Option 1 Do nothing	Very Poor (1)	Poor (2)	Very Cheap (5)	Excellent (5)	Very Poor (1)	Poor (2)	Poor (2)	15-20 years (4)	22	40%
Option 2 Shipyard style treatment, including pressure washing	Very Poor (1)	Poor (2)	Cheap (4)	Excellent (5)	Very Poor (1)	Poor (2)	Poor (2)	30-35 years (7)	24	43%
Option 3 Chemical treatment Tannic acid or phosphoric acid coatings	Poor (2)	Poor (2)	Cheap (4)	Excellent (5)	Very Poor (1)	Poor (2)	Poor (2)	40-45 years (9)	27	49%
Option 4 Removal of chlorides by alkaline sulphite washing	Good (3)	Very Good (4)	Expensive (2)	Poor (2)	Poor (2)	Good (3)	Good (3)	50-55 years (11)	30	54%
Option 5 Removal of chlorides by water diffusion	Good (3)	Excellent (5)	Expensive (2)	Poor (2)	Poor (2)	Good (3)	Good (3)	50-55 years (11)	31	56%

Option	Long term retention of original material	Reversibility of treatment (b)	Cost	Practicability (ease of actually doing the treatment)	Effectiveness of treatment in halting corrosion	Long term accessibility of vessel to public	Effect of treatment on interpretation	Period from treatment until 30% of original material is left (years)	Option score (out of 55)	Score as a percent of maximum available score
Option 6 Removal of chlorides by electrolysis	Good (3)	Poor (2)	Expensive (2)	Poor (2)	Poor (2)	Good (3)	Good (3)	50-55 years (11)	27	49%
Option 7 Removal to dry or anaerobic environment	Very Good (4)	Excellent (5)	Very Expensive (1)	Very Poor (1)	Very Good (4)	Very Poor (1)	Very Poor (1)	100+ years (20)	37	67%
Option 8 Storage in situ under cover	Poor (2)	Poor (2)	Moderate (3)	Excellent (5)	Poor (2)	Excellent (5)	Poor (2)	50-55 years (11)	32	58%
Option 9 Storage in Inert argon atmosphere	Excellent (5)	Excellent (5)	Expensive (2)	Poor (2)	Excellent (5)	Very Poor (1)	Very Poor (1)	100+ years (20)	41	74%
Option 10a Dehumidify with glass cocoon	Excellent (5)	Very Good (4)	Expensive (2)	Excellent (5)	Very Good (4)	Poor (2)	Very Poor (1)	100+ years (20)	43	78%
Option 10b Dehumidify under a roof	Excellent (5)	Excellent (5)	Expensive (2)	Excellent (5)	Very Good (4)	Excellent (5)	Poor (2)	100+ years (20)	48	87%
Option 10c Dehumidify with modified waterline	Excellent (5)	Excellent (5)	Expensive (2)	Excellent (5)	Very Good (4)	Excellent (5)	Excellent (5)	100+ years (20)	51	93%

Notes:

(a)Two scales of rankings are used: (Very Poor (1), Poor(2), Good (3), Very Good (4), Excellent (5)) and (Very Expensive (1), Expensive (2), Moderate (3), Cheap (4), Very Cheap(5) Each period of 5 years of life span is given one point, up to 100 years

(b) Some of the treatments such as the 'do nothing' approach are classed as non-reversible in that if they are adopted, there will be irreversible long-term decline in the ship's structural integrity and irredeemable loss of material. From a short term point of view, however, they may be reversible

15. Option 1 - Do nothing

- Re-paint ship's hull over corroded areas using traditional ship-yard paints
- Add more wooden shoring to weaker areas of hull

15.1. If no remedial action is taken to halt or slow the ship's corrosion, and given current loss rates of material, it is considered that within 3 to 5 years her hull, appearance, and structure will have degraded to the point where she will no longer be capable of accepting visitors on board without risk. Within 15 to 20 years, most of her hull plates may have as little as 30% of their original thickness remaining.

15.2. Although there is no cost to this option, if it was adopted the ship would not be likely to survive, but would quickly become more and more visually and structurally degraded. A similar outcome occurred in the United States, following the recovery of the Civil War ironclad *USS Cairo* in the early 1960's. Like the *ss Great Britain*, the *Cairo* was constructed from wrought iron, but had the advantage of having been submerged in mud in a fresh water river for just under 100 years, and thus probably had little chloride contamination. Raised and left unprotected for 20 years, by the mid 1980s she had virtually disintegrated in the humid conditions of the southern United States. Her significance was recognised too late, and she is now displayed under shelter, with much of her superstructure and hull now shown as 'conceptual reconstructions'

15.3. Further, under this option the Caisson and its dry dock entrance seals would progressively degrade, leading to the risk of failure and catastrophic failure.

16. Option 2 - Shipyard-style treatment

- Remove all visible corrosion products from the ship's interior and exterior by grit blasting or high pressure washing to SA 2 ½ or 3
- Fill holes with GRP patches and/or replacement welded steel inserts
- Re-coat with high quality paint system
- Replace all suspect structural elements with steel
- Repair and protect the caisson
- Install 24 hour heating system
- Install sophisticated fire prevention system

16.1. Over the period since the *Great Britain's* recovery in 1970, a variety of conventional shipyard mechanical cleaning practices have been employed to deal with the ship's corrosion. These measures have included subjecting the hull to high pressure water-cleaning at 10,000 psi, chipping, needle-gunning and wire-brushing. Various surface treatments, including the application of tannic acid coatings, have been applied experimentally.

16.2. None of these treatments have been able to overcome the key problem: that the hull remains contaminated with chlorides and exposed to a highly humid environment, in which accelerated corrosion can continue unabated. The ship's wrought iron laminar structure and multiplicity of slag inclusions, have allowed the easy ingress of seawater deep into the interior of the metal.[45] In the presence of high relative humidity, chlorides go into solution and travel by capillary action through the end grain of the plating[46]. Hidden deep within these layers, chlorides cannot be removed by the simple washing or grit-blasting techniques of a conventional shipyard.

16.3. In a similar manner, the ship's riveted overlapping plate construction has also served to harbour corrosive elements and shield them from cleaning[47]. The holes punched in each of the ship's plates for the ship's rivets have also allowed chlorides to migrate into the interior of each plate, by providing a multiplicity of 'end grain' laminar surfaces.

16.4. The surveys have shown that it is doubtful if the iron could withstand ultra-high pressure washing or shot-blasting and still remain intact. The further loss of original hull material in trying to pursue this solution would be considerable.

16.5. If this option is chosen, the vessel's hull plates could have corroded to 30% of their original thickness within 30 to 35 years. This increase over Option One would largely be due to the weather resistance of the best available paint coating, the principal function of which would be to provide a protective coating against the deterioration of the surface from agents in the environment.[48] During that time, the vessel would be steadily degrading as for option 1.

17. Option 3 - Chemical treatment –Tannic acid and or phosphoric acid coatings

- Remove all visible corrosion products from the ship's interior and exterior by grit blasting or high pressure washing to SA 2 ½ or 3
- Fill holes with GRP patches and/or replacement welded steel inserts
- Recoat the hull with tannic acid or phosphoric acid coating systems
- Replace all suspect structural elements with steel
- Repair and protect the caisson
- Install 24 hour heating system
- Install sophisticated fire prevention system

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[45] North N, and MacLeod 1987, 'Corrosion of Metals' in Pearson, ed, Conservation of marine archaeological objects, Butterworth p77)

[46] Thompson J, The Manual of Curatorship, op cit, p365

[47] Baker H R, 1969 discussed a similar problem in Examination of the corrosion and salt contamination of structural metal from the USS Tecumseh, Naval Research Laboratory, Washington DC

[48] Hallam, J, in Thompson 1992, Manual of Curatorship, op cit, p 381

17.1. A number of chemical cleaning treatments are used for iron artefacts recovered from archaeological environments where there are negligible chlorides present. The most common chemicals used are oxalic acid, citric acid, phosphoric acid, tannic acid solutions, and ethylenediamine tetra-acetic acid (EDTA). However none of these products removes chlorides and hence they cannot prevent subsequent corrosion where chlorides are present. Therefore, they can not be considered as conservation alternatives for treating iron recovered from salt water.[49]

17.2. Two of these chemicals, phosphoric acid (and its derivatives in commercial rust removers) and tannic acid solutions, are often used to form a corrosion-resistant film of phosphate or tannate on the surface of treated iron pieces. The corrosion-resistant significance of phosphate and tannate films was first made apparent when iron articles recovered from an ancient Roman tannery were found to be in an excellent state of preservation.[50] Before either chemical can be used, however, the chlorides must be removed by electrolysis, alkaline sulphite treatment, or water diffusion.[51] It was for this reason that when they were applied experimentally to the hull of the *ss Great Britain*, and more recently to the submarine *Holland 1*, they met with little success.

17.3. If this treatment was to be used on the ship's hull, following full ship-yard style treatment, the vessel's hull plates may have corroded to 30% of their original thickness within 40 to 45 years. This is largely based on these products giving a marginal increase in protection over the coating systems used in Option 2. It is likely that, given the poor and variable quality of the wrought iron, its weakness from stress corrosion, accelerated chloride corrosion, and damage from various incidents during the vessel's life, there could then be significant risk of structural collapse of portions of the vessel.

18. Option 4 - Alkaline sulphite removal of chlorides

- Establish an hermetic seal around the vessel.
- Replace the oxygen within the sealed area with an inert gas, such as argon
- Remove as much soluble corrosion product as possible from the ship's interior and exterior by washing with alkaline sulphite at a temperature of 60 degrees
- Re-coat hull with high quality paint system
- Repair and protect the caisson
- Install 24 hour heating system
- Install sophisticated fire prevention system

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49 Plenderleith, H.J. and A.E.A. Werner, 1971, in The Conservation of Antiquities and Works of Art. Revised Edition, London, Oxford University Press, give details concerning the use of these and other chemicals.

50 Farrer, T.W., L. Biek, and F. Wormwell, 1953. The role of Tannates and Phosphates in the Preservation of Ancient Iron Objects. Journal of Applied Chemistry, 1953: 80-84.

51 Hamilton D, 1999 The conservation of marine archaeological material, Texas A&M, unpublished Chapter 10b

18.1. Alkaline sulphite washing is highly effective at removing chlorides when measured against other aqueous washing techniques,[52] but requires that the metal be both treated in an oxygen free environment and heated to around 60 degrees centigrade over a prolonged period. Theoretically, therefore, the hull would have to be flooded with an inert gas, such as argon, to allow treatment to take place.

18.2. The difficulty both of effecting an hermetic seal for the gas, and of heating the vast bulk of the vessel's metal sufficiently and over a sustained period makes this option impractical. Further, the absence of oxygen within the storage facility would severely inhibit public access. Additionally, while the treatment is effective on iron objects that are moderately to heavily corroded, the objects still must have a metallic core present for the treatment to be effective; otherwise, the iron object may break apart during treatment.[53] In addition, while this system has been shown to have higher chloride extraction rates than other methods, like the other chloride removal systems it does not guarantee complete removal of the chloride compounds.[54] The ship would remain in its humid environment, the corrosion process would be maintained, and the long-term survival of the ship would be in doubt. The vessel's life until around only 30% of material survived could be extended due to a reduction in chlorides, up to between 50 and 55 years.

19. Option 5 - Water diffusion of chlorides

- Flood the dock, and the vessel, bringing the water level at least up to the level where she was flooded in the Falkland Islands.
- Remove all soluble corrosion products from the ship's interior and exterior by continued flushing
- Re-coat hull with high quality paint system
- Repair and protect the caisson
- Install 24 hour heating system
- Install sophisticated fire prevention system

19.1. As noted above, the vessel's topsides show a considerable lack of corrosion product. This may have been because they were less contaminated with chlorides than the below-waterline areas, but they may also have benefited from the effects of water diffusion over at least the last 30 years. To carry out this treatment effectively below the waterline area, the vessel would need to be flooded, and a pumping system instituted that would flush the hull with

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[52] Watkinson, D, 1996, found that it had a mean chloride extraction rate of 87%. In 'Chloride extraction from archaeological iron: comparative treatment efficiencies' Archaeological conservation and its consequences, International Institute for Conservation of Historic and artistic works. London 1996

[53] Bryce, T. 197.9 Alkaline Sulphite Treatment of Iron at the National Museum of Antiquities of Scotland. In: The Proceedings of the symposium The Conservation and Restoration of Metals held in Edinburgh, U.K. March 1979, pp. 20-23. Edinburgh: Scottish Society for Conservation & Restoration esp page:21)

[54] Watkinson 1996 op cit

uncontaminated water. The procedure could take as long as 10 years. This would require management of the waste water - it could not simply be released into the floating harbour, as it would contain various heavy metal elements (such as lead) and other contaminants. The requirement to flood the vessel would also greatly restrict public access to the vessel, and impose a host of safety issues.

19.2. This simple technique is often employed in cleaning smaller objects, but is both very time-consuming, and requires large quantities of de-ionised water. The water must be corrosion-inhibited to prevent the metal from corroding while the process is underway, using chemicals such as sodium sesquicarbonate, sodium carbonate, or sodium hydroxide solution.[55] In a 'bath' of such size as the Great Western dry dock, it would be very difficult to control the mix of chemicals and to monitor the chloride content being diffused out of the hull.

19.3. In common with other chloride removal techniques, water diffusion does not completely remove chlorides. The ship would remain in its humid environment, the chloride corrosion would be maintained, albeit at a reduced level, and the long-term survival of the ship would be in doubt. The vessel's life, until around only 30% of material survived, could be between 50 and 55 years.

19.4. A variation of this method using a solution of sodium carbonate and chlorinated tap water is being tried by the Royal Naval Submarine Museum on the submarine *Holland I*, after a previous application of tannic acid coatings failed to halt corrosion. Despite this, research has shown that it is highly doubtful that all chlorides will be able to be removed.[56]

20. Option 6 - Treatment by Electrolysis

- Flood the dock, and the vessel, with electrolyte, bringing the solution least up to the level to which the ship was flooded in the Falkland Islands
- Remove all chlorides and corrosion products from the ship's interior and exterior by impressed current electrolysis
- Re-coat the hull with high quality paint system
- Repair and protect the caisson
- Install 24 hour heating system
- Install sophisticated fire prevention system

20.1. Removal of chlorides by impressed current electrolysis has been used since the mid 1940's successfully to stabilise smaller, more homogenous archaeological and historic metals from other maritime sites, such as cannon and anchors. This technique is being applied experimentally by the Hampshire County Council in the treatment of the First World War Monitor *M33*.

[55] Hamilton 1999 op cit chapter 9
[56] Watkinson 1996 op cit

20.2. *M33* is a steel vessel, contaminated with quantities of chloride ions, particularly below the water line. The internal surfaces below the water line are being treated to remove chlorides and corrosion products. The hull of the vessel is divided into sections, with each section filled with an electrolyte (tap water containing 1 part per million of sodium carbonate). Anodes following the profile of the hull have been made from stainless steel, using the hull as the cathode. An electric current, driven from a commercial battery charger, is passed between the two at the rate of 350 milliamps per square metre. Lead contamination from the remains of lead paint causes a scum to form on the electrolyte, and the anode to pit. This slows down the process and necessitates the emptying out of the electrolyte, cleaning out the hull and the replacement of the anodes.

20.3. Some parts of the hull exterior below the waterline also require treatment. Hampshire County Council are experimenting with capillary matting in order to carry the current electrolyte to areas that cannot be submerged. Here the anode takes the form of a mesh sandwiched between two layers of capillary matting. The electrolyte is pumped to the top of the capillary matting and flows down under gravity[57].

20.4. The process may not be successful for the *ss Great Britain*, for the following reasons:

20.4.1. The hull of *M33* is composed of riveted steel plating, in good condition, and manufactured this century to fairly close tolerances and to a high standard. The *Great Britain's* hull, however, is the product of early Victorian experimentation with wrought iron. Each plate is virtually handmade, and contains multiple slag inclusions and other impurities within its laminar structure.[58] This metal is severely degraded and corroded, with the products of corrosion having expanded in volume to slough off large areas of metal. The use of electrolysis carries with it the risk that the resultant evolution of hydrogen bubbles on the surface between cathodic and anodic areas would be produced **within** the metal's laminar fabric, flaking off individual layers on the hull plates.[59] In addition, the removal of corrosion product on the hull could be difficult to control over such a large surface area. The process could remove more of the ship's hull than could be considered acceptable.

20.4.2. The system at Portsmouth relied on filling the hull interior with electrolyte. This is easily achievable for M33, but not so for *ss*

[57] Peter Lawton, 1999, Personal Communication

[58] Metallographic examination in 1998 of a number of hull plates by Sandberg Consulting Engineers noted that they had 'large non-uniform slag inclusions in a coarse ferritic matrix typical of poor quality wrought iron' Test certificates 17499 /M/3, 4,5,6, and 7

[59] Hamilton 1999, op cit chapter 10b, and MacLeod, I 1999, Conservation of the ss Xantho engine Lessons learnt (unpublished)

Great Britain – the hull is appreciably longer, has more dead-rise, is not waterproof, has little compartmentalisation and is poorly supported externally or internally. It is extremely doubtful that the hull could support the weight of electrolyte (given that a cubic metre may weigh about one tonne). To flood the entire dry dock with the electrolyte would be difficult, as it would be virtually impossible to control the electrolyte mix, monitor the chloride content being diffused out of the hull, and ensure that fresh electrolyte could be exchanged for old, without contaminating the floating harbour with the by-products of the cleaning process, such as lead paint residue.

20.4.3. It is extremely doubtful that all chlorides would be removed using this process, and it would also be impossible to measure the extent to which chloride products were still present in the ship's laminar fabric, in her rivet holes, and under her lap joints. M33 has been able only to guarantee that chloride levels measured within their used electrolyte have reduced to 30 parts per million, which is the background chloride level of the solution. This is well above the level needed to ensure the metal's stability for adhesion of paint coatings[60], and even so, it does not guarantee that chloride levels in the treated metal have reduced to this level.

20.4.4. The caustic vapours and hydrogen gas produced in the dry dock during electrolysis may have health and safety and access considerations that would necessitate restricting public entry to the site. Combined with a lack of access to the interior of the ship and to the dry dock, this would severely curtail visitor admissions, on which the ss Great Britain Project relies for its long-term viability. By contrast, M33 has been able to carry out its cleaning uninterrupted by concerns as to public access – there simply is none.

20.5. This option may give the ship a lifespan beyond that for Option 1, but it may not present a means by which the ship can be preserved in perpetuity. As with other chloride removal options, the ship would remain in its humid environment, the accelerated chloride corrosion process would be maintained, albeit at a reduced level, and the long-term survival of the ship could be in doubt. The vessel's life, until around only 30% of material survived, could be between 45 and 50 years.

[60]There is no uniform standard for the maximum chloride level which will guarantee the stability of metal under a paint surface – it varies from 5 ppm for components used in the nuclear power industry to between 10 and 15 ppm in general structural engineering use. (Leighs Paints, personal communication 1999)

21. Option 7 - Record and deposit in an anhydrous or anaerobic environment

- Carry out full documentation and recording exercise on ship
- Remove key samples of iron and wood to museum
- Identify new anaerobic or anhydrous environment into which the ship can be moved
- Remove ship to the new environment until such time as future technology may permit her rescue

21.1. This option relies on the ability to move the ship to an appropriate environment. However, this is unlikely to be achieved without irreparable damage to the structure and hull,[61] and great expense in moving and relocating the ship. The combination of severe corrosion, multiple perforations of the hull, the large crack in the starboard side, and the additional weight of the replica engines, coupled with the stresses suffered during her time aground in the Falkland Islands, preclude her being floated from the dock without a massive program of hull re-patching and strengthening. Such an exercise could severely compromise the original material of the hull and frames, and thus conflict with the preservation requirements.

21.2. The likelihood that an appropriate environment could be identified accurately that would be either dry or anaerobic and safe from human or environmental action is also remote. Further, the removal of the ship to a remote location would reduce considerably the income available from visitors, to the point where the Project would cease to be viable, and essential security and presentational services could no longer be provided. While the vessel's fabric might well survive indefinitely once a location had been secured, a great deal of original fabric could be compromised and lost in the process.

21.3. A recording exercise would go some way to mitigating the loss of information about the ship, should the preservation goal of the Project fail. However, this option, recognised as a necessary exercise, would not entirely replace the tangible significance of the original material. Neither can it have the same educational or interpretational effect upon future visitors. Therefore, it should be the Project's aim to carry out full documentation in parallel with the preservation programme, not instead of preservation. The need for documentation is considered in greater detail in the recommendations below.

[61] L F Porter, Report on the Hull, State and Status of the ss Great Britain - 29 December 1997

22. Option 8 - Storage in situ under cover

- Construct a roof over the ship
- Treat the vessel by removing as much chloride as possible from the ship's interior and exterior by either electrolysis, water diffusion, or alkaline sulphite washing.
- Re-coat hull with high quality paint system
- Repair and protect the caisson
- Install 24 hour heating system
- Install sophisticated fire prevention system

22.1. Were this option to be taken, the environment around the hull exterior would be greatly stabilised. However, the damp conditions generally existing within the dry dock's weeping walls would nonetheless be maintained, together with the high relative humidity in the surrounding air. The environmental stability encouraged by the shelter may reduce the accelerated chloride corrosion, but may not stop it, and the long-term survival of the ship could be in doubt. Further, the construction of such a roof would impose an alien construction on the fabric of the dry-dock. The vessel's life, until around only 30% of material survived, could be similar to that of the chloride removal options, at between 45 and 50 years.

23. Option 9 - Storage in a sealed, inert environment

- Establish an hermetic seal around the vessel.
- Replace the air within the sealed area with an inert gas, such as argon, to prevent corrosion
- Repair, protect and seal the dry dock and caisson

23.1. The vessel would be surrounded by a sealed envelope containing an inert gas such as argon, which would replace the oxygen or moisture necessary to fuel the corrosive process. Such an approach could minimise direct running costs involved with her preservation, and may allow the preservation goal to be achieved more directly.

23.2. However, as noted previously, the nature of such a gas, and the need for perfect levels of sealing, would restrict visitor access substantially, impairing the ability of the Project to display and interpret the ship to the public, and rendering it inaccessible to researchers. The income available from visitors would decrease, to a point where the Project would cease to be viable, and essential security and presentational services could no longer be provided. If successful, it may secure a near indefinite life for the vessel.

24. Option 10 - Environmental control

- Control the environment inside and outside the ship to a relative humidity at or below 20% to stabilise and prevent accelerated chloride corrosion.
- Install 24 hour climate and structure monitoring system
- Research methods of corrosion consolidation and presentation of the conserved hull
- Provide supporting internal armature or external cradle for ship
- Repair, protect and seal the dry dock and caisson
- Install sophisticated fire prevention system

24.1. Experience elsewhere in the very long term preservation of archaeological objects, has shown that control of the environment around the object can be fundamental to its successful preservation. This is recognised clearly within the Museum and Galleries Commission Standards in the Museum Care of Larger and Working Objects, [62] and is the manifest explanation for the exceptional longevity and preservation of ships such as the Cheops barge, [63] the Gokstad ship, and HMS Unicorn.

24.2. While these vessels are wooden, and clearly subject to a different series of decay mechanisms, the same overall solution – protecting the ship within a controlled environment - is appropriate to the iron hull of the *Great Britain*. The corrosion of the *Great Britain's* metal is an electrochemical reaction, highly reliant on the presence of moisture in the form of rainwater, or high levels of relative humidity. Establishing a controlled environment in and around the ship in which these moisture sources are prevented from coming into contact with the ship's metalwork may therefore form a major part of the program to halt the corrosion process.

24.3. This can be done by protecting the ship as far as possible in a controlled environment, in which the relative humidity is kept at a stable, low, level. Electro-chemical corrosion of the metal should slow once the relative humidity drops below 40%[64] and will stop completely once a relative humidity level of 20% is achieved.[65] To understand the environment which surrounds the ship, the ss Great Britain Project instituted an environmental monitoring system in 1997. This has already shown both that high levels of relative humidity are present in the vessel's interior, and that there are extreme fluctuations in those levels. These fluctuations are themselves extremely

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[62] Museums and Galleries Commission, 1994, Standards in the Museum care of larger and working objects in Social and Industrial History Collections, MGC, London. In particular, Section 20 (p 71)

[63] The Cheops barge dates from 2500BC, and was preserved in extremely low levels of relative humidity. The Gokstad boat dates from AD 850, and was preserved in waterlogged, anaerobic conditions. HMS Unicorn was launched in AD 1824, and immediately placed 'in ordinary' or mothballed by constructing a roof on her hull.

[64] Pye, E, 1992, Conservation and storage: archaeological material, in Thompson, 1992, Manual of Curatorship, p415.

[65] Briggs, J R, in Cassar M,1999, op cit p 20, and Turgoose S, 1982, op cit pp 97-101

damaging, as they can lead to changes in dimension and so to stresses in the metal and in the protective coatings which have been applied.[66]

24.4. Dehumidification is a well recognised and well tried solution to the storage of metal museum objects, and for the storage of large metal machinery. It has been used since the 1950's by the US Military for long term storage of inactive ships, machinery and weapons.[67] Since the 1970's desiccant dehumidification has been successfully used by Swedish and Danish military for similar equipment.[68] It is now a standard treatment in the UK for protecting expensive military equipment and maintaining the same state of combat readiness. It is used, for instance, in dehumidifying the Tornado aircraft hangers at RAF St Athans. Dehumidification is also used for drying the outside of ship's hulls before application of paint systems.[69]

24.5. The control of the environment within the ship could be achieved using a large scale desiccant dehumidifier. This could be situated outside the vessel in the dry dock. Control of the environment outside the vessel is more problematical. It cannot be achieved without creating an artificial envelope around the ship. There are three main options:

25. Option 10(a) - Dehumidify inside a glass cocoon

25.1. The hull exterior would be encased in a cocoon of geodesic glass plating, closely following the shape of the hull (Figure 8). The space between the glass and the hull would be dehumidified, along with the hull interior. This option has the advantage of requiring low volume dehumidification plant, and no treatment work upon the dry-dock. The disadvantages are that the hull exterior may be almost completely hidden by reflection, that there would in effect be a visual and tactile barrier between the ship and the visitor, and that the attachment method of glass plate to hull may require perforation of the hull, and thus damage the original fabric. Further, dehumidification could not occur at the same time as consolidation and cleaning of the hull, (as for the other dehumidification options) but could only occur after this had happened. There would be considerable ongoing loss of material during this time-lag. Preservation of the surviving material, once the system was in place, is likely to be excellent.

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[66] Pye, E, 1992, op cit p417

[67] Harriman, L, ed, 1990, The Dehumidification handbook, Munters, Amesbury 1990

[68] There are two types of dehumidifiers: Desiccant dehumidifiers draw air over a drying agent in a rotating drum. Refrigerant dehumidifiers draw air across refrigerated pipes to condense out the moisture.

[69] Harriman, 1990 ibid p

Figure 8 Concept drawing of the ship dehumidified inside a glass cocoon

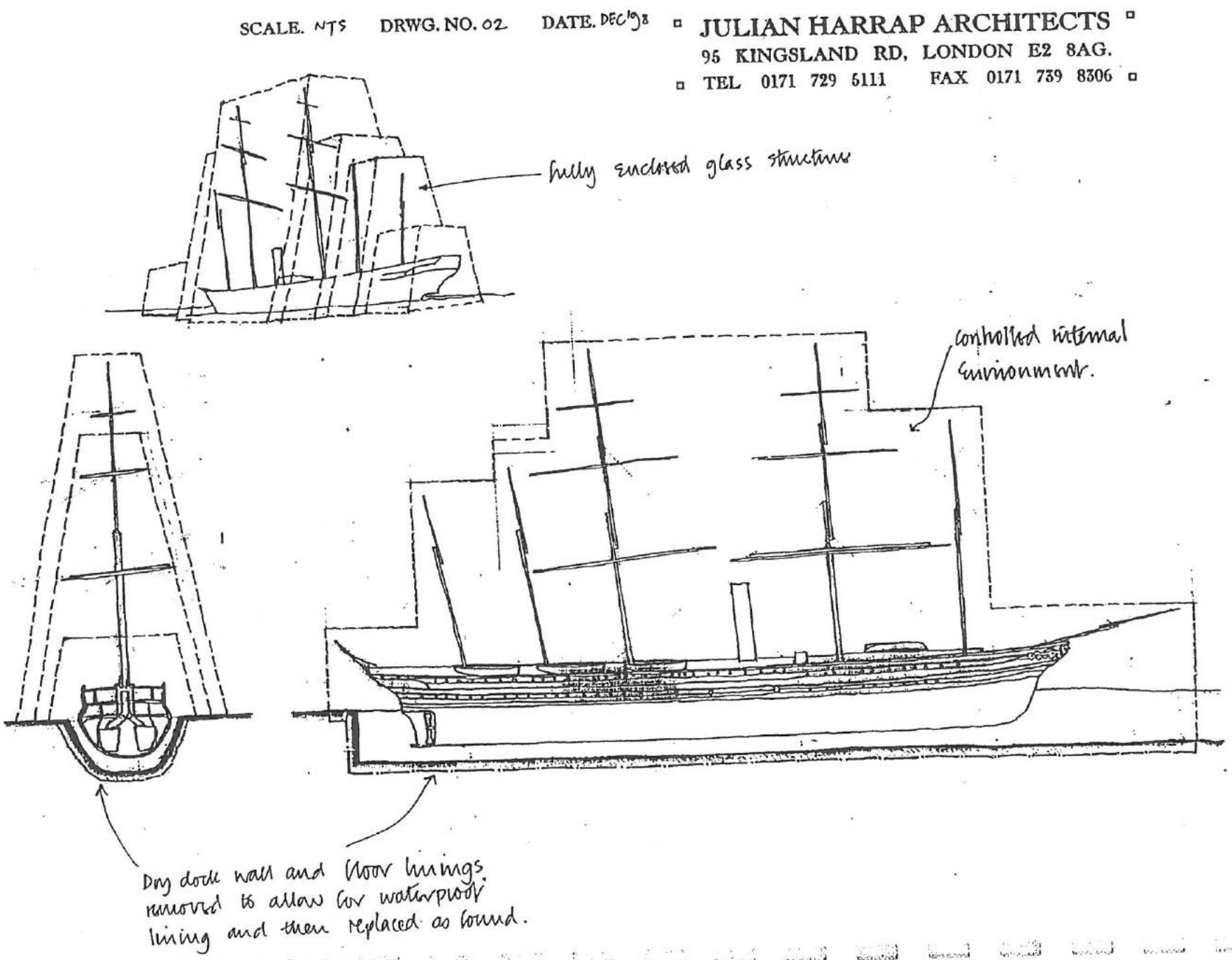

Figure 9 Concept drawing of the ship dehumidified under a glass roof

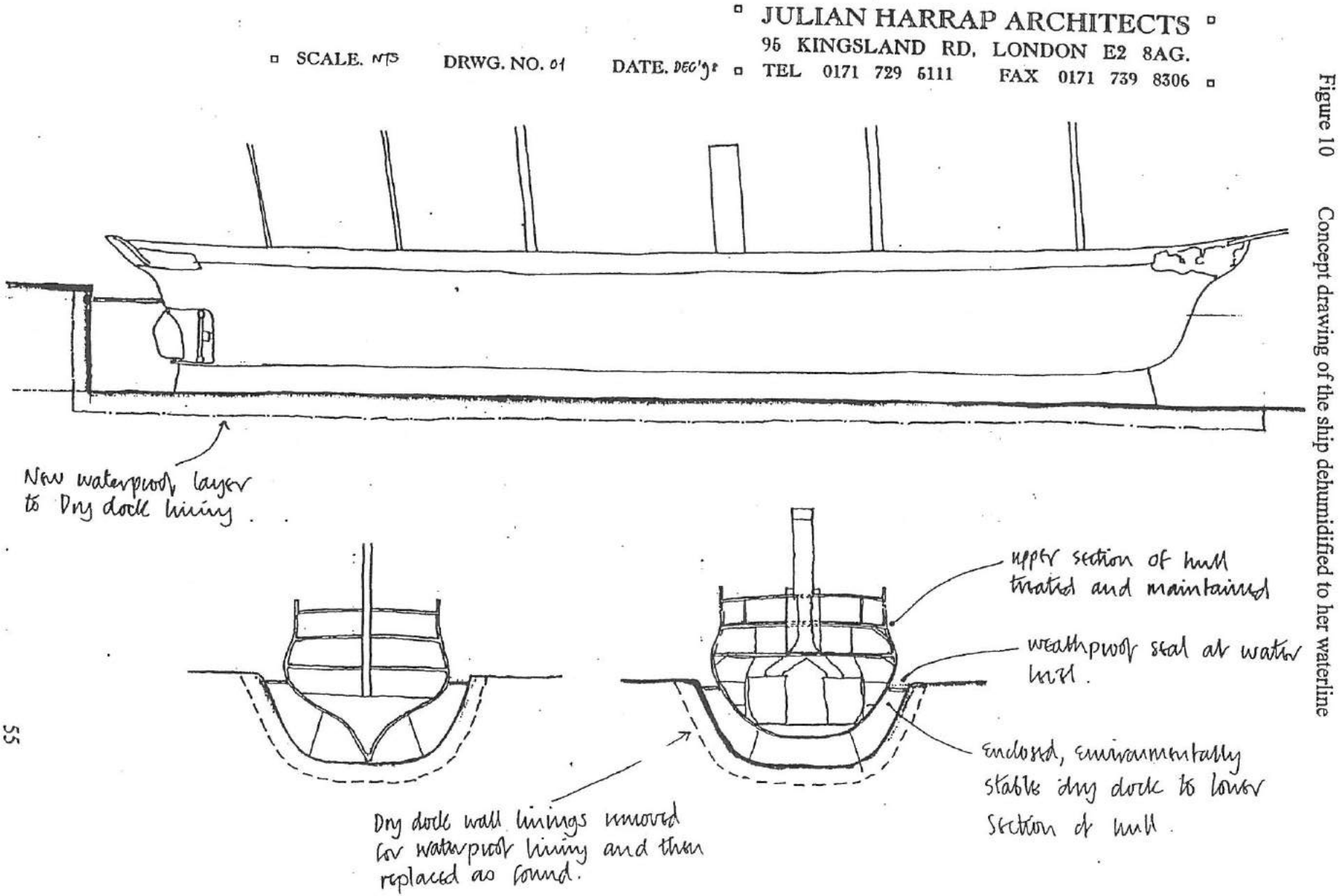

Figure 10 Concept drawing of the ship dehumidified to her waterline

26. Option 10(b) - Dehumidify under a glass roof

26.1. A glass roof could be built over the whole ship, either just above the weather deck, or completely over the masts (Figure 9) Either approach would satisfy the need to preserve the original fabric of the vessel, with excellent preservation of original material. Access would also be excellent. The visitor would be able to walk unimpeded around the original metal of the hull. However, the disadvantage to both schemes is that the roof would be extremely intrusive, destroying the dry-dock context, and thereby substantially reducing the quality of visitor interpretation

27. Option 10(c) - Dehumidify under a modified waterline

27.1. A controlled environment could be created by glazing over the ship's dry dock, at the level of the ship's waterline, to create a seal between the ship and the side of the dock (Figure 10). The overall impression given to the visitor would be that the ship lies afloat. A controlled environment would be maintained in the dry-dock, under the glass roof, protecting the area of the ship below the waterline. A controlled environment would also be maintained within the interior of the ship. Approximately 18% of the vessel's original ironwork (the element in the exterior topsides where there are negligible chlorides), would not be dehumidified. The whole of the upper deck would remain exposed, but there is no original material here.

27.2. This solution will present the vessel in a manner that greatly aids the quality of visitor comprehension and interpretation. The proposed 'waterline' dehumidification scheme gives the illusion of the ship floating or riding at anchor. By contrast, options that see the ship being encased in a complete 'glass box' would create significant intrusion into the dock yard context.

27.3. Visitors viewing the hull from the bottom of the dry-dock will also be presented with a unique 'underwater' aspect, that will provide a sense of drama by emphasising the huge underwater presence of the ship, reinforcing the object's nature as a formerly floating, mobile ship, and reinterpreting the dry-dock as a 'building' that was designed to be flooded.

27.4. Leaving the exterior topsides exposed to the environment can be acceptable from a conservation perspective. This area is in a fairly good state of repair, as confirmed in the visual, acoustic and chloride surveys, as well as by the ultra-sound testing on the steel plating.

27.5. This option is able to deliver long term preservation of the ship, with a loss rate of original fabric of less than 0.07%[70], will arrest the accelerated chloride corrosion to which the ship is currently subject, and will give an enhanced visitor experience.

[70] The ss Great Britain Project's 1998 Mission Statement set as its target a loss rate of no more than 0.1% per annum

27.6. There are no health and safety implications – indeed, experience in other dehumidified spaces suggests that as the air is drier and more frequently changed than in some workspaces, airborne bacteria are 'cleaned' out of the atmosphere.[71] Indeed, relative humidity within passenger aircraft cabins is regularly maintained at levels far lower then 20%.[72]

27.7. It is a completely reversible process, if the humidity level is controlled in a well monitored manner, and fluctuations are avoided. In common with the other dehumidification measures, it has the drawback of being fairly costly, both in terms of capital equipment, (plant, ducting, and sealing measures) and in terms of running costs (gas and or electricity). However, by creating a proper museum-like environment for the vessel, the corrosion process can be stabilised, and her remaining fabric can be adequately treated. This option may secure a near indefinite life for the vessel.

28. Selection of Preferred Option

28.1. Analysis of each option, having regard to the selection criteria in section 14. clearly shows that option 10 (a, b, and c) are the only ones able to deliver long term preservation of the ship, with no substantial loss of original fabric, in an achievable, cost effective, reversible manner, and that also control the effects of chloride accelerated corrosion.

28.2. Option 10 (c) is the only one of these that presents the vessel in a manner that leaves the vessel fully accessible to the public, and enhances the quality of visitor comprehension and interpretation, rather than detracts from it. For this reason, Option 10(c) is the preferred choice of treatment.

[71] Stuart Gale, Sutton Seeds, 1999, Personal Communication

[72] Peter Meehan, 1998, Personal Communication. On one flight, a relative humidity of 0% was recorded

29. STRUCTURAL OPTIONS[73]

29.1. Given the variable nature of the hull framing and plating, and the difficulty in assessing how corrosion within the ship's various elements may have depleted its overall strength, three basic approaches have been considered to provide structural support for the ship.

29.1.1. Provide a cradle for the ship that will carry the loads currently borne by the ship structure

29.1.2. Provide an armature within the ship that will make the internal structure redundant

29.1.3. Provide a compound armature within the ship which relies on connecting the existing keel, bulkheads, stringers and frames to strengthen and recreate a sound structure

29.2. Alternatives 1 and 2 make the existing structure redundant. These imply an addition to the interior or exterior that may impinge on the appearance of the vessel.

29.3. Alternative 3, on the other hand, is more integrated with the ship's fabric, and would retain the delicately balanced ship as she stands. It would attempt with minimum intervention to reinforce existing decayed elements such as the frames and tank tops in a fully reversible way, would retain the bulkheads in their present configuration and strengthen and reinforce the bracketed stringers conceived by Brunel. Any post 1970's adaptations and discontinuities to the ship's structure could be added to, removed, or adapted as necessary.

29.4. The columnar structure of the ship could be reinforced to transmit loads from deck to tank top. All these loads would then be concentrated on to the keel which would serve as the foundation. The concentrated linear load would then pass through the keel blocks to a new beam inserted above the dry dock keel stones to ensure as even a distribution as possible to the existing foundation system.

29.5. Each of the three options is practicable and reversible. However, alternative 3 would provide for the vessel's security in a much more discrete, harmonious manner than the other two alternatives, as well as giving maximum accessibility to the interior and exterior. Its effect on the quality of visitor interpretation would be minimal. For these reasons, Alternative 3 is the preferred choice.

[73] This section is largely reliant on information provided by Julian Harrap Architects

RECOMMENDATIONS FOR PREFERRED OPTION

30. Recommendation 1 Pre-treatment documentation and survey

30.1. As part of any treatment all pre-1970s material should be surveyed and documented before, during and after the conservation process. Where conservation treatment of a particular area or object may affect its context, the documentation demands equal emphasis and first priority. The basic attitude and approach should be cautionary.

30.2. Proper records should include detailed measurements of the vessel, including existing hull lines, indications of any deformities, including hogging or sagging, all the pertinent data on relationships between objects and parts of the ship and sequencing of various elements, including descriptions of historic fabric and fastenings, identifications, descriptions, and the complete conservation procedure for each area.[74] Much of this information will largely be obtainable only by observation and recording by the conservator.

30.3. The form such records take may include radiographs, black and white photographs, plans and drawings, colour slides, film and video, archaeological sketching,[75] and notes on the preservation procedures utilized. Since all photographic negatives and prints will be kept as a permanent record, they should undergo archival processing and be stored in a cool, dry, dark cabinet for maximum protection. Digital images are also recommended. All records should be well organized in a well-designed and readily accessible database.

30.4. The conservation data should record the treatment history of every specimen, thereby accumulating valuable research records on the evaluation of particular conservation techniques. If any part of the ship needs re-treatment in the future, there should exist information on why the original treatment failed and how to reverse the process.

30.5. The form of survey and documentation will require considerable input from the curator. It will be important that the information is accurate, accessible to those that will have to use it and in a form that can be preserved and read for many years.

30.6. All extraneous, non historic material should be removed from the ship. Much of this is a fire risk, a potential source of moisture & organic acids and unnecessary weight.

30.7. Above all, in all conservation work on the ship a preliminary examination of the area or object must be made in order to determine a course of action that will preserve its integrity and maintain any significant attributes or any

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[74] US Department of the Interior, 1990, The Secretary of the Interior's Standards for Historic Vessel Preservation Projects, with guidelines for applying the standards. US Department of the Interior, National Parks Service, p 19

[75] Museums and Galleries Commission, 1994, Standards in the Museum care of larger and working objects in Social and Industrial History Collections, MGC, London p 18

features relating to its manufacture or microstructure. In some cases, the ship's plates may entirely or largely consist of corrosion layers, in which case they should be preserved and not indiscriminately removed.[76] Only in those instances where the corrosion is unstable or conceals underlying details should it be removed. The main aim should be to stabilize the metal so that it retains its form and diagnostic data.

31. Recommendation 2 Monitoring of the ship and her environment

31.1. The current continuous monitoring regime of the ship's environment should be expanded. This will enable decisions to be taken as to the efficacy of the dehumidification program in each part of the ship. Given that temperature and relative humidity can vary widely within an individual room, careful consideration will therefore have to be given to installing an appropriate number of sensors within the ship. These sensors should be fitted once most of the interpretative building work and dehumidification ducting has been completed.

31.2. A complementary monitoring regime, measuring ship movement and the weights imposed on the ship's shores and keel, should be instituted. This will assist in determining whether and to what extent there is dimensional change and movement in the hull and the dock, will anticipate problems, and provide early warning of any movement that may damage the ship. It will allow more informed decisions to be taken on the placement of replacement shores, and will assist in identification of areas of the ship that will require interior or exterior structural support.

31.3. To this end the timber shores should be replaced with purpose-designed, adjustable steel shores and supports, to which are attached load sensors. It may also be possible to fit the new keel support system with a similar system, and to fit movement measurement sensors. These should all be linked to the environmental monitoring system, allowing temperature, movement and load for all parts of the ship to be related to one another. The primary aim of such a system would be to help prioritise maintenance and inform curatorial decisions, but also to forewarn of serious changes if either the loading in the ship changes dramatically or the dock floor moves, or if breakdown of dehumidification equipment occurs.

31.4. Alongside the environmental monitoring programme, a regular programme of visual monitoring of the vessel's condition should instituted as part of the regular maintenance and cleaning schedule.

[76] Plenderleith and Werner, 1971 pp16-17

32. Recommendation 3 Dehumidification

32.1. The ship should be protected from further chloride-accelerated corrosion by removing moisture from the hull of the ship, and then maintaining the ship in a museum style controlled environment, at a stable relative humidity level of no higher than 20%.

32.2. The controlled environment should consist of two elements:

32.2.1. a vapour impermeable seal (such as a glass roof) between the ship and the side of the dry dock, at the level of the ship's waterline, which would allow a controlled environment to be maintained in the dry-dock, under the vapour seal roof, protecting the area of the ship below the waterline, where the ironwork is deteriorating at the fastest rate, and

32.2.2. an equally impermeable deck seal which allows the interior of the ship to be controlled. The key requirement, fundamental for maintaining protection from the weather and for ensuring that the hull can be adequately dehumidified, is to ensure that the steel weather deck is extended over the wooden bulwarks, and connected to the ship's hull to form a completely airtight and watertight seal. This will also have the ancillary (but critical) effect of helping to conserve the timber of the bulwarks themselves.

32.3. The vapour seal should take the form of a glass roof, which will give the overall impression to the visitor that the ship is afloat. This could be further enhanced by providing a layer of water over the plate, which could also reduce any thermal gain through the glass, and assist in cleaning the glass. The glass roof will need to be supported independently from the ship, to ensure that the ship and the dock can move independently and that neither is restrained from seasonal or progressive movement and to reduce the load on the ship.

32.4. Some rooms within the ship that are not in direct contact with the hull iron may be dehumidified to a lesser degree than those in contact. This may reduce the running load on the dehumidification equipment. If this course of action is taken, it will be important that leakage of air from one type of area to the other is kept to a minimum. This will require work in dividing up and sealing the ship. The exact form of division will be a matter for discussion with the curator.

32.5. Ideally all the outermost panelling of the accommodation should be dismantled and moved inboard, by at least ¾ metre. This should provide a gap large enough for maintenance and a free flow of dehumidified air. The accommodation should be carefully sealed off from the hull allowing the gap behind to be a fully sealed area.

32.6. All areas to be dehumidified will require careful cleaning, as well as sealing off. They could be painted, although this decision will be informed as much by curatorial considerations as conservation ones.

32.7. The system will be able to detect and control condensation on the exterior and interior of the hull

32.8. The system could be capable of responding to the ship's environmental monitoring system

32.9. The machinery, ducting, and any system of air locking will be installed with a minimum of interference to the physical integrity of the ship.

32.10. Any machinery or ducting should be placed as unobtrusively as possible, and be placed so as not to hamper other conservation treatment or research work.

32.11. The bulk of the dehumidification system should where possible be placed outside the ship's hull, to allow ease of maintenance and access for both the ship and the machinery and to prevent damage to the ship from excessive loading, vibration or fire.

33. Recommendation 4 The need for controlled decrease in humidity

33.1. During the period when the environment within and around the ship is being brought down to the appropriate humidity level, constant monitoring of the state of the ship's hull metal will be necessary. Condensation within the hull is one factor that may have to be guarded against during this time.

33.2. If the temperature outside the ship is low, such that the interior surface of the hull has a lower temperature than the dewpoint temperature inside the ship, the air on the inside of the ship may condense, with moisture forming on the inside of the ship. For instance, if the temperature inside the ship was 25 degrees, the Dew Point at which moisture would form would be 1 degree.

33.3. One potential solution is to fit dewpoint controllers to the hull interior.[77] These measure the RH at the surface of the metal rather than in the air. If there is any danger of condensation, these will control the dehumidifying and air conditioning machinery to allow the temperature inside the ship to be either increased or decreased, and thus the dewpoint, while the RH is kept at the same level. The following table shows how temperature inside the ship can be manipulated (whilst maintaining a constant RH of 20%) to bring the dewpoint down to a level where condensation will not occur.[78]

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[77] Harriman 1990, op cit

[78] Chartered Institute of Building Services, Standard Psychometric Chart, reproduced in Thompson G, 1999, The Museum Environment 2nd ed p211

Table 4 Relationship between Dewpoint and temperature

Temperature inside the ship (Degrees)	Hull dewpoint at which condensation forms (Degrees)
25	1
20	-3
15	-7
10	-10

33.4. It is possible that the area between the dehumidified metal of the waterline and the 'humidified' area above in the topsides could create something of a galvanic cell, with corrosion occurring at their meeting point. It may be possible to guard against any possible corrosion by taking one or some of the following steps:

33.4.1. Ensuring the metal in the exterior topsides (the area more likely to be electro-chemically active) is adequately shielded from moisture and oxygen. A well maintained paint coating may provide an effective barrier; or

33.4.2. Providing the hull with some form of galvanic protection. This could take two forms. The first type might comprise a sacrificial anodic girdle, comprised of zinc, or aluminium alloys, electrically connected to the iron hull via copper cabling. The anodic metal would be possibly formed in strips of a couple of feet in length, and fitted around the hull at the level of the waterline, sandwiched between the hull and the glass plate. The iron hull would gain cathodic protection as the electrons released from the corroding anodic metal flowed through the copper wire into the hull. Such a protective system has been used successfully in a number of marine archaeological excavations, notably those on the engine of the ss Xantho, and on artefacts from HMS Sirius and the Duart Point wreck.[79] Any such fixture would have to be readily removable and replaceable, and unobtrusive. Alternatively, it may be possible to make use of the bolt holes which were drilled in the topsides during the 1880's, to fit a network of sacrificial anode plugs in the place of the current cosmetic bolts. These could be electrically connected to each other and to a low voltage power source to provide a matrix of sacrificial metal.

33.5. While the overall process of dehumidification is well tried and in common use for storage purposes worldwide, over the initial period when the system is initiated it will need constant monitoring and adjustment. The potential problems discussed may never occur, and similarly, if they do occur, other

[79] MacLeod 1987, 1995 and 1999