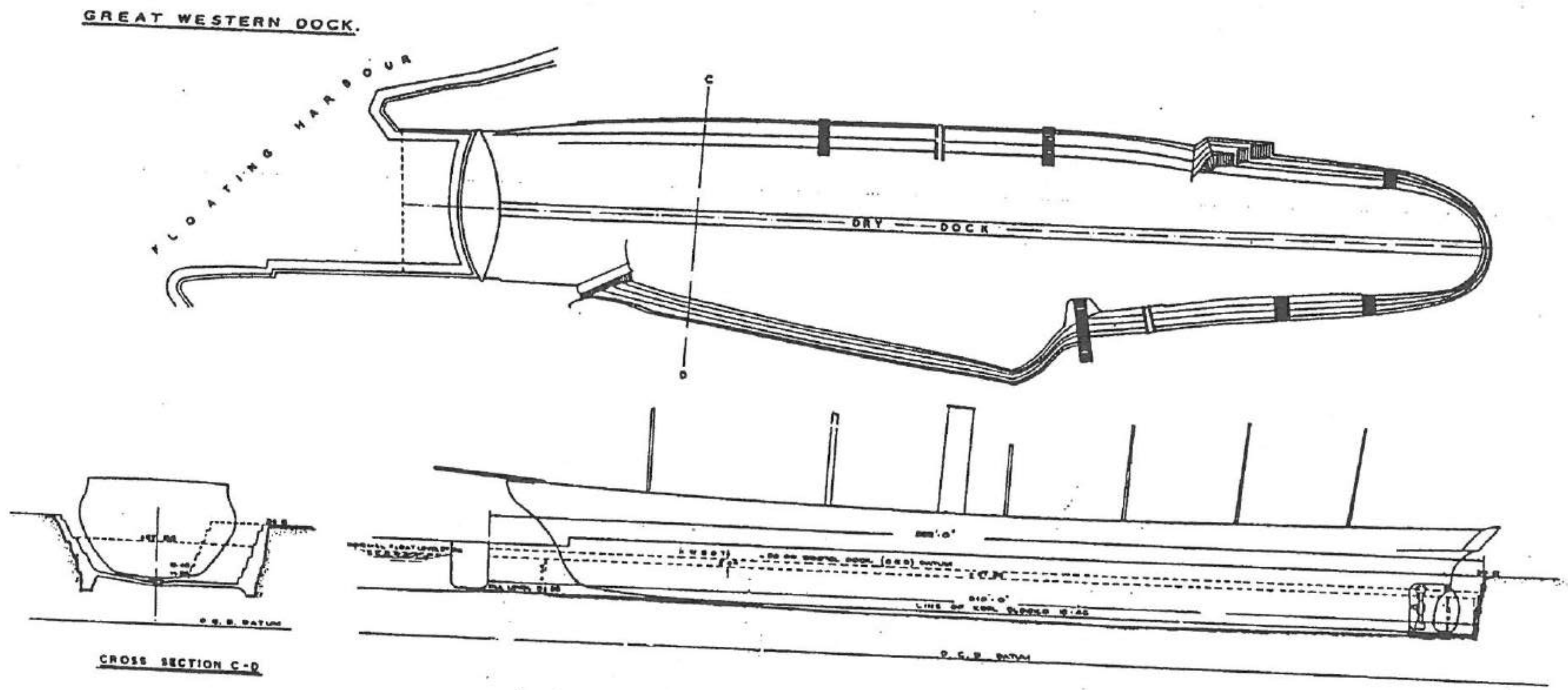


Figure 2. Dry Dock Layout

Temporary Dam

The proposed temporary wall will have to support a maximum 4.6m depth of water and silt across the dock entrance to allow a full inspection of the existing dry dock caisson.

The underlying soft ground and the depth of water to be excluded preclude the use of a cantilever sheetpile wall. It is proposed that a propped sheetpile wall is used to form the temporary dam. Props from the existing dock walls will provide support for the wall. The proposed temporary dam is shown in figure 3.

The wall alignment has been set to avoid the remains of the original eastern pier at the entrance to the dock. The pier appears to have been cut back since the construction of the dry dock. The remains are identified in the Archaeological Appraisal.

Precast reinforced concrete load spreaders have been provided at the prop ends. These with the props and sheetpile wall can be removed once the caisson inspection is completed.

The design proposed within this document is based on available information. Should this project proceed a site investigation would be required to establish actual site conditions and obstructions.

Work Sequence

1. Dredge dry dock entrance to clear silt and debris.
2. Determine extent of the existing east pier below water level to set the temporary sheetpile wall alignment.
3. Install sheetpiles.
4. Construct temporary mass concrete plugs at each end of the sheetpile wall.
5. Install precast concrete load spreaders on dock walls.
6. Install temporary support/restraint to the existing caisson to maintain its stability when the impounded water is removed.
7. Reduce water level within the impounded area by 800mm
8. Install Steel waling and tubular steel props.
9. Complete dewatering of the impounded dock area to allow full inspection of the existing dock caisson.

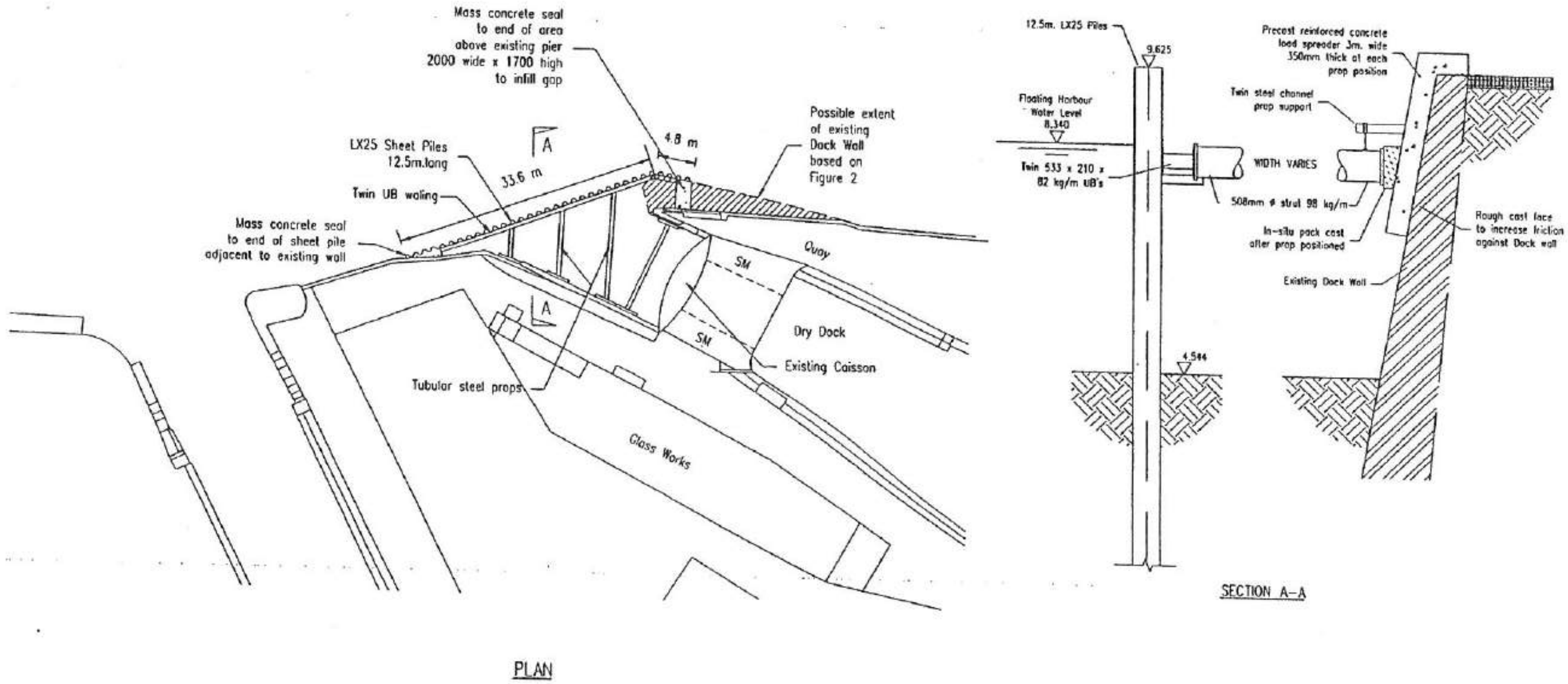


Figure 3 Great Western Dry Dock Temporary Dam Proposal

References

1. HADFIELD C. and SKEMPTON A. W. *William Jessop, Engineer*

2. CORLETT E. G. B. *The Steamship Great Britain* Trans. R. Inst. Nav. Architects, 1971.

3. WESSEX ARCHAEOLOGY *Great Western Dry Dock and Quayside Archaeological Appraisal*

4. BUCHANAN R.A. *I.K. Brunel and the Port of Bristol*. Trans. Newcomen Soc., 1969 –1970.

5. *Civil Engineering Heritage, Wales and West Central England* Thomas Telford Publishing.

Appendix G

Report on the ss Great Britain's scuppers and on-ship drainage
Maurice Ball, 1998

To: Matthew Tanner ✓

24 August 1998

From: Maurice Ball

Copies: Frank Porter
Chris Young

ss GREAT BRITAIN DECK DRAINS - PRESENT AND FUTURE

This report cannot be as complete as I would wish as the deck drainage grids are under the "loose" margin boards most of which are not loose and cannot be lifted due to expansion or warping of the wood or dirt collecting between the margin boards and adjacent fixed planks. Therefore the position and condition of the grids cannot be checked.

The attached deck plan shows the positions of the deck drainage grids (except for P4 which has not yet been installed.)

1. DRAIN PIPE LAYOUT - PORT SIDE

1.1 Forecastle PF and Weather deck P1

Refer to the layout drawing

1.2 Weather deck P2

Refer to the layout drawing

1.3 Weather deck P3

Refer to the layout drawing

1.4 Weather deck P5

Discharge through a flexible tube through the hull at a high level

1.5 Weather deck P6 and P7

Holes are cut in the deck but no pipes are connected. *Holes blanked off.*

2. DRAIN PIPE LAYOUT - STARBOARD SIDE

2.1 Forecastle SF and Weather deck S1

Refer to the layout drawing

2.2 Weather deck S2 and S3

Refer to the layout drawing
Water collected by grid S2 is discharged at the side of the forward entrance and is collected again by the grid at the side of the entrance

2.3 Weather deck S4 and S5

Holes are cut in the deck but no pipes are connected. The holes are blanked off

NOTE The term "grid" is used wherever there is a drain hole cut in the deck. It may be cast with narrow slots or a wire grille as mentioned under 3.5 which we shall probably use in the future. At present some deck drain holes have neither type.

3. ACTION REQUIRED

3.1 Lift loose margin boards and modify to make them easily removeable.

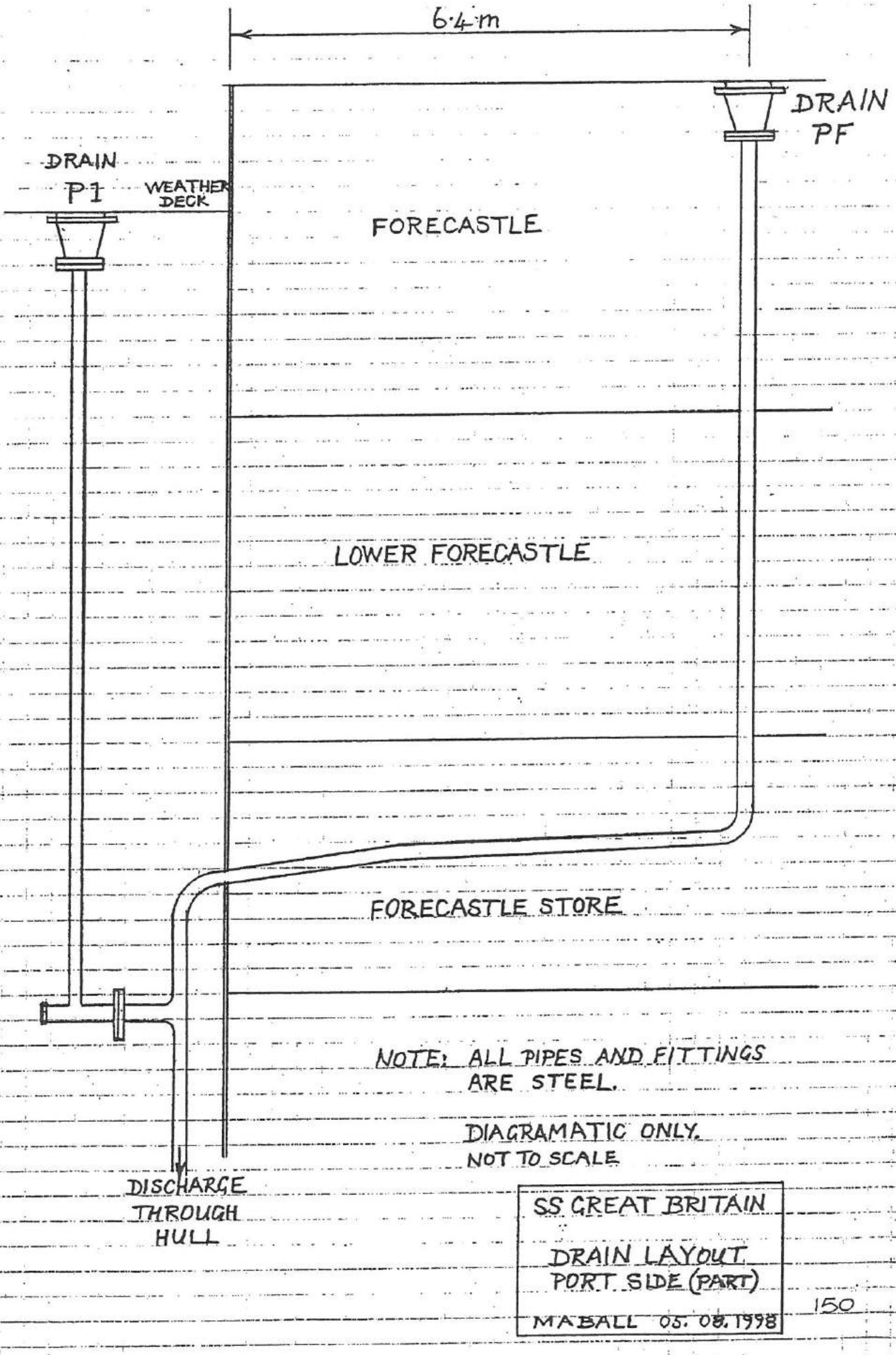
3.2 Establish a maintenance routine to check and clean the deck drainage grids and clear any accumulation of rubbish at the deck margins.

3.3 Run tests to check whether the present and proposed grids are sufficient in number and in the best positions to minimise standing water.

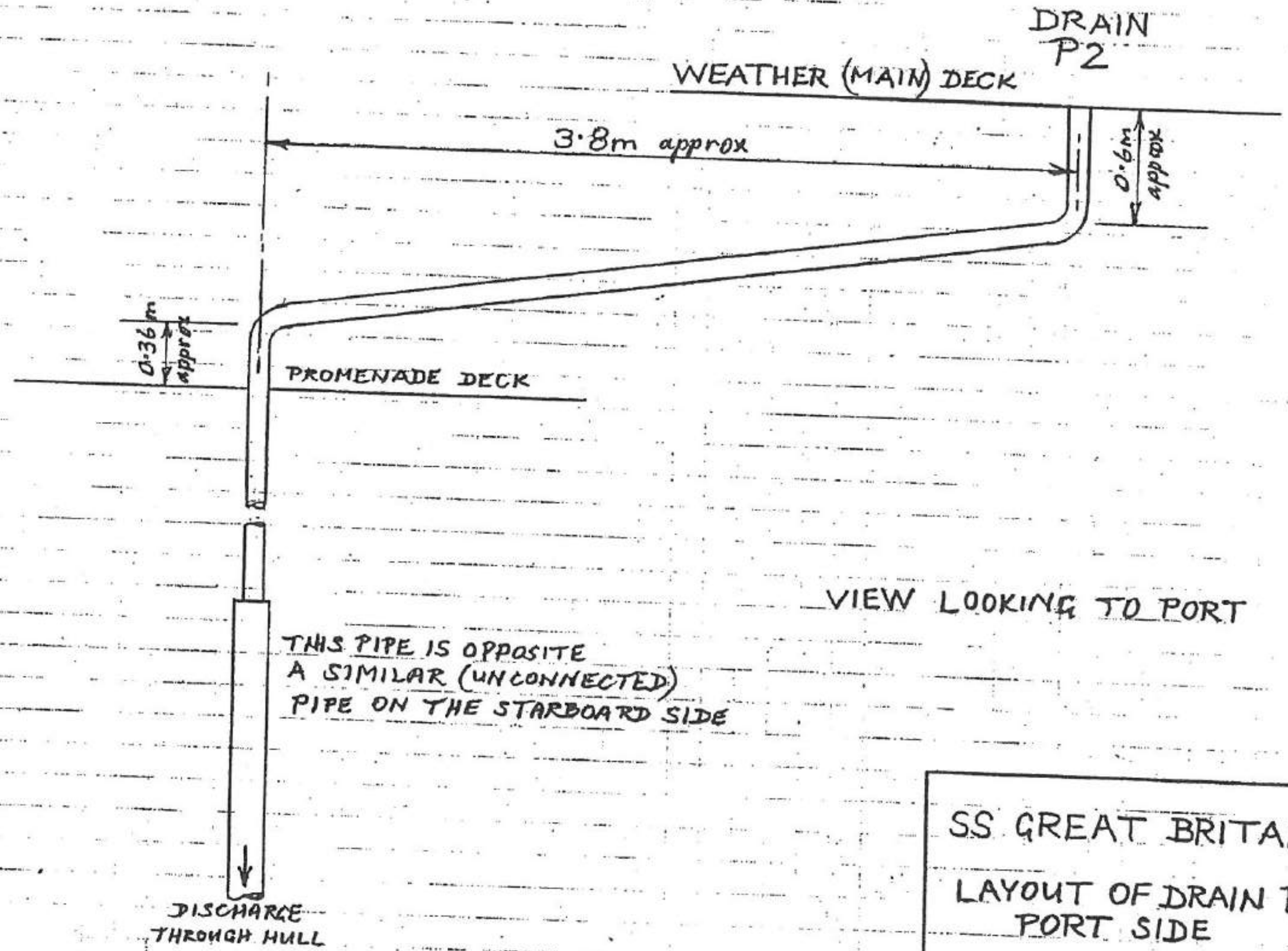
3.4 Establish an overall principle for the drain pipe runs, for example, individual pipes discharging through the hull or one or more networks of pipes with fewer discharge points (if practicable).

3.5 Design a suitable interface between deck and pipe (where one does not exist), easy to make and able to keep leaves and rubbish out of the pipe system. This might incorporate a wire grille similar to the one I drew 25.03.96. (COPY attached)

3.6 The forward (concrete) section of the forecastle deck requires its own drainage as it is lower than the planked section. There are at present pipes port and starboard which collect the water but these pipes are cut off about 150mm below the steel deck. This is clearly not satisfactory. It may be better to try to channel the water under the planked area.


6·4 m
DRAIN PF
DRAIN P1
WEATHER DECK
FORECASTLE
LOWER FORECASTLE
FORECASTLE STORE
NOTE: ALL PIPES AND FITTINGS ARE STEEL.
DIAGRAMATIC ONLY.
NOT TO SCALE
DISCHARGE THROUGH HULL
SS GREAT BRITAIN
DRAIN LAYOUT
PORT SIDE (PART)
M A BALL 05. 08. 1998

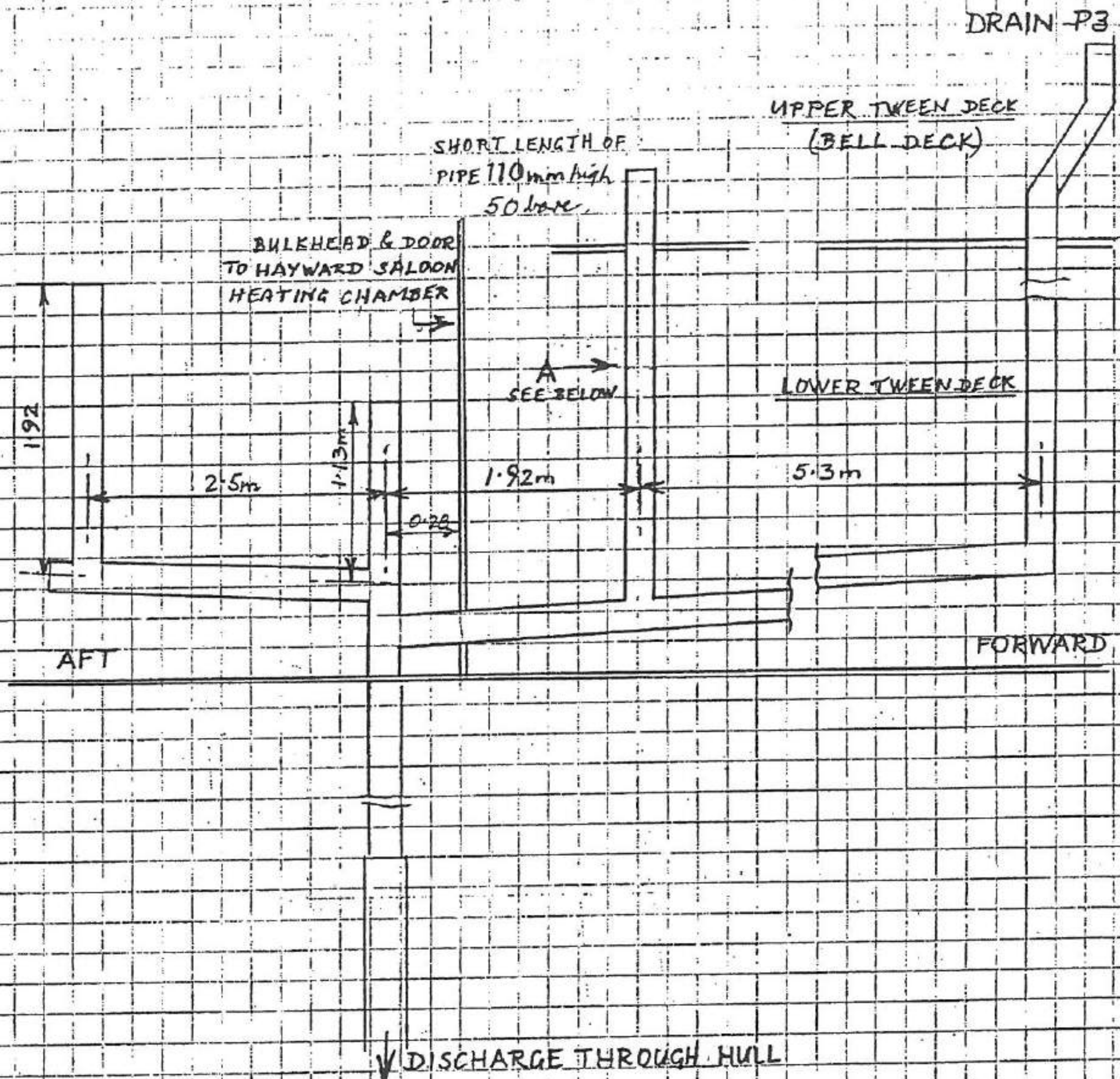
150

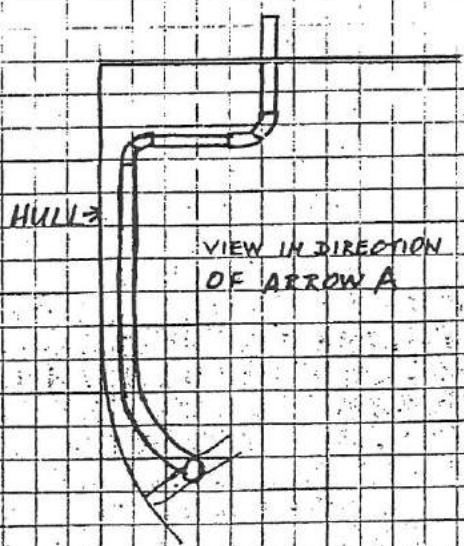


SS GREAT BRITAIN

LAYOUT OF DRAIN P2
PORT SIDE

M.A BALL 09. 10. 1997

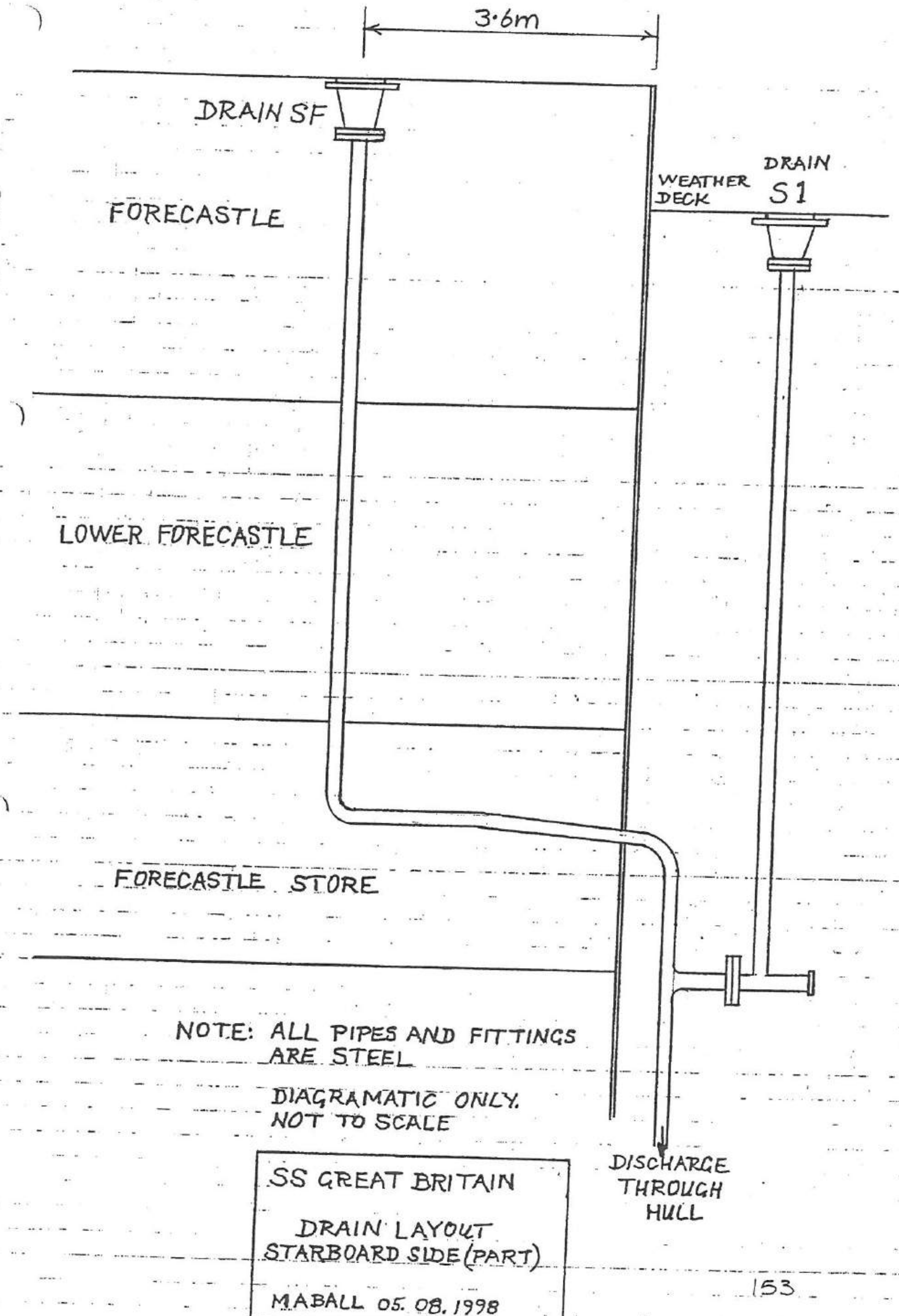


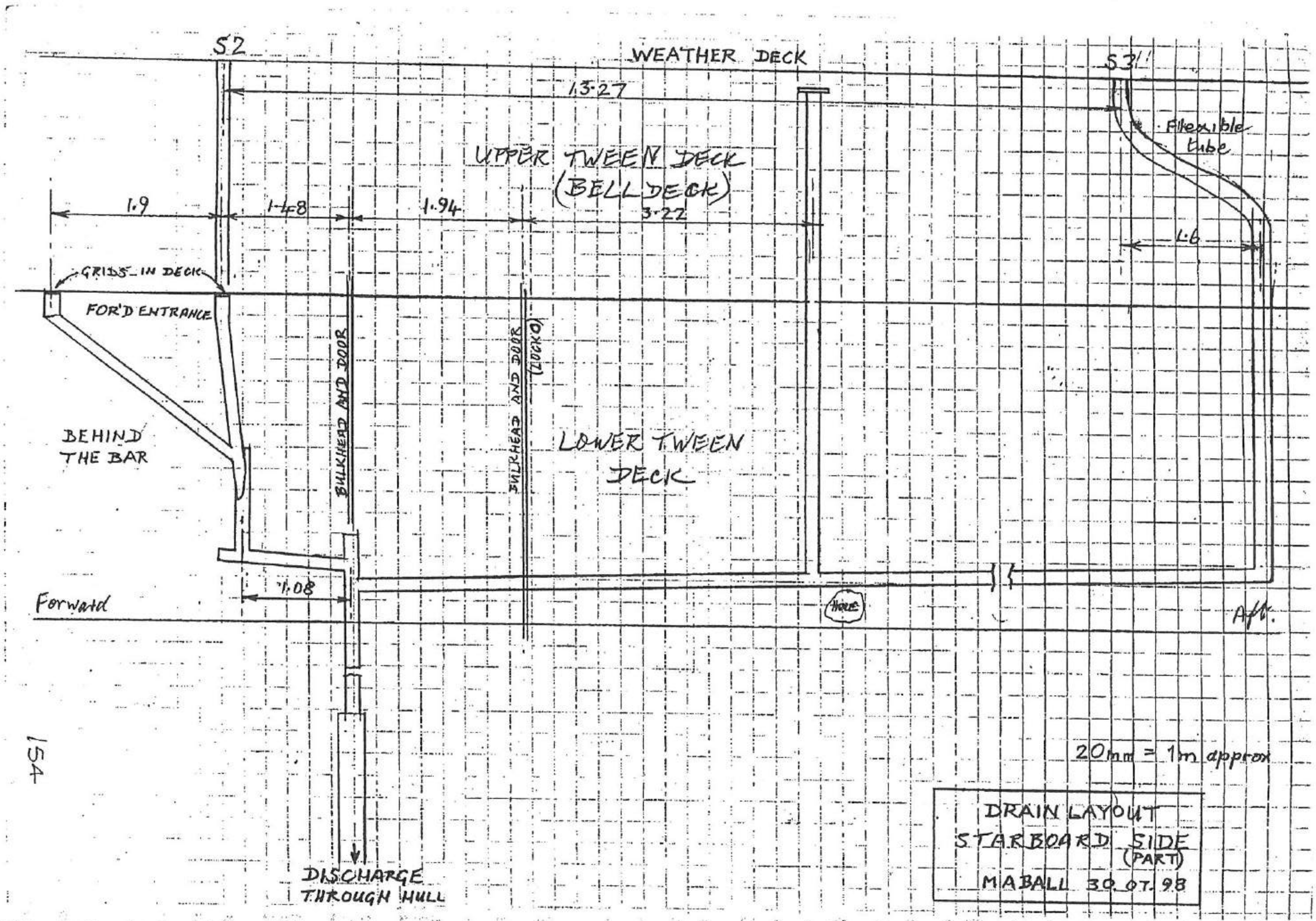


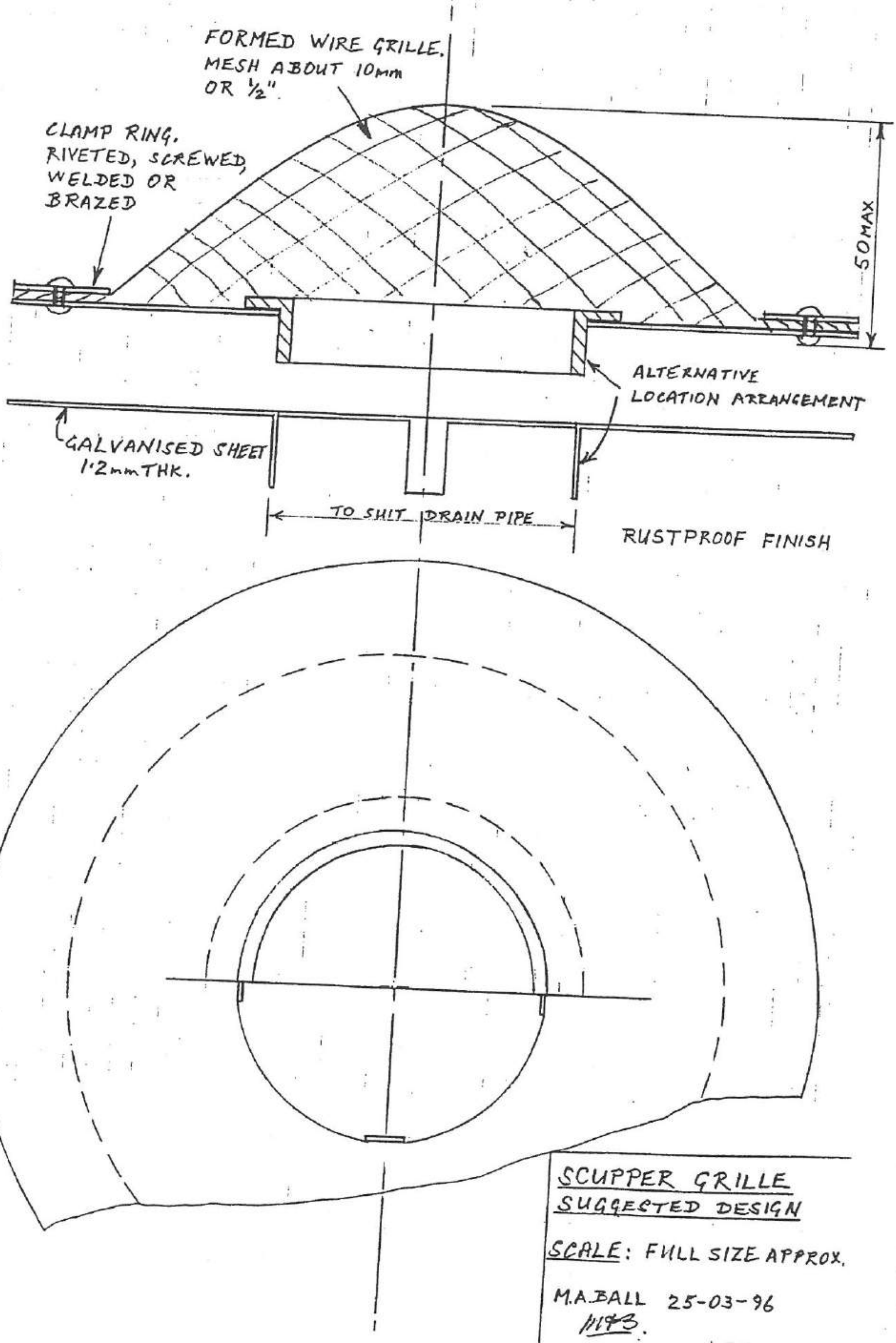
SS GREAT BRITAIN

DRAIN LAYOUT
PORT SIDE (PART)

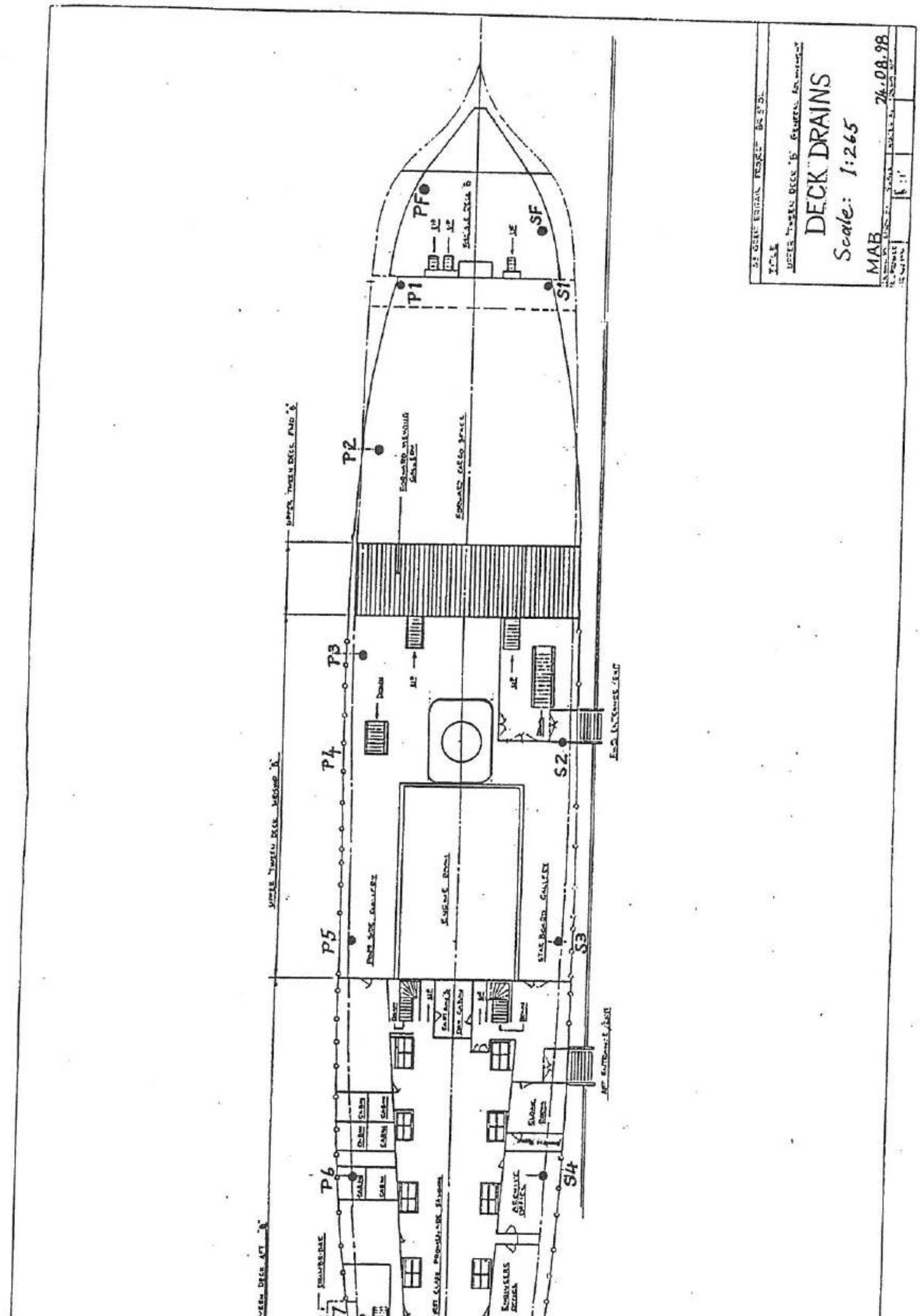
M. A. BALL 30.07.98


3·6m
DRAIN SF
FORECASTLE
WEATHER DECK
DRAIN S1
LOWER FORECASTLE
FORECASTLE STORE
NOTE: ALL PIPES AND FITTINGS ARE STEEL
DIAGRAMATIC ONLY. NOT TO SCALE
DISCHARGE THROUGH HULL
SS GREAT BRITAIN
DRAIN LAYOUT STARBOARD SIDE (PART)
M.A.BALL 05. 08. 1998


S2
WEATHER DECK
S3
13·27
UPPER TWEEN DECK
(BELL DECK)
Flexible tube
1.9
1·48
1.94
3·22
1·6
GRIDS IN DECK
FOR'D ENTRANCE
BULKHEAD AND DOOR
BULKHEAD AND DOOR
(LOCKO)
BEHIND THE BAR
LOWER TWEEN DECK
1·08
Forward
Aft.
DISCHARGE THROUGH HULL
20mm = 1m approx
DRAIN LAYOUT
STARBOARD SIDE
(PART)
MA BALL 30 OT. 98



FORMED WIRE GRILLE.
MESH ABOUT 10mm OR ½".
CLAMP RING. RIVETED, SCREWED, WELDED OR BRAZED
50 MAX
ALTERNATIVE LOCATION ARRANGEMENT
GALVANISED SHEET 1·2mm THK.
TO SUIT DRAIN PIPE
RUSTPROOF FINISH
SCUPPER GRILLE
SUGGESTED DESIGN
SCALE: FULL SIZE APPROX.
M.A.BALL 25-03-96



DECK DRAINS
Scale: 1:265
MAB
24.08.98
PF
SF
P1
S1
P2
P3
P4
S2
P5
S3
P6
S4
P7
S5

Appendix H

Report on leaks into the ss Great Britain's Promenade deck from the weather deck - Shane Casey, 1999

SS Great Britain - Report on Water Leaks

Issue

Documentation of sources of leaks into the interior of the Great Britain's hull.

Background and methodology

During periods of heavy rain in early May 1999 visual checks were made of accessible areas of the hull to determine the extent to which rainwater was entering. The table below lists leaks observed during this process.

The area in which the leak was observed is defined by port, starboard, or keel, frame number, and height above keel, measured in metres. Thus, the 8.5 metre level referred to frequently in this report relates to leakage from the weather deck onto the promenade deck level, while a 10 meter level refers to the Forecastle. A frame location of 'minus' is for those frames aft of the stern post, which is numbered '0'.

Skylights were numbered from the stern to the bow, as either port and starboard 1 to 5, and 7 and 8. Skylight number 6 is the central engine skylight. See the attached sketches for further information on locations of leaks.

Leak Number	Area in which leak was observed	Description of the leak
1	p/minus 1/8.5	Pin prick hole at butt strap
2	p/minus 3/8.5	Extreme rear of ship. Leaks in hull plating under paint, puddles forming. Leaks through weather deck causing corrosion of new metal deck edges, where they butt the wooden bulwark
3	p/3-5/8.5	Promenade deck. Pin prick holes in hull plate or fibreglass producing rust staining on paint.
4	p/7-8/8.5	Promenade deck. Small leak from port hole
5	p/50/8.5	Promenade deck. Port hole in passenger cabin showing signs of mold
6	p/73-74/8.5	Leak through hole in hull plating, behind sponsorship board
7	p/76-77/8.5	Leak through hole in hull plating, near to box girder
8	p/skylight 1	Crack in port forward pane of glass
9	p/skylight 1	Small leak on starboard side
10	p/skylight 2	Leak from centre of skylight
11	p/skylight 3	Leaks from centre
12	p/skylight 4	Small leaks port and starboard. Not running onto floor
13	p/skylight 5	Small leaks port and starboard. Not running onto floor

Leak Number	Area in which leak was observed	Description of the leak
14	p/107-109/8.5	Promenade deck curved overhead stringer plate - extensive leaks
15	p/112/8.5	Drip from light switch. Source unknown, probably junction of bulwark and steel weather deck
16	p/116/8.5	Drip from promenade deck curved overhead stringer plate. Source unknown, but probably as for 15
17	Main mast	Aft side, rivulets running down mast, and drips onto mast partner
18	p/116/skylight 7	Drips from dead centre of skylight, next to mainmast. Constant drip
19	p/120-121/8.5	Top of longitudinal box girder wet. Heavy constant drips from upper deck curved overhead stringer plate
20	p/122/skylight 8	Drip, not constant, onto hull plating at 2 meter waterline
21	p/122-123/8.5	Drips on forward side of mid-frame 'frame'
22	p/123-124/8.5	Leaks from port hole and through rivets in hull plating. (Bad leaks)
23	p/125-126/8.5	Top of box girder wet. No obvious source
24	p/128-129/8.5	Grey drain pipe elbow cracked and leaking. Bad drip onto shelf next to box girder. Subsequently fixed.
25	p/130-131/8.5	Drips from promenade deck curved overhead stringer plate onto box girder
26	p/132-133/8.5	Drips from promenade deck curved overhead stringer plate onto box girder
27	p/134-135/8.5	Slight leak from hull plate. No hole obvious, but leak is running onto butt plate
28	p/134-137/8.5	Constant heavy drip from promenade deck curved overhead stringer plate onto box girder
29	p/136-137/8.5	Leaks through port hole and rivets
30	p/137-138/8.5	Leaks from Lead scupper. Heavy drip
31	p/138-139/8.5	Drips from promenade deck curved overhead stringer plate and possibly rivets at butt pad. Too wet to tell exact location
2	p/139-140/8.5	Drips from promenade deck curved overhead stringer plate
33	p/141/8.5	Drip from promenade deck curved overhead stringer plate Unknown origin, onto shelf next to box girder.
34	p/141-142/8.5	Bad drip from promenade deck curved overhead stringer plate onto butt plate

Leak Number	Area in which leak was observed	Description of the leak
35	p/142/8.5	Leak from second bolt down from plate junction
36	p/143-144/8.5	Drip from promenade deck curved overhead stringer plate
37	p/146-147/8.5	Drip from drain pipe? Not sure of origin, but much water on horizontal triangular shelf plate
38	p/147-148/10	Both port-side companionway coopered ceilings leaking
39	p/147-148/10	Port side of port-most companionway - edge-jointed timber has separated 1/8 inch on glue line and is leaking
40	p/147-148/10	Port companionways - Both door floor lintels leaking
41	p/151-2/8	Area under steps ascending to deck above. Drips from deck above through deck flooring
42	p/152-153/8	Drips from deck above through deck flooring
43	p/153-154/8	Drips from deck above through deck flooring
44	p/158/10	Steady drip through torn -off heads pipe close to edge of upper weather deck
45	p/158/163/10	Leaks from side of weather deck onto hull plating
46	p/159/10	Drip through crack in weld line in new metal weather deck
47	p/162/10	Leak through hull plating, around iron bolt in wooden blocking
48	p/164/10	Leak through wooden blocking joint between 3rd and fourth block same as on starboard side.
49	p/164/weather deck	Puddling at junction of concrete and wood decks
50	p117-118/8.5	Top of longitudinal box girder wet. Source unknown, but probably as for (15)
51	k/100/weather deck	Glass lenses in ventilator grids forward and aft of funnel leaking, dripping into cut-out in wooden deck, onto steel deck below
52	k/147 Centre of ship.	Heavy dripping noise onto main deck? Couldn't see drip but could hear 2-3 heavy drips every second
53	k/155/8	Drip from deck above, through junction of old and new deck beam angle iron
54	k/162/8	Drip from deck above, forming puddles on shelf at extreme bow
55	k/94-95/skylight 6 over engine	Extensive leaks.
56	s/75-76/8.5	Leak through Port hole

Leak Number	Area in which leak was observed	Description of the leak
57	s/skylight 1	Leaks from port side, dripping onto floor
58	s/skylight 2	Leaks from both sides, and centre of skylight, dripping onto promenade deck floor.
59	s/skylight 3	Leak from centre of skylight
60	s/skylight 4	Leaks from port, starboard, centre
61	s/skylight 5	Leaks from starboard and centre, onto signboard.
62	s/83/8.5	Drips onto deck at base of box girder. Source unknown
63	s/90-91/8.5	Leak through hull rivets
64	s/95/8.5	Leak through hull plating
65	s137-147/8.5	Whole area of hull plating wet
66	s/100-101/8.5	Drip, source unknown onto box girder
67	s/102/8.5	Drip, source unknown onto box girder
68	s/116/skylight 7	Occasional drips, not too bad.
69	s/123-125/8.5	Port hole and promenade deck curved overhead stringer plate
70	s/125/skylight 8	Occasional drip along whole length of skylight, onto longitudinal girder at 8.5 meter level and onto hull plating at 2 meter level
71	s/127-129/8.5	Promenade deck curved overhead stringer plate, and rivulets of unknown origin down hull plating. Damp, but not too bad
72	s/130-131/8.5	Hull plating wet, source unknown, probably bulwark
73	s/132-136/8.5	Leak through hull plating and from promenade deck curved overhead stringer plate. Heavy drips
74	s/137-138/8.5	Scupper. Very bad and frequent drip
75	s/138-139/8.5	Bad drip from promenade deck curved overhead stringer plate - every 2 seconds
76	s/146-147	Torrent of water on outside of drain pipe. Box girder, hull plate wet. Subsequently repaired.
77	s/147/-148/10	Drips through coopered ceiling of companionway hatch cover.
78	s/147/6	Drain pipe elbow leaking badly
79	S/147-148/10	Direct entry of rain into forecastle through open companionway door. Water running onto forecastle deck, leaking tthrough planking to decks below
80	s/150/8	Leak through Forecastle deck planking onto deck of lower forecastle

Leak Number	Area in which leak was observed	Description of the leak
81	s/157-158/8	Leaks through hull plating next to frame
82	s/158-159/6	constant leak over wide area, no obvious source
83	s/158-164/10	Leaks from weather deck on side of bulwarks directly onto hull plating
84	s/160-161/6	Constant leak over wide area, no obvious source
85	s/160-161/8	Leaks through hull plating next to frame
86	s/161-162/10	Leaks around starboard side of starboard knighthead, onto iron hawse pipe, and thence leaking onto wooden blocking on interior starboard side of bow
87	s/163/10	Leak through wooden blocking joint between 3rd and fourth block (no 4 being that which rests on the floor of the forecastle.
88	s/164/10	Leak through hull plating, around iron bolt in wooden blocking at extreme forward side of bow
89	s/164/weather deck	Puddling at junction of concrete and wood decks

Comment and Recommendations

Clearly the above list should not be regarded as exhaustive. Further, the source of each leak noted above should be accurately determined. Most leaks had their source in the junction of the bulwark and the newly installed metal weather deck. Often, as this junction is obscured, the source of the water is observed to be the longitudinal curved overhead stringer plate which runs for most of the length of the promenade deck. Minor leakage is evident through holes in the hull, rivets or port holes. Major leakage is occurring through all skylights, and all three forecastle companionways. It may be true that this leakage is particularly bad after a dry spell, when the wood has contracted. However, it seems fairly obvious both that it is occurring all year round, and that the current study was made over a period in which the wood had not dried out completely.

The following recommendations may reduce leakage in some areas

1. Investigate possibility of extending the metal weather deck over the wooden bulwarks

2. Some leaks have already been attended to. Known problem areas such as these, and other lavatory and drainage pipes should be periodically rechecked in accordance with an agreed maintenance schedule.

3. Close the starboard forecastle companionway door in inclement weather

4. Recaulk and revarnish the companionway roofs, and their coamings. Possibly place canvass roofing on top of forecastle companionways

5. Repaint canvass roofing of midships companionways.

6. Ensure limber holes in skylights and companionway hatches are free of debris

7. Ensure gutters and scuppers are kept clean.

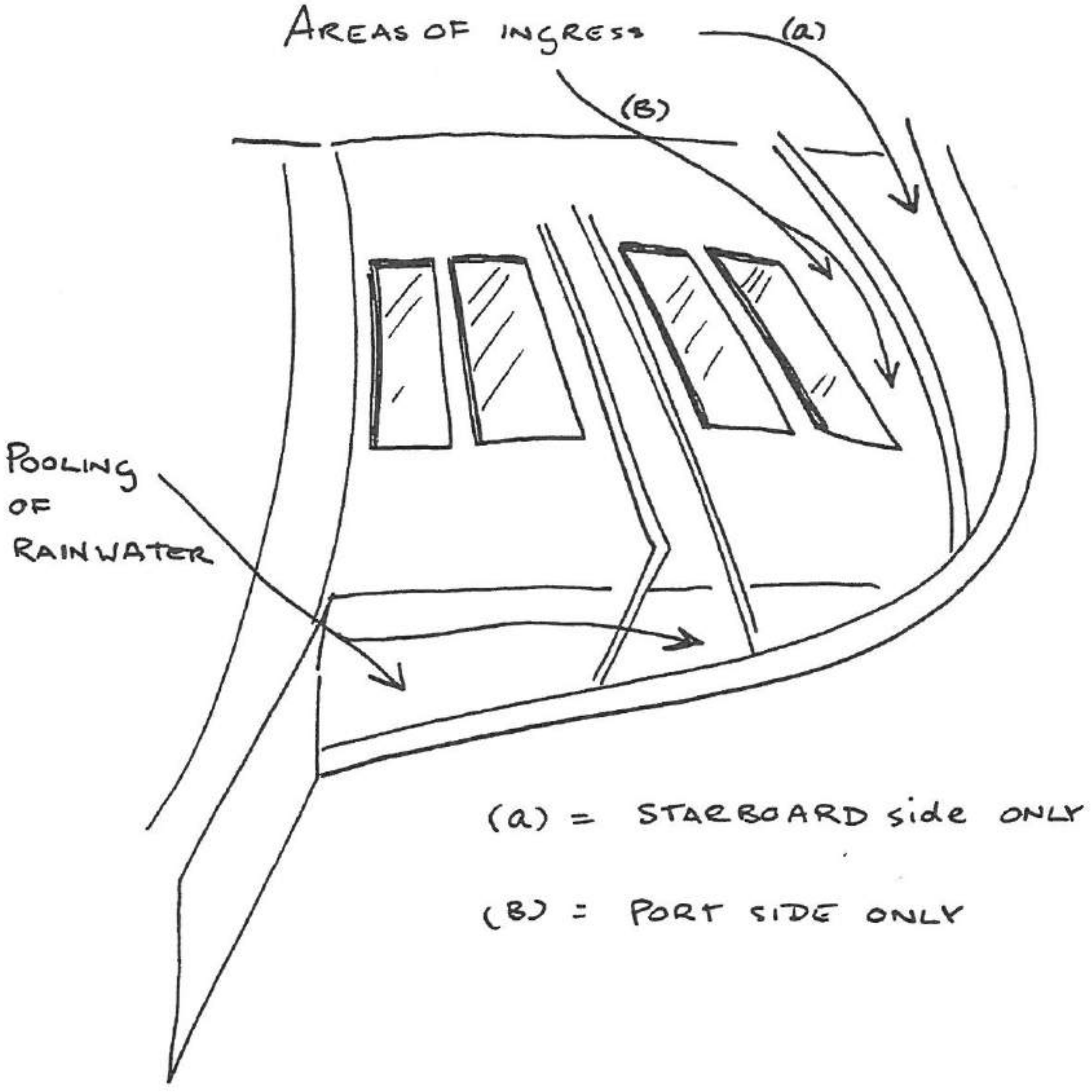
8. Re-attach lead scupper pipes

9. Ensure any leakage onto public areas of the promenade deck are sign-posted or mopped up during periods of inclement weather

10 Investigate means of Blocking holes in the hull

LEAKS 1 & 2

SKETCH VIEW OF STERN SHOWING RAINWATER INGRESS.

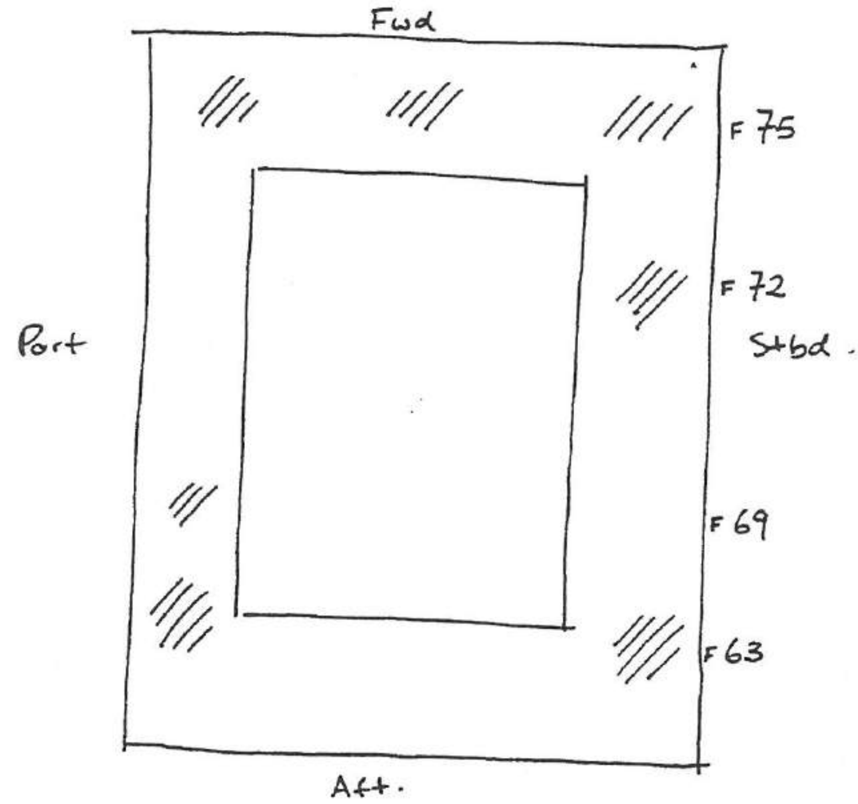


(a) = STARBOARD side ONLY

(B) = PORT SIDE ONLY

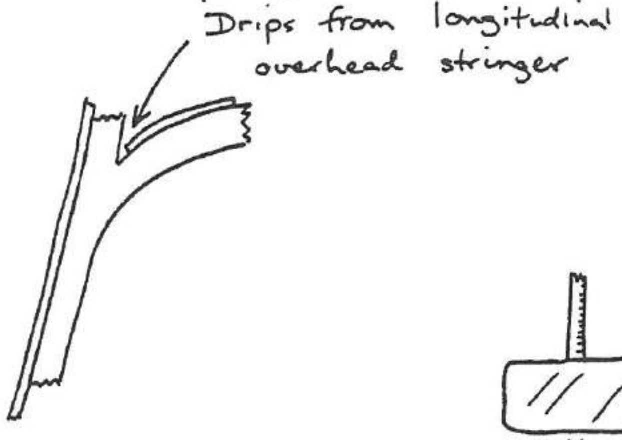
LEAK NO 55

Plan view, Engine Skylight leaks

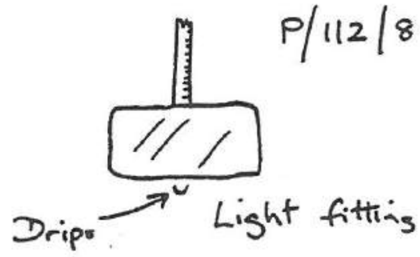


Cross hatching shows major leaks

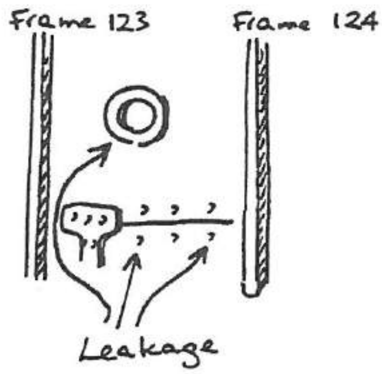
P/120/8·5 LEAK No 19



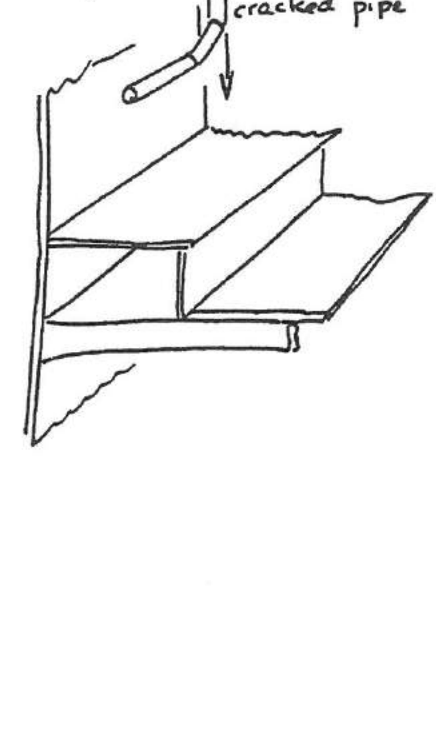
P/112/8·5 Leak No 15

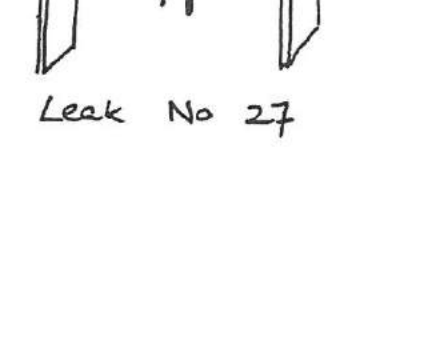


Leak No 22 P/123/8·5



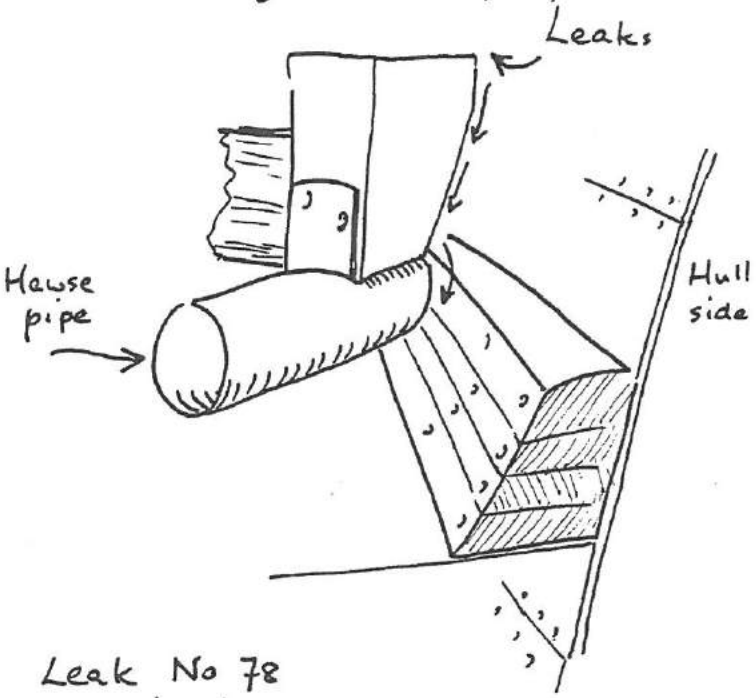
Leak No 24
P/128/8



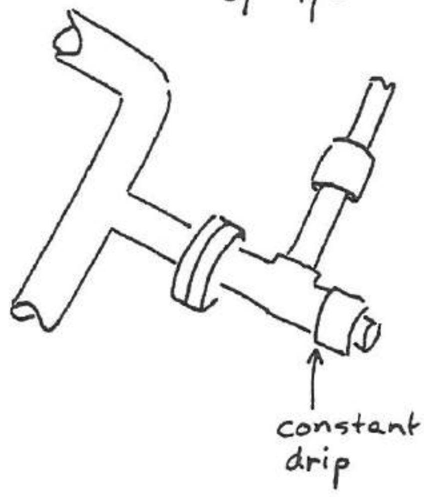


Leak No 27

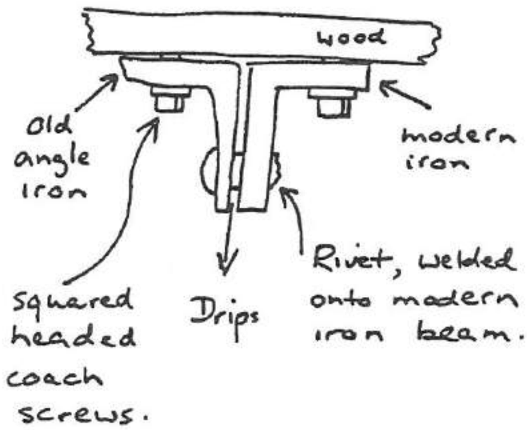
Leak No 86
Knightheads S/161/10.

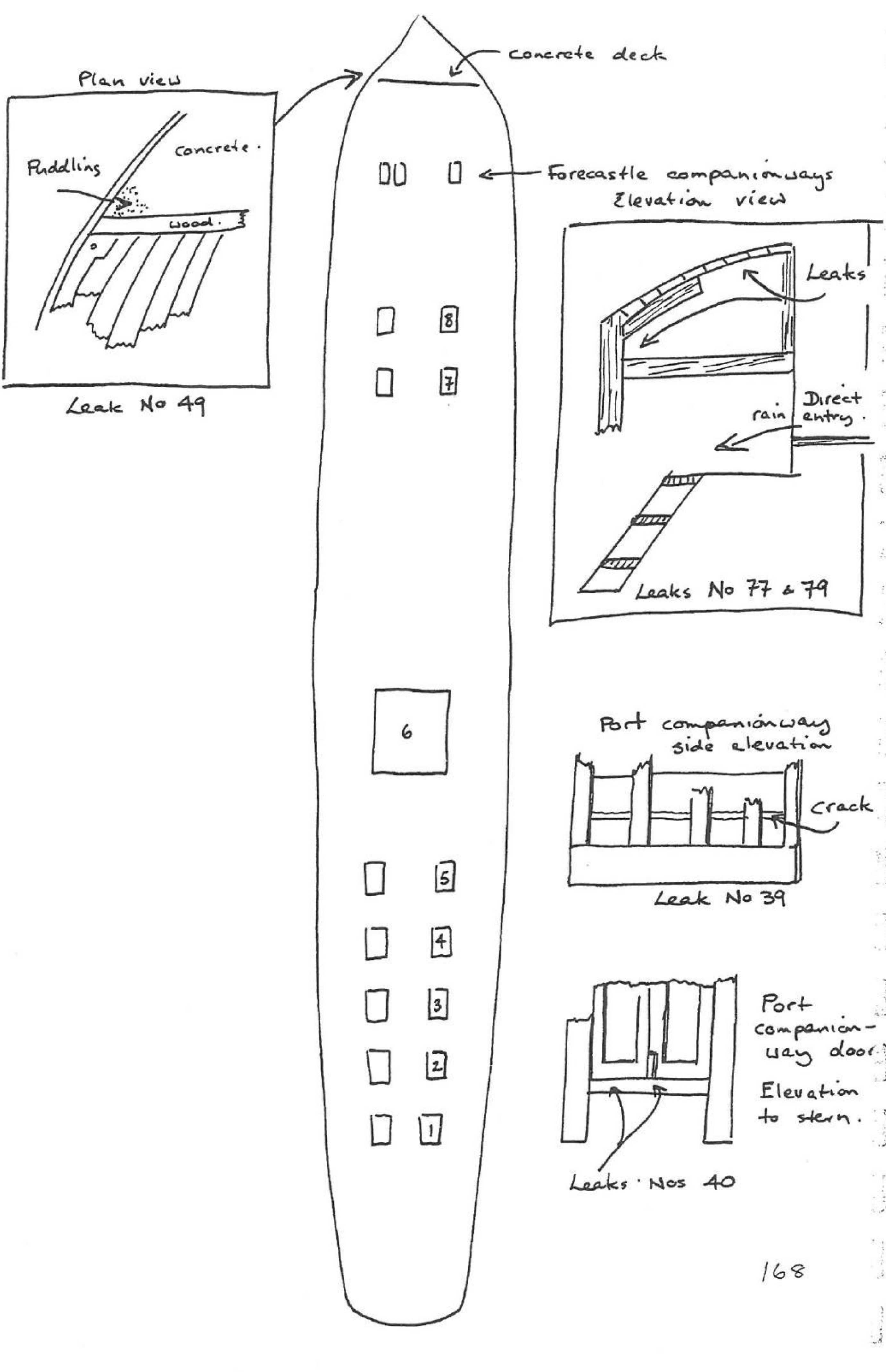


Leak No 78
5/147/6



Leak No 53
K/155/8.




concrete deck
Plan view
Concrete.
Puddling
wood.
Leak No 49
Forecastle companionways
Elevation view
Leaks
Direct
rain entry.
Leaks No 77 & 79
8
7
6
5
4
3
2
1
Port companionway
side elevation
Crack
Leak No 39
Port
companion-
way door
Elevation
to stern.
Leaks Nos 40

Appendix I

Evaluation of the chloride content of the ss Great Britain's iron
Shane Casey September 1999

ss Great Britain - The extent of Chloride contamination.

1. Introduction - the corrosion cycle

1.1. From the moment of her manufacture, the various metals within the ss Great Britain's hull began reacting with their environment to convert to more stable compounds - the process of corrosion. This process is an electrochemical one, in which the various metal components operate as primitive batteries, with oxygen and water providing the fuel. The cycle has been exacerbated by the Great Britain's immersion in seawater, because her hull became slowly ever more contaminated with chlorides, (salts), which function as highly effective electrolytes.

2. Steps taken in the past to prevent corrosion

2.1. Over the period since the Great Britain's recovery in 1970, a variety of conventional shipyard practices have been employed to halt the ship's corrosion. These measures have included subjecting the hull to high pressure water-cleaning, chipping corrosion off, and wire-brushing. Various surface treatments, including the application of tannic acid, and phosphoric acid coatings credited with 'turning rust into metal', have been experimented with.

2.2. These measures have all failed to halt the corrosion cycle. Some may have even had the effect of removing or damaging original material, of hiding corrosion, or of actively accelerating the corrosive cycle. Additionally, as the ship had gradually been converted to her 1845 appearance, and been adapted for tourism and commercial functions, she has been subjected to increased weight, vibration, and fluctuations in temperature and humidity.

3. Why corrosion has continued

3.1. The Great Britain's hull will continue to corrode for as long as it is exposed to the combination of oxygen and moisture. This process is aided by the presence of chlorides, which have not only accelerated the electro-chemical corrosion process, but which have also combined with the chemical constituents of water, oxygen and iron to produce other corrosive compounds. This process has continued unabated and largely unseen under the surface of the paint.

3.2. This paper address the extent to which free or soluble chlorides have been detected in the ship's fabric.

4. Object of the Experiment

4.1. To test for the presence of free or soluble chloride contamination in the ss Great Britain's hull plates, and to measure those levels empirically

4.2. To map levels of free or soluble chloride contamination, and to determine whether any pattern can be found for its presence.

4.3. To present the information in such a way that it aids in selection of a conservation strategy - specifically, whether the chloride contamination is present to a greater degree outside the hull or is present at all in the topsides.

5. Method selected

5.1. A Soxhlet extraction system was selected as the best means of achieving the three objectives. While it is recognised that this system does not remove all soluble chlorides from a given sample, and thus cannot give an absolute quantum, it nonetheless was sufficiently efficient at highlighting the magnitude of the problem in each sample. It was, additionally, considered to be safer, easier and more cost effective than other methods for removing soluble chlorides, such as alkaline sulphite extraction, high temperature, high pressure washing or repeated aqueous boiling. [1]

5.2. 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. The residue that remains in the solvent is then tested for chloride levels. A full listing of apparatus used is at <u>Attachment A</u> The Soxhlet extraction 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 the Cutty Sark and HMS Belfast. This allowed us to employ a system that had been tested on similar ship conservation projects, and benefit from their advice.

6. Method of recording samples

6.1. Each sample was given a reference code reflecting its three dimensional spatial location:

(a) transverse location in the ship (port, starboard, or keel)

(b) interior or exterior location

(c) longitudinal location - frame number, or plate between two frames. A frame location of 'minus' is for those frames aft of the stern post, which is numbered '0'.

(d) Height in metres above a datum. The datum was selected as a point on the interior of the keel plate, at the aft base of the mainmast. Heights above the datum to the hull sides forward and aft of the mainmast were established by measuring up from this point and extending outwards using a line level.

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

6.2. Thus a completed code might be p/I/125-6/2. (Port, interior, between frames 125 and 126, two meters up from the datum.)

7. Selection of samples

7.1. The aim of sample selection was to:

(a) select areas that allowed the collection of at least 50 to 80 grams of pure corrosion product to enable the Soxhlet process to be repeatable,

(b) give enough pure corrosion product (uncontaminated by paint or fibreglass) to allow uniformity between samples,

(c) give a good spread of samples throughout and up the hull

(d) ensure that every main compartment within the hull was sampled (ie the focsle, forward compartment, boiler room, engine room, aft tank top).

7.2. As frame spacing in the ship is irregular, and various parts of the ship's hull were inaccessible or had no corrosion product, it was not possible or desirable to take samples at regimented intervals throughout the ship. Further, absolute reliance on a precise distance would have produced an over-abundance of sampling in (say) the aft tank top area, and none in the engine room. A total of 59 samples have been tested to date.

8. Method of preparing a sample

8.1. Measuring up from the keel datum point, a line level was used to establish a 2, 4, 6, and 8 metre waterline level within the ship's interior. Once a location was selected for sampling, a trowel was used to scrape or pick a 50 - 80 gram corrosion sample off the hull. This was then placed inside a sterile plastic container, which was then labelled with the location code. Care was taken to select samples from close to the interface between the metal and the corrosion products, where chlorides were more likely to be found, and samples with paint adhering were excluded.

8.2. Each sample was then placed in an aluminium tray and dried in an oven for 45 minutes at 120 degrees centigrade. By removing excess moisture, the samples could be more easily ground in a mortar with a pestle, and sieved to produce uniform grain size. Removing moisture also ensured that the sample weight was uniform.

8.3. 25 grams of corrosion product were then weighed to 0.1 gram accuracy and placed in a cellulose extraction thimble.

8.4. All flasks, measuring beakers and the Soxhlet extractor were rinsed in de-ionised water.

8.5. The extraction thimble was then placed inside the Soxhlet extraction tube, which was in turn connected to a condenser and a conical flask. as shown in Figure 1 The flask contained 250 millilitres of de-ionized water, to act as the solvent.

8.6. The solvent was then was heated on an electric hotplate. As the solvent boiled, its steam rose and entered the water cooled condenser and reliquified. This dripped into the cellulose extraction thimble, and the thimble gradually filled up with purified near-boiling water. When the liquid level in the extractor thimble reached the top of the Soxhlet siphon tube, siphoning action returned the chloride-enriched solvent sample to the conical flask, where the process was repeated. The cycle was repeated for one and a half hours, after which time an automatic timer cut the electricity supply to the hotplate.

8.7. After the solvent had cooled sufficiently, 200 ml of sample was tested using a Lovibond tintometer tablets count method. Each tablet contains an accurately standardized reagent combined with a colour indicator. To carry out the test, tablets are added one at a time to a measured sample of solvent sample until a colour change occurs. The result is calculated from the number of tablets used, in relation to the size of the solvent sample used. The results are expressed as chloride parts per million.

9. Results and Observations

9.1. It should be noted that Soxhlet extraction does not remove all the soluble products from a test sample, but only a proportion. This proportion would probably increase with a comparable increase in the time an extract spent undergoing extraction. Despite this, the results of the sampling program (as shown in Table 1 and Figure 2) indicate that:

(a) Free or soluble chlorides **are** present in elevated quantities within the hull. Levels of up to 300 ppm were recorded. Most levels internally were between 30 to 80 ppm (Bristol tap water measured using the same reagent tablets showed a level of 30 ppm, whereas the de-ionised water was 5-8 ppm.)

(b) Internally there is little consistency longitudinally or in waterline heights as to the spread of chloride contamination, as 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 implication here is the whole interior of the vessel is contaminated to various degrees, and that there is consequently a general need to protect the hull from the combination of moisture and oxygen by creating a stable environment for the ship.

(c) Some of the highest levels were recorded within the steel box girder at the 8 metre level. This level was probably due to the fact that these areas acted as dams or water traps, and may never have been adequately flushed with water in the same was as the rest of the hull. The implication from this is that these areas should be dehumidified to the same extent as the lower, more visible parts of the ship.

(d) Samples of an adequate size could not be taken on the bell deck, promenade deck, nor on the saloon deck, as most of these parts of the ship's hull were covered with well-adhering paint, and there was little obvious active corrosion evident. The lack of corrosion was probably due to heavy layers of paint having protected the metal from moisture and/or oxygen. The paint was in all probability originally applied to clean, dry surfaces.

(e) there is considerable evidence that large parts of the ship's external and internal topsides may have benefited from water diffusion of chlorides. This evidence manifests itself in the lack of adequate areas of corrosion on the hull exterior above the waterline from which samples of sufficient size could be taken.

This conclusion is supported by the earlier analysis by Sandberg consulting engineers (Report 17499/M/01) who conducted tests on four corrosion samples, showing that there was negligible chloride levels. They concluded that the low levels were due to the samples having been subject to regular rain washing. (p4-5). Essentially, over the past thirty years, the vessel's topsides have been subjected to the effects of repeated rinsing with rainwater, diffusing the soluble chlorides out of the metal and into solution.

This effect would have been pronounced on areas of tumblehome, where the hull plates presented a flatter surface to falling rain than, for instance, areas at the bow or stern. This area of tumblehome also accounts for a far greater proportion of topsides surface area than the bow and stern areas. There may be additional reasons, including the fact that during her working career, her topsides were more regularly painted and kept rust free than area under the waterline. Even after her return from the Falklands, this has been the case, with this area having received, for instance, preferential tannic acid and paint treatments. The ship's topsides are also inherently less contaminated with chlorides for the very reason that they were never submerged in salt water, but only exposed to the effects of spray and wave action.

(f) Extremely high chloride levels were recorded in the lower hull, under the turn of the bilges. It is possible that this is because this area has neither been exposed to direct and sustained rainfall, but also because 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 each strake. The chloride testing program has certainly proven that there are elevated levels in this area (although the causal connection between water diffusion and deposition is purely conjectural)

10. Conclusion

10.1. The testing regime has confirmed the presence of high chloride levels within the ss Great Britain's hull. These chlorides will adversely affect the ship's longevity and visitor security if no remedial action is taken.

10.2. Various cleaning systems have been mooted for removal of the chlorides from the ship's hull. Most have been used to successfully stabilize archaeological and historic metals from other maritime sites. However, none appears appropriate for cleaning the Great Britain's hull.

10.2.1. Alkaline sulphite washing, for instance, is highly effective (Watkinson 1996 found that it had a mean chloride extraction rate of 87%), but requires that the metal being cleaned be treated in an oxygen free environment.

10.2.2. Mechanical cleaning of the hull has been well tried over the past thirty years, but has proved largely ineffective. One of the major reasons for this is that the ss Great Britain's wrought iron, with its laminar structure and multiplicity of slag inclusions, has allowed the easy ingress of seawater deep into metal's interior. Hidden deep within these layers, chlorides cannot be removed by simple washing or sandblasting techniques. In a similar manner, the ship's riveted overlapping plate construction has also served to harbour corrosive elements and shield them from cleaning. 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.

10.2.3. The size and complexity of the ship's structure also makes it highly unlikely that electrolytic cleaning, using impressed current systems, would remove all the damaging chlorides. Indeed, given the friable nature of much of the corrosion product in the hull, such cleaning systems might in fact remove more material than is considered desirable. Further, it would be difficult to measure the extent to which corrosion products had been removed or were still present in the ship's fabric.

10.3. The overall conclusion therefore is that removal of the chlorides is impractical; the only achievable solution is to create a suitable protective environment in which the ship's structure can be stabilised.

References

MacLeod, I 1999, Conservation of the ss Xantho engine: lessons learnt (unpublished paper)

North N and MacLeod I, 1987, Corrosion of Metals, in Pearson C, ed *Conservation of marine archaeological objects*, Butterworths, London

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Attachment A

Description of Apparatus used for Soxhlet extraction process.

1. 1 x extractor, Soxhlet, 'quickfit' Pyrex glass, 100ml capacity, with a 40/38 top socket, and a 24/29 cone.
2. 1 x condenser, Graham coil, pyrex glass, 200ml capacity, with a 40/38 cone.
3. 3 x boxes of 25 extraction thimbles, cellulose, Whatman.
4. 2 x flasks, conical estenmeyer, Quickfit, Pyrex, 1000ml capacity, with a 24/29 socket.
5. 1 x Balance, Ohaus Ls200, accurate to 0.1 grammes.
6. 1 x battery, Alkaline manganese, 9 volt, for Ohaus balance.
7. 1 x box of 5 Cylinders, Kartell, polypropylene, 50ml, blue gradations
8. 1 x box of Beakers, Fisherbrand, Polypropylene, squat form, spouted, graduated 50ml
9. 1 x box of Beakers, Fisherbrand, Borosilicate glass, tall form, spouted graduated 400ml
10. 1 x bottle, ph7 buffer, twin neck bottle, 500ml
11. 1 x boiling ring, double hob, Russel Hobbs brand, Model 9934
12. 1 x timer, electrical, 24 hr, Pact International.
13. 2 x 2 metre lengths of 9mm interior diameter flexible polyethylene transparent hosing
14. 3 x boxes of 250 chloride test tablets, Lovibond
15. 2 x trays, baking, Yorkshire pudding, sheet metal
16. 1 x box of 100 containers, sample, plastic with press on cap. 150ml
17. 1 x Mortar and Pestle, Porcelain, unglazed, 300 ml.
18. 1 x Ph handheld measurement stick, pHep3. Hanna brand
19. 1 x retort stand base, pressed steel, 160mm x 100mm
20. 2 x clamps, three prong, rubber grip
21. 2 x rods, for retort stand, aluminium
22. 1 x box of bossheads, zinc alloy, for retort rods.

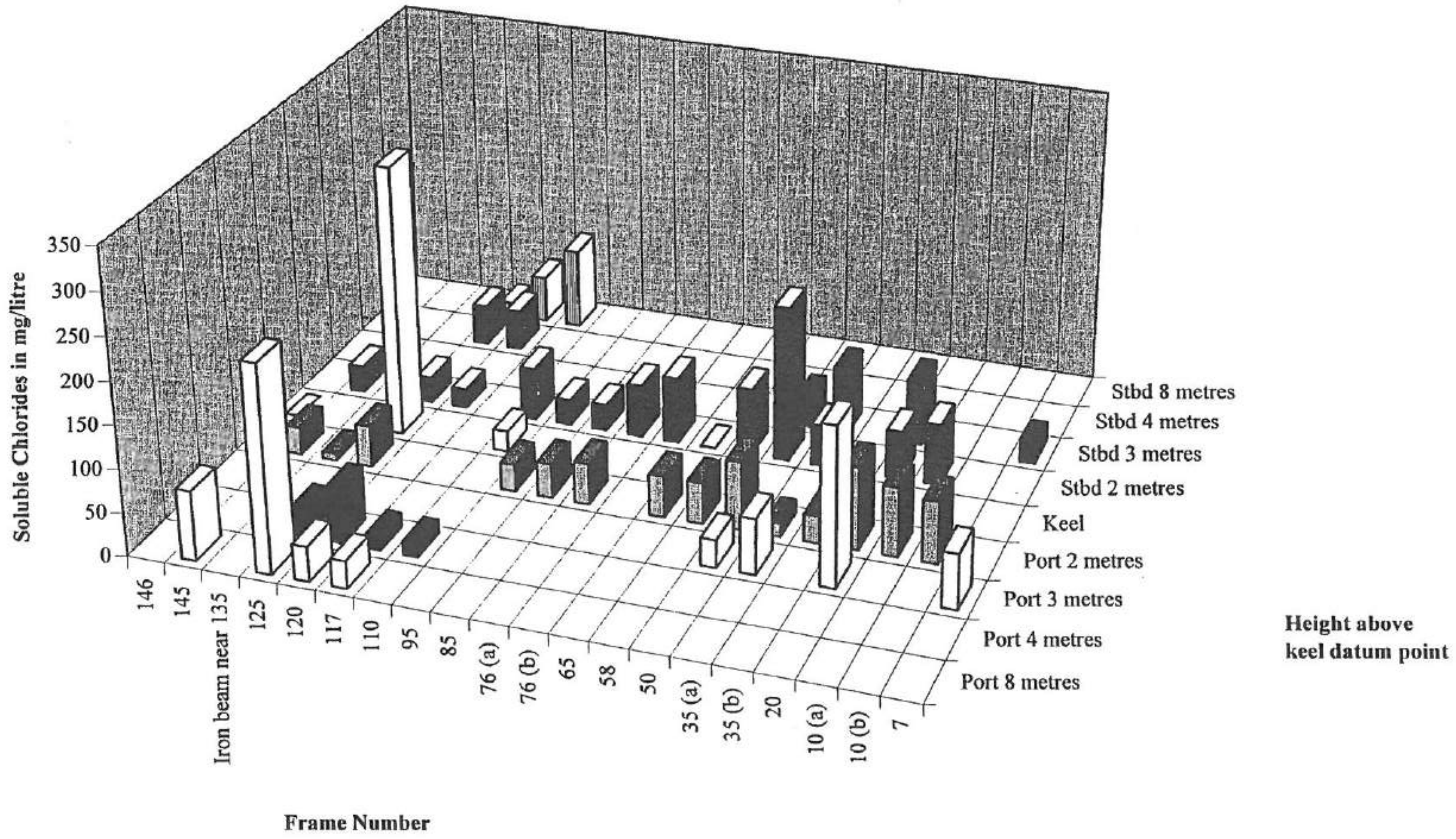
Soluble Chlorides found in corrosion samples
(parts per million)

	Port					Starboard			
Frame	8 metres	4 metres	3 metres	2 metres	Keel	2 metres	3 metres	4 metres	8 metres
150			80				36		
146					0				
145	80			32		32			
Iron beam near 135				8					
125	240	32		48	320	32		48	16
120	40	64				24		48	56
117	32	16							96
110		16			24	64			
95				32		32			
85				40		32			
76 (a)				48		64			
76 (b)						80			
65				48		n/a			
58				48		80			
50			32	80		184	40		
35 (a)			64	16		48	80		
35 (b)				32					
20			184	96		56	80		
10 (a)				80		72			
10 (b)				72					
7			64				24		

Note: See text for explanation of locations of samples within the ship

ss Great Britain - Condition Survey

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.

Appendix J

Brief Structural Appraisal of Steam Ship Great Britain
Report by the Morton Partnership Ltd, October 1998

BRIEF STRUCTURAL APPRAISAL
OF
STEAM SHIP GREAT BRITAIN

Client : *Matthew Tanner - Curator*
s.s Great Britain
Great Western Dock
Bristol BS1 6TY

Conservators: *Eura Conservation Ltd*
Unit H3
Halesfield 19
Telford
Shropshire TF7 4QT

Prepared by : ***Structural Engineers***
The Morton Partnership Ltd
61 Islington Park Street
London N1 1QB

Ref : *EJM/KC/REP/6216.rep rev a*

Date : *October 1998*

1.0 INTRODUCTION AND BRIEF

1.1 Eura Conservation have been appointed to carry out a condition survey of the fabric of Brunel's Iron Steam Ship Great Britain and put forward proposals for the long term conservation.

1.2 As part of the study Eura Conservation approached The Morton Partnership to undertake a brief structural appraisal of the ship in terms of its overall integrity and put forward proposals for strengthening if appropriate.

1.3 The Ship was visited a number of times during August and September 1998. Discussions were held in conjunction the Curator, Matthew Tanner, and Eura Conservation to ensure that any proposals paid reference to the intended interpretation of the Ship where these have been developed.

2.0 BRIEF DESCRIPTION

2.1 The ship can be split vertically into four sections by bulkheads forming the aft, midships, forward and forecastle or focsle (see 6216/A3/Sk01 in appendix C). The forward sections contained the boilers and pumps used to power the steam ship.

2.2 Horizontally the ship is split into a number of decks denoted as weather deck, promenade deck, main deck, and tank top (see 6216/A3/Sk01 in appendix C). The levels vary slightly in some sections.

2.3 Externally the hull of the ship is strutted by a series of substantial timbers within a dry dock, originally purpose built for the construction of the ship. These props assist in providing the ship with overall stability as well as providing more local support to sections of the hull.

2.4 It is not intended to cover the history of the ship or its subsequent life and alterations as this is dealt with in detail by others.

2.5 Reference has been made to Sandberg Consulting Engineers report on 'Testing of the Structural Materials' of the ship dated 2 October 1998.

3.0 STRUCTURAL SURVEY DETAIL

3.1 General Structural Description

3.1.1 The general structure of the ship can be seen to consist of wrought iron angles forming frames extending up around the hull. These are predominantly 6" x 3½" but with some within the focsle reducing to 4" x 4". To these are fixed the external metal plates or strakes forming the hull. The frames have been tagged for reference purposes and this report uses the same numbering system.

3.1.2 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 to the top face. The girders commence at the forecastle bulkhead with a pair, with additional girders added as the base of the ship widens up to ten in total. The girders are stiffened by the addition of plates between adjoining girders along their length. This tank forms an extremely stiff platform to the structure of the ship, being approximately 990mm deep at the centre line of the hull at midships.

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

3.1.4 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 we presume used to form the access openings to the cargo holds.

3.1.5 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.

3.1.6 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.

3.2 **Focsle**

3.2.1 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 (see photograph 1). 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.

3.2.2 The main mast rising up through the focsle is supported at tank level on two iron stanchions extending down to the keel (see photograph 1). Above this an approximate 500mm diameter later mast rises with stiffener plates at the base onto a large plate, and with a shoe to the bow to support the spine beam supporting the focsle store and angles running back to the bulkhead (see photograph 2).

3.2.3 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 is satisfactory.

3.2.4 At frame 154 a small bulkhead has been formed to the bow which has been filled with concrete at some time.

3.2.5 The deck to the focsle store is constructed of 95mm deep timber boards spanning across the width of the ship and supported to the hull via longitudinal plates, themselves supported at every other frame position by a diagonal raking strut (see photograph 3). The decking also takes support from the central spine beam described previously. A timber stringer runs along the hull over the deck boards (see photograph 4).

3.2.6 The structural layout of the fore peak levels repeats in the 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 (see photograph 4).

3.2.7 The deck to the lower focsle is of 75 mm deep boarding spanning lengthways over 3 ½" x 3 ½" angle irons spanning across the ship at each frame position. This take support from the timber spine beam described previously (item 3.2.6) and raking struts to the ends (see photograph 4), except two frames at the bow where the span is short.

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

3.2.9 The decking to the focsle also spans lengthways over 3" x 3" 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 35mm diameter stanchions which are positioned over the tops of the raking struts below (see photograph 5).

3.3 Forward

3.3.1 The focsle bulkhead (see photograph 6) has been supplemented by the addition of a frame. This is freestanding for much of its height but 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.

3.3.2 No tank plating survives, thus exposing the longitudinal girders and web stiffeners between (see photograph 7). 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.

3.3.3 The girders are formed of vertical plates with two 3" x 3" angles rivetted top and bottom forming an 'I'-beam section. The depth of this varies along the length of the ship from 480mm at the focsle bulkhead to 990mm at the deepest. The girders rest directly on the keel section, or onto the frames with connecting angle cleats.

3.3.4 Between frames 131 and 135 there are the remains of an earlier mast with the timber housings bearing onto four of the longitudinal girders (see photographs 8 & 9). Between frames 117 and 121 a steel mast extends up with stiffeners at the base welded to a base plate supported off the longitudinal girders and intermediate stiffeners (see photograph 10).

3.3.5 Two rows of cast iron stanchions (approximately 50mm diameter) extend back from frame 136 rising up from the two central girders to the support the deck beams over, and at varying centres. Forward of this single stanchions exist as the width of the ship decreases.

3.3.6 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 forth frame position (see photograph 11).

3.3.7 The two central stanchions support 3" x 3" angles running down the length of the ship. These in turn support 3 ½" x 3 ½" angles spanning across the width of the ship tying the frames. These ties take further support off the second set of cast iron stanchions.

3.3.9 Directly over the second set of stanchions 90mm 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 (see photograph 12).

3.3.10 At approximately mid-height of this deck there is a horizontal plate running around the hull, extending out approximately 850mm and supported off raking struts to the frames below. Some stiffening plates have been added over (see photograph 13).

3.3.11 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 cast iron stanchions to the main beams, presumably forming access for cargo etc.

3.3.12 The deck beams increase in depth at the junction with the frames forming a deep web for additional stiffness of the joint which is rivetted (see photograph 14). The beams are spliced along their length at the positions of the support stanchions below. In between the frames angles span providing additional support to the decking when this existed.

3.3.13 The framing for the missing mast remains (see photograph 9) as well as the rear mast being trimmed around at promenade deck level.

3.3.14 The structural pattern repeats at the upper levels to the underside of the weather deck although detailed inspection was difficult to access. 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.

3.3.15 The weather deck has been replaced comparatively recently and the new steel plate decking set slightly above the supporting beams by means of the 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.

3.3.16 To the port side there is quite significant decay to the ends of the deck beams which co-insides with damp staining to the deck finish over. It is assumed that the level of decay relates to this been an area which will have, and possible still, collects surface water form the deck. The ends of the beams arch down to meet with the frames and plates are incorporated over.

3.4 Midships

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

3.4.2 A crack in the hull of the ship is obvious in the girders between frames 90 and 93 (see photograph 15). This is also clear externally in inspecting the hull. The vertical crack is longstanding and has been temporarily repaired prior to its salvage from the Falklands Islands. It appears alternatively in the shell plating and at the butt strap positions in the hull to the starboard side. The crack also exists in some of the longitudinal girders.

3.4.3 Above tank level the midships partly houses the facsimile of the original engine. It is contained by the after engine room bulkhead and the screen set up to replicate the boilers.

3.4.4 To the forward section of midships 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 (120mm diameter), one centrally and the remaining two to the sides. These are supported on new plates over the girders, whilst the central beam we assume bears directly over a stiffener between the girders (see photograph 16). These have been inserted to allow part of the main deck over to be used as a dance floor.

3.4.5 Deck beams at main deck level extend from the hull frames at positions 84, 97, 100 and 103 for the full width tying the hull. At frames 88 and 93 the deck beams are curtailed spanning from the hull trimmer beams supported off the cast iron stanchions. This created an open area presumably to pass cargo but which has now been infilled for the dance floor.

3.4.6 Between frames 82 and 83 the false boiler bulkhead is positioned which is supported on a frame on the line of frame 84 (see photograph 17).

3.4.7 The engine house area is open up to the weather deck level with a 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 having been cut short and welded to the longitudinal plate forming the vertical upstand at the head of the raking section of steel sheeting inserted as part of the recent works (see photograph 18).

3.4.8 *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 (see photograph 19).*

3.4.9 *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.*

3.4.10 *Again the beams to the weather deck structure are visible from the promenade deck.*

3.5 ***Aft***

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

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

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

3.5.4 *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 form a blocked up opening. Over the beams is a relatively modern decking of steel.*

3.5.5 *Much of the structure above main deck level is concealed by finishes of offices or interpretation areas for the original ship. We assume 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 appears to be confirmed where the structure is visible.*

4.0 CONCLUSIONS

4.1 *Important to our analysis of the ship is that it no longer is acting in the way it was intended in its original design. It was obviously designed as a compression structure, below the water line, to withstand the pressure applied to it from the sea.*

4.2 *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'.*

4.3 *We have not carried out a detailed investigation of the condition of the structure as this forms part of Eura Conservation's brief. However we have formed an opinion of the overall condition based on our discussions with Eura, our own assessment of the structure and by referring to the report produced by Sandberg's on the material qualities. This later report indicates the wrought iron is of a low strength and poor quality typical of the period.*

4.4 *It is clearly evident that much wasting of the structure has occurred, particularly related to the angle irons forming the frames and of which some have wasted to the extent where the upstand leg no longer exists. In addition the integrity of many of the plates is questionable as are the heads of the fixings connecting the elements.*

4.5 *This decay is principally due to the action of corrosion of the iron possibly linked to the action of chlorides. Although the future extent of corrosion can be reduced it is unlikely, with current technology, to be able to be completely halted.*

4.6 The ship, in our opinion, is in a state of tenuous equilibrium and we believe that movement or 'spread' of the structure is probably slowly occurring. This is backed up by the load testing carried out on the timber support props, which indicate that loads of up to 30kN were recorded and bowing of some of the props was noticeable.

4.7 Our overall concern relates to the fact that as the material wastes its strength will significantly decrease. The majority of the decay relates to the hull where the strength of the frames is compromised by the partial or complete loss of the up stand leg. With the similar reduction in thickness of the plates the load from the upper sections of the hull, where the condition is not as poor, may cause the lower section to start buckling.

4.8 This may be partly countered by the ability of the deck beams to cantilever out to support the hull, although it should be realised that these are of relatively small section to perform such a structural function.

4.9 The hull plating will tend to create a stressed skin structure, although this relies on continuity of strength of the plates, which we know have wasted particularly around the rivet holes.

4.10 With regard to the damage to the port side of the forward section below the weather deck we are not overly concerned as it is situated at the top of the hull and is not therefore supporting a significant load over which may cause buckling. However it is an area where the public can access over and we recommend that some repairs will be necessary in due course to ensure continuity of support.

5.0 PHILOSOPHY OF STRENGTHENING

5.1 At the present time with the ship in dry dock, the weight of the superstructure of the Ship is in the central section and carried down to the keel through a series of stanchions, some of which have been inserted since the original design. Around the periphery of the ship the load is transferred from the superstructure down through the hull plates which were originally stiffened by Iron angles; a significant amount of which have eroded away through corrosion.

5.2 Although there is not unreasonable support down the middle of the ship the vertical load of the hull plates is providing a bursting force within the hull below decks.

5.3 The ship of course was not designed to rest in a dry dock for considerable periods, thus whereas in the water the hull is the correct structural shape to resist the forces imposed on it, it is absolutely the wrong shape to sit in a dry dock.

5.4 The philosophy of any repair must relate to transferring as much load down onto the keel or central section of the ship as possible whilst restraining the hull from bursting outwards. Generally retention of historic fabric is the predominant factor. Where strengthening is carried out it will be reversible to allow future removal if alternative methods of support become available through changes in technology. Limited localised replacement of elements may be required in places.

5.5 We are concerned about areas of the hull where plates have rusted through and here a decision needs to be made as to whether one simply repairs these holes, or the complete bad plate by repairing perhaps welding on new internal plates; or alternatively whether one simply replaces defective plates in a piecemeal manner.

6.0 STRENGTHENING PROPOSALS AND BUDGET COSTS

6.1 Any strengthening proposals need to be compatible with the 'Visitors' Centre' approach to the ship and thus we have discussed with the Curator possible systems of providing the additional strengthening.

6.2 It would appear from our inspection that the most vulnerable section of the hull is the unrestrained section where the free height below decks without any support for the frames is considerable. We believe that in this section of the ship it is possible to insert some "Warren" lattice girders across the hull to act as ties to the frames to stop the hull bursting, whilst also being stiff in their central section to carry loads down onto the centre of the ship at bottom tank level through a series of additional stanchions provided as part of the truss structure. Thus looking at the ship one would see a 'T' shape with a lattice girder over the full width of the ship with a further lattice at lower level beneath the middle section of this truss.

6.3 The trusses themselves will not require lateral restraint down the length of the Ship because they are tension members, but the middle section of the truss at lower level will require some restraint down the centre of the hull produced by somewhat shallower lattice girders.

6.4 In this section of the hull the light and airy nature of the hull will remain and visitors able to see its construction.

6.5 The middle section of the ship is restrained in the height of the hull by the existing structures, i.e. staircases, floors, etc. whilst towards the front of the Ship once again we have long frames which are not restrained.

6.6 The Curator's proposal in this section of the ship is to create a part open section of the hull where visitors can walk around a platform following the line of the hull, with perhaps half a deck set in showing the hull in sectional form. We believe it is perfectly possible to use the walkways to produced support against the bursting action of the hull, but there may need to be some ties across the width of the Ship which could take the form of single steel bars, effectively 'lost in space'.

7.0 LIMITATIONS AND ASSUMPTIONS

7.1 This report is based on comparatively brief surveys of the ship. Strengthening proposals are provisional and final details will need to be based on detailed further investigations, design and detailing.

7.2 This report has been carried out to the Clients requirements and no liability is intended or will be accepted from any third party whatsoever. The limits of liability are restricted to the contents of the report.

7.3 We have not inspected woodwork, or other parts of the structure, unless specifically detailed in the report, which are covered, unexposed or inaccessible and we are therefore unable to report that any such part of the ship is free from defects.

Appendix K

Initial report on the overall structure of the ship and its means of support.
Report by Alan Baxter & Associates 15 October 1998

ALAN BAXTER & ASSOCIATES
CONSULTING ENGINEERS

14-16 COWCROSS STREET, LONDON EC1M 6DR
TELEPHONE 0171-250 1555 FAX 0171-250 3022

S.S. GREAT BRITAIN

AN INITIAL REPORT ON THE OVERALL STRUCTURE OF THE SHIP AND ITS MEANS OF SUPPORT

15 October 1998

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S.S. GREAT BRITAIN: AN INITIAL REPORT ON THE OVERALL STRUCTURE OF THE SHIP AND ITS MEANS OF SUPPORT

1.0 INTRODUCTION

1.1 This report has been prepared at the request of Eura Conservation Ltd, and is intended to form part of the Conservation Plan for the S.S. Great Britain. The report concerns the overall structure of the ship and its current means of support, to which is added a discussion of the main issues for the long term conservation of the structure.

1.2 We visited the S.S. Great Britain on 13 August 1998 and were able to see most parts of the ship, including parts which are not open to the public. This report is based on what we observed on that visit, plus some research on the history of the ship. We have not attempted to repeat the detailed historical analysis carried out by Keystone Historic Buildings Consultants, for the Conservation Plan, which we have read in draft form.

1.3 Following this introduction there are three main sections to this report:

- Section 2 summarises the structural evolution of the ship, and the possible impact on the structure of the various alterations made over the years.
- Section 3 discusses the main structural problems affecting the ship, and their long term implications.
- Section 4 outlines the issues which will need to be addressed to ensure the conservation of the ship for the foreseeable future.

1.4 We have dealt with the overall condition of the ironwork of the hull and frame; the detail is the subject of a separate report by Eura Conservation. We have not looked at the current condition of the dry dock which houses the S.S. Great Britain, although that presents issues which will have to be taken into account in any discussion of the ship's long term future.

1.5 A fundamental premise of this report is that the S.S. Great Britain is an artefact of immense importance, which should be preserved for as long as reasonably possible. Much has already been written about why this ship is so important and although some of these claims could usefully be qualified no-one has challenged its overall historical status. For this report the question is not whether the ship is important, but how its importance can be conserved for the appreciation and enjoyment of future generations.

2.0 THE STRUCTURAL EVOLUTION OF THE SHIP

2.1 BRUNEL'S ORIGINAL DESIGN

The structure of the SS Great Britain explains her long, active life and, more remarkably, how she was able to survive for nearly a century (1886-1970) without substantial maintenance; indeed, during the last 34 years of this period she was scuttled.

Brunel's hull, as designed and constructed in 1839-43, is based on two key elements: a series of closely spaced wrought-iron ribs - the intervals vary but are mostly 18" apart - gathered together by one of the ship's most innovative features, a wrought-iron bottom "box girder", 3' 3" deep at centreline (Figs 1-2). This keel structure is formed from ten longitudinal girders (these are made from 1/2" plate) sitting on top of the frame ribs. A 3/8" thick plate closes this construction and the result is an extremely strong, rigid spine analogous to the box girders found in bridge construction. The overall form of this keel structure tapers fore and aft to follow the curve of the hull.

Above this bottom the ribs are tied by iron angle beams which, in turn, form the support structure to the various decks. To achieve longitudinal strength and minimise the tendency for the decks to move independently of one another Brunel designed composite timber-and-iron stringers for the points at which each deck member meets its corresponding rib. These stringers consisted of a flat plate or "shelf" (36" wide by 1/2" to 5/8" thick) sandwiched between timber beams. On the upper face of the upper deck this plate is reinforced by a massive beam of Baltic pine; on the decks below, pairs of similar timber beams sandwich the iron plate above and below the deck member. Angle iron struts strengthen the join between rib and tie. All of the metal connections are riveted.

To reduce the span of the angle iron beams at the main deck and lower deck levels, Brunel inserted timber posts founded on the keel structure. These were repeated in the dining saloon but not in the promenades, where the vertical loads were picked up by the bulkheads. Many of these wood uprights have been replaced by metal ones.

This integrated structure stops amidships to make room for the engine room, on either side of which, in the lower decks, there are secondary frames to compensate for the interruption of structure. The engine itself and the screw propeller shaft were supported by timber. The masts appear to have sat in shoes which cut across decks. The final element in the structure of the hull was the plating itself. Brunel adopted the "clinker" method where the adjacent strakes (horizontal runs of plate) overlap each other and are riveted together. This had several advantages, since fitting could be done with less precision. Damaged plates can also be removed more easily. The hull plates, all riveted together, can be thought of as a shell which both ties the ribs and distributes the loads over them.

The real defect of this structure was, according to Ewan Corlett, the bracketing arrangements between the ribs and deck ties at the upper deck levels and the lack of a metal deck right across the ship at the level of the weather deck. Subsequent refits went some way to rectifying these inherent deficiencies. Still, when one considers that Brunel's ship was not only without precedent but also designed without the benefit of any technical literature on iron ships, the original structure was remarkable for the way that it anticipated what would later become the standard structural form.

2.2 SUBSEQUENT ALTERATIONS

(see Fig. 3)

The First Refit, 1845-46

The effect of this was to increase the engine's horsepower. The innovative wire rigging was removed along with one of the masts. Bilge pieces 110' long by 2' by 2' were fitted to try to stop rolling in addition to a four-bladed propeller. During its first voyage many of the angle irons in the ship's bottom were broken; these were repaired on arrival in New York.

The Refit of 1851-52

Some 150' of the bottom severely damaged by the grounding in Dundrum Bay was replaced. At the same time double angle irons were installed under engine room. These extended ten feet beyond each of its ends. Wrought-iron uprights replaced some of the original wooden posts; many of these replacements have since been removed. The bow and stern were strengthened by double angle-iron framing. An oak keel covered in zinc was added. Six masts were replaced by four, two of iron.

The 1856-57 Refit

After a short spell as a troop carrier during the Crimean War, the owners decided on a major refit. A new two-bladed screw was fitted. As this screw was to be lifted out of the water to improve sailing efficiency it was necessary to fit a new sternpost and lifting frame. A poop deck was added to provide additional first-class accommodation and a forecastle. Existing masts were removed to be replaced by three larger masts in new positions.

Refits Spanning the Period 1858-71

These are less well documented and known primarily from the Lloyds Register report. In 1861 the flat of the bottom amidships was renewed, and the main deck was doubled in thickness by the addition of 4" pine. In December 1866 the iron box side stringer on the lower deck [probably the promenade deck] was introduced as well as the bulb beams to the main or upper deck. The new iron box stringer corrected some of the defects noted above. In 1871 there was some strengthening around the foremast.

1881-82 Conversion into a Sailing Ship

All passenger accommodation was removed, including the deck added in the 1850s. Timber planking was bolted to the hull above the water line. Additional structural members were inserted into the engine room, in particular Butterley Company patent bulb beams supported on wrought-iron stanchions. The 3/8" tie plate that topped the box girder keel was also removed, and much of the original keel structure cemented up (thus effectively destroying its structural integrity). The propeller aperture was also plated in.

1886 Conversion to a Hulk

The rigging was removed to the level of the lower masts, and two cargo doors were cut in the side of the ship; the cutting of the fwd door entailed removing part of the hull.

Works Carried out since Salvage in 1970

One of the first works carried out was the cleaning of the hull by high pressure water jets. A protective coat of red lead was then applied. In the intervening years some plating has been renewed in steel or fibreglass.

A replica of the original rudder has been fitted, taking the place of the 1857 rudder, which still exists on site.

Two steel decks - upper and promenade - have been installed to make her accessible for the public, and the three major bulkheads from the original design have been reinstated.

Some fittings have restored based on documentary evidence, and a room has been made in the upper part of the boiler space. Planking (salvage from a period ship) has been installed on the weather deck as well as some steel decking to the engine room wings and former dining saloon. The figureheads and trailboards have been remade.

Work on a replica engine is in progress.

2.3 STRUCTURAL IMPLICATIONS OF THE VARIOUS ALTERATIONS

As already emphasised, the S.S. Great Britain has proved to be extremely robust, having survived for a long period without major maintenance. However some of the alterations made in the nineteenth century were detrimental to the overall structural integrity of the ship, in particular:

- the removal of top plates to the keel box girder has impaired the overall rigidity of the keel structure;
- the removal of some of the deck beams has increased the load on adjacent beams and weakened the restraint to the hull frame ribs.

These are alterations which would have had long term implications even if the ship had been well-maintained. However, because of lack of maintenance in the latter part of the ship's working life and the deterioration of the ironwork their overall impact is considerably more significant.

For an iron ship to have spent almost 100 years afloat and 34 years scuttled is quite remarkable. But despite the inherent robustness of the original design and material the ship is now delicate and its future must be out of the water. However the load conditions of the ship in dry dock are quite different from when the ship was afloat (Fig. 4). In dry dock:

- support is concentrated at particular points - the keel and props;
- parts of the frame which were subject to bending from the pressure of the sea are now in tension.

The fact that she is no longer afloat has important implications for the long term conservation of the ship.

3.0 STRUCTURAL ISSUES

3.1 Having considered the history of the Great Britain, this part of the report looks in more detail at the problems which apparently are occurring to the hull and frame. Some of these problems are the result of the alterations made over the years, including the transfer of the ship to dry dock, and some are the result of the general deterioration of the ironwork. In most cases what is happening can probably be traced to more than one cause; indeed it is the combination of more than one effect that has the most serious consequences for the structure of the ship.

3.2 In considering the structural issues we have started with four main presuppositions about what may be occurring to the fabric of the ship:

- There may be loss of redundancy in the overall structure because of alterations, and because of the deterioration of the ironwork, with the result that there is overloading of individual frames (Fig. 5). (Redundancy is the spare capacity within a structure which allows for the failure of an element without endangering the whole structure.)

- A combination of reduced thickness of the hull plates and diminished support from the framing may result in some buckling of the hull (Fig. 6).

- There may be uneven loading on the hull and framing due to (a) the settlement of the timber keel support and (b) the concentrated loads at the timber props (Fig. 6).

- There are overall structural consequences resulting from the storing of the ship in dry dock.

3.3 Those are the main points we have had in mind in looking at the structure. Our main observations are summarised here in terms of what can be seen outside and inside the ship.

3.4 Observations: External

3.4.1 The timber keel strapped onto the external hull plates appears to be in poor condition, and is in places quite rotten. In some places it can be seen that the timber is compressing under the weight of the ship over its supports. This suggests that the ship is settling over its supports. If this is happening, it is possible that distortion of the keel structure is taking place. The nature of the discrete supports in combination with any keel distortion will induce uneven loading within the internal keel structure.

3.4.2 Supplemental support to the hull is achieved through timber shipwrights' props. It has not been possible to ascertain how the positions of these props relate to the hull frame ribs. Bearing in mind the condition of the hull plates in general, it should not be assumed that these plates are capable of transferring prop loads back to the structural ribs (cf. point 3.4.5 below). The apparently random spacing of the props means that uneven loading of the props, and hence the hull structure, is a possibility. Also the props may be affected by damp at the points where they spring from the wall of the dock.

3.4.3 There appears to be a slight bulging of the hull to the starboard side amidships. This may be caused by a loss of support to the hull ribs.

3.4.4 There is a large crack on the starboard side. This will result in a loss in continuity of the hull and stress concentrations local to the crack.

3.4.5 The shell-like nature of the plated hull and the static situation of the ship in the foreseeable future would suggest that the hull would be quite forgiving of the loss of small areas of iron plating. However, as corrosion is rife throughout the hull it is impossible to say without further investigation how much hull structure can be lost (though corrosion) without some form of failure occurring.

3.5 <u>Observations: Internal</u>

3.5.1 The keel structure has already been described. In some areas, the top plate of the box-girder has been removed. This seriously compromises the rigidity and a significant amount of the strength of this element. Furthermore, it can be seen in some areas that the iron plates forming the longitudinal girders have corroded right through. This means that the keel is no longer a continuous, single element and longitudinal strength of the overall ship's structure cannot be assured.

Corrosion of the bottom plates of the keel structure right through can also be seen, particularly in the areas where concrete ballast has been introduced.

3.5.2 In some areas, especially the cathedral-like cargo hold, it appears that the original angle iron tie beams have been removed without replacement. This means that the frame ribs have to span up to twice their original distance without restraint. This they may not be able to do, leading to lateral (outward - we can assume the hull plates prevent sideways displacement) movement and distortion in the hull. Some evidence of distortion was noted in point 3.4.3 above.

3.5.3 Severe corrosion to the riveted connections of the angle iron beams to the ribs was noted throughout the ship, although in some areas this appears to have been repaired. Where there has been no remedial action, the effect on the overall structure is as noted above at 3.5.2. Some original angle iron beams have been replaced with patented T-bulb beams, although possibly not at the same centres as the original elements. Overloading of the ribs may thus become a problem and the hull plating may need to work quite hard to spread load over adjacent ribs (see point 3.4.5).

3.5.4 The Great Britain was not originally fitted with iron decks, relying on the plate action of the timber floor structures to add strength and rigidity to the overall structure. In areas where this has been removed, or is in a poor state, it must be assumed that there is a corresponding detrimental effect on the ship's overall structure.

3.6 Structural Issues: Conclusion

Even with the alterations made over the years, the way the Great Britain was constructed suggests that in its current situation - supported in a dry dock - there is a significant degree of redundancy in the structure, and that redundancy works in the ship's favour. However, there are a number of factors which will severely weaken the overall strength of the structure, in some areas worse than others. The areas which matter most of all are those where corrosion is attacking parts of the structure which have already lost some of their integrity because of alterations.

At present it is impossible to say how much more the fabric can take in terms of the failure of individual elements before the structure fails, either in isolated areas or as a whole. To reach a more definitive conclusion on the condition of the structure will require a more detailed investigation of the main elements than was possible as part of this study.

4.0 CONSERVATION ISSUES

4.1 One of the main axioms of the conservation of buildings and structures is that every effort should be made to retain as much of the original fabric of the structure as possible. By "original" is meant not just the surviving fabric of the structure as first constructed, but also the evidence of any significant alterations.

4.2 Generally speaking the most appropriate engineering approach to dealing with historic buildings and structures follows the same broad principle. Sensitive, low key works which enable a structure to perform as originally intended are preferable to a major engineering intervention. But depending on the alterations that have taken place, and the effect they have had on the structure, in some cases it is appropriate to reinstate the integrity of the original structure by replacing parts which have previously been removed.

4.3 This conservation approach has been developed primarily with buildings in mind, but it is also directly relevant to the case of the S.S. Great Britain. Working ships undergo a constant process of alteration, repair and replacement, more thoroughgoing than most buildings experience. But if at the end of their working lives they are singled out for preservation that constant process of change is arrested, and there is a presumption that they will be conserved very much as historic buildings are.

4.4 The salvage operation which resulted in the return of the S.S. Great Britain to Bristol in 1970 signified a recognition that she should be preserved as a historic artefact, not as a working ship (a function she had long ceased to perform). As described in paragraph 2.2, many repairs have been carried out and some historic features reinstated, not just to help conserve the fabric but also to enable the public to visit and enjoy the ship.

4.5 Despite the valuable work that has been done over the last twenty-eight years, there remain three major conservation issues to be addressed:

- How to arrest the continuing deterioration of the ironwork.
- Whether parts of the structure which have been altered or removed should be reinstated so as to maintain the ship's structural integrity.
- On the assumption that the ship remains in dry dock as at present, whether the present means of structural support should be replaced by an alternative long term method of support.

4.6 Other contributions to the Conservation Plan address the first of these issues, so the future treatment of the ironwork is not discussed in detail here. We have assumed that whatever method is chosen for the conservation of the ironwork, the main aim will be to retain as much of the original fabric as possible. In the future, just as now, people will want to see Brunel's ship (plus some of the historic changes made to it), not a replica of the ship.

4.7 But the conservation of the ironwork, by whatever method, is only one aspect of the required strategy. There is also the issue whether parts of the fabric should be reinstated to allow it to the function structurally as originally intended. This applies in particular to:

- the top plates of the "box girder" keel;
- the deck beams.

The S.S. Great Britain appears to be a clear example of a structure which would benefit from a degree of structural reinstatement, if this can be achieved without harming the overall integrity of the fabric. This is an aspect of the ship's conservation which requires more detailed study and analysis.

4.8 The third conservation issue - the way that the ship is supported in dry dock - highlights the fact that the S.S. Great Britain is being stored in conditions quite unlike those that she was designed to experience. In particular the concentrated loads on the timber keel and timber props result in uneven loading on the hull and frame, which may produce significant distortions in the structure. A different method of support which spreads the loads more evenly, perhaps through the use of continuous cradles, will be highly beneficial to the long term conservation of the ship.

5.0 CONCLUSION

5.1 The importance of the S.S. Great Britain is indisputable. Even after a century and a half, for a significant part of which she was stripped of her fixtures and had no maintenance, enough of the Brunel fabric survives to merit preservation. She is one of the most important surviving artefacts from an immensely creative period in the history of ship design and the use of iron.

5.2 On the presupposition that it is the authentic fabric of Brunel's ship which should be preserved, not a replica of it, there are a number of major issues to be addressed. Perhaps the most important of these is how to slow or halt the deterioration of the ironwork. But almost equally important are how to maintain the ship's structural integrity, and how to support her in dry dock without damaging that integrity.

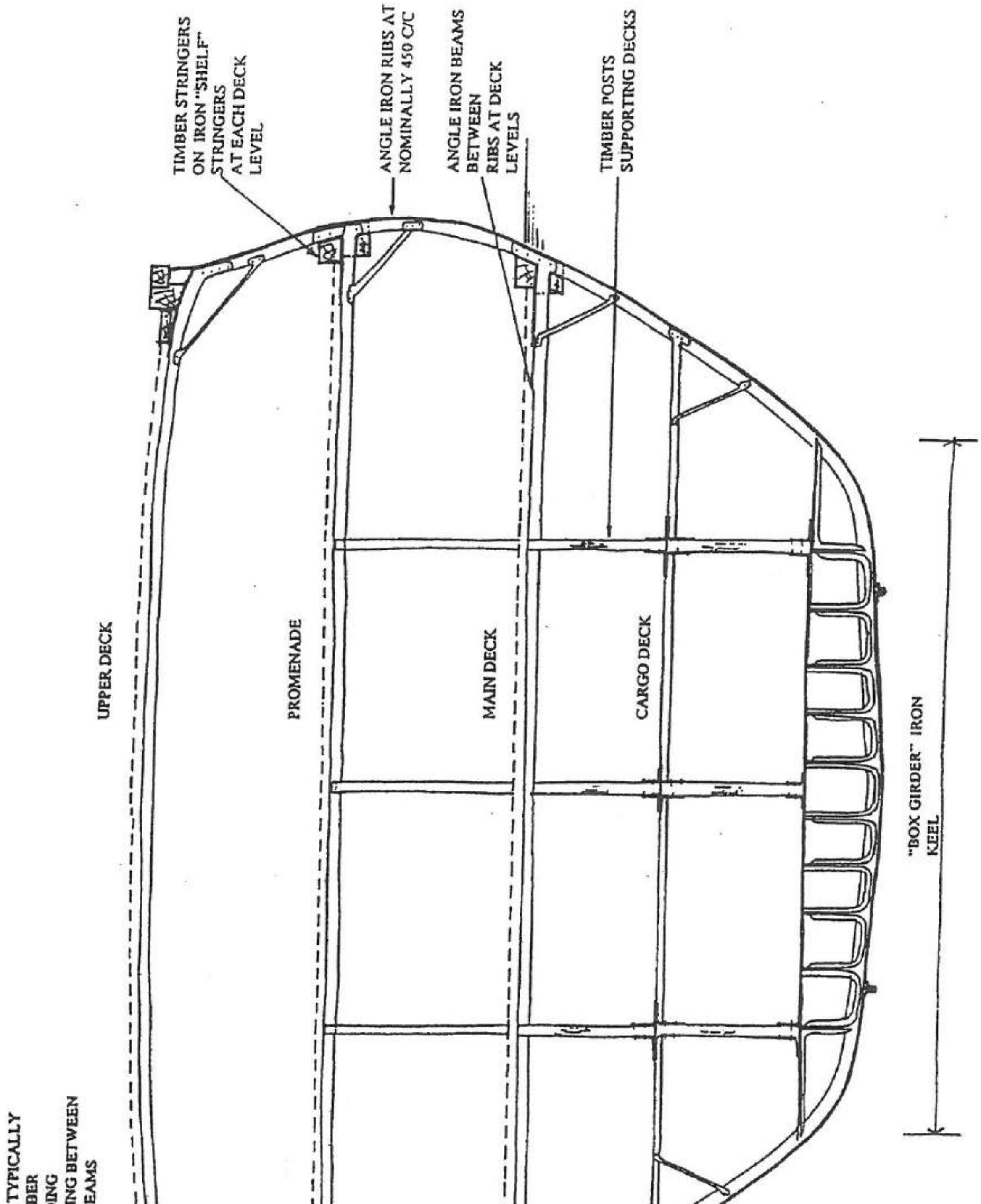
5.3 What is said here should be read in conjunction with reports prepared by others on the condition of the ironwork and methods for its conservation. Since the ship is now essentially a museum artefact there is a need to create the right environmental conditions for her long term preservation, which may mean protecting her from the weather with some form of covering.

5.4 In addition to the condition of the ironwork, this report highlights two other related issues:

- The need to reinstate the structural integrity of the ship to allow the structure to work as originally intended. Just what needs to be reinstated should be the subject of further study and analysis.

- The need to introduce a new method of support for the ship in dry dock, to avoid the severe point loads generated by the present arrangement. Some form of continuous cradle will probably be the preferred solution.

5.5 Since the S.S. Great Britain returned to Bristol in 1970 a large amount has been done to conserve the ship and to make her accessible to the public. The present review, of which this report is a part, has come at a critical moment in her history. Despite the work done in recent years she is now in a delicate condition, and there is an urgent need to establish a new conservation strategy to ensure her long-term survival. Without such a strategy her deterioration will accelerate to the point that she can no longer be seen and enjoyed as those who worked to save her intended.

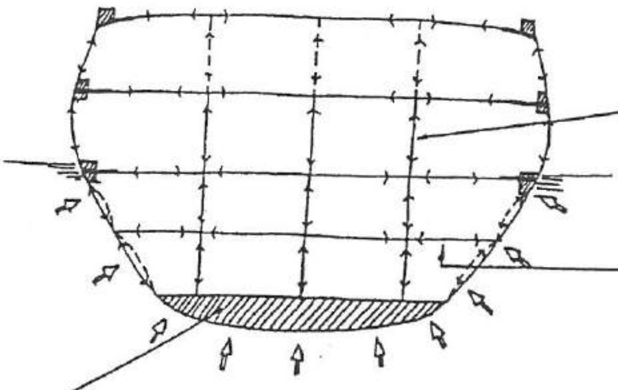


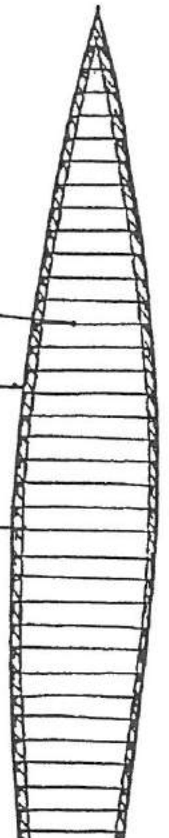
ALAN BAXTER & ASSOCIATES

S.S. GREAT BRITAIN

ASSUMED TYPICAL SECTION AMIDSHIPS SHOWING STRUCTURAL ELEMENTS AS BUILT 1839-43

FIGURE 1





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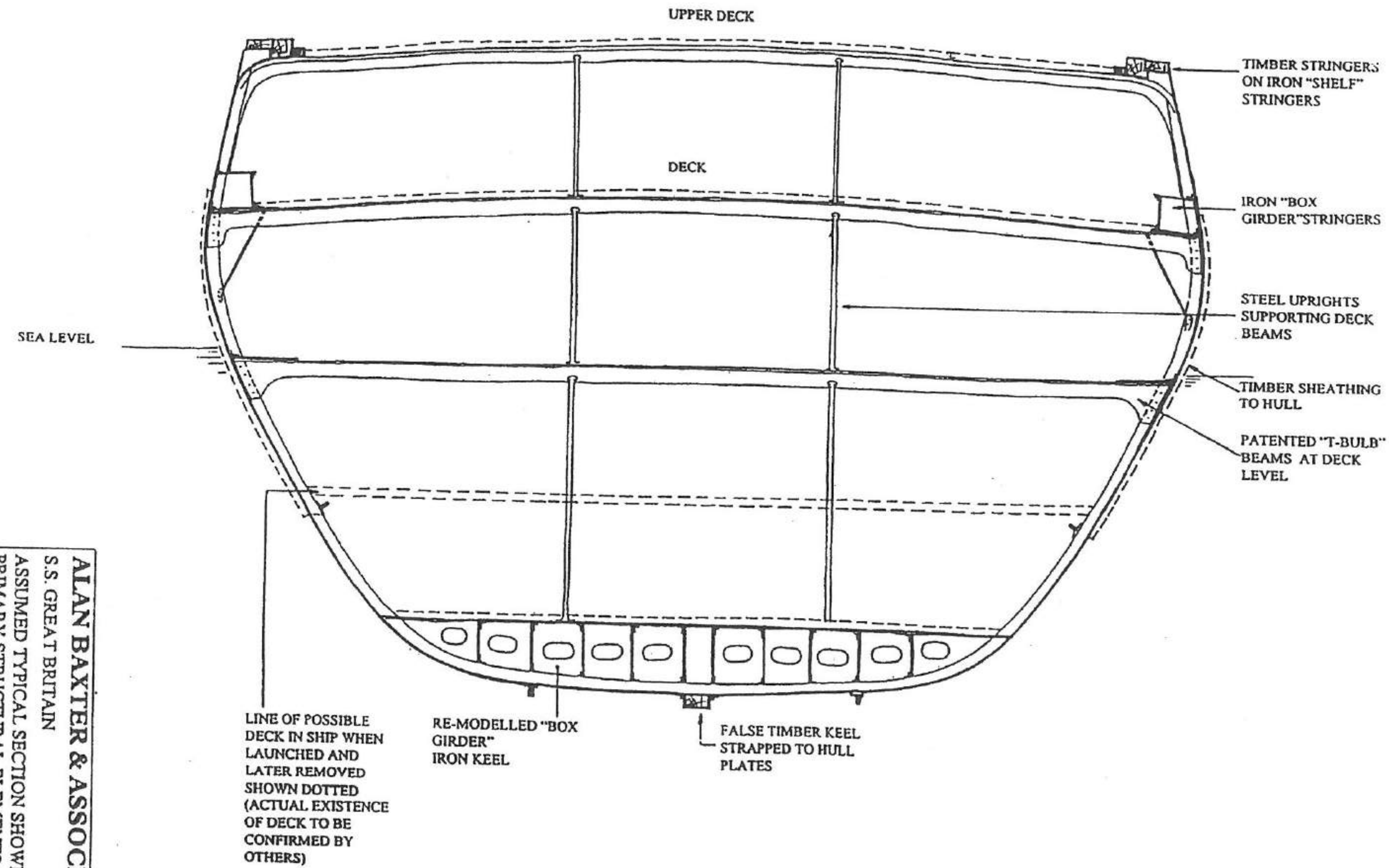
TYPICAL SECTION AND DECK PLAN

FIGURE 2 203



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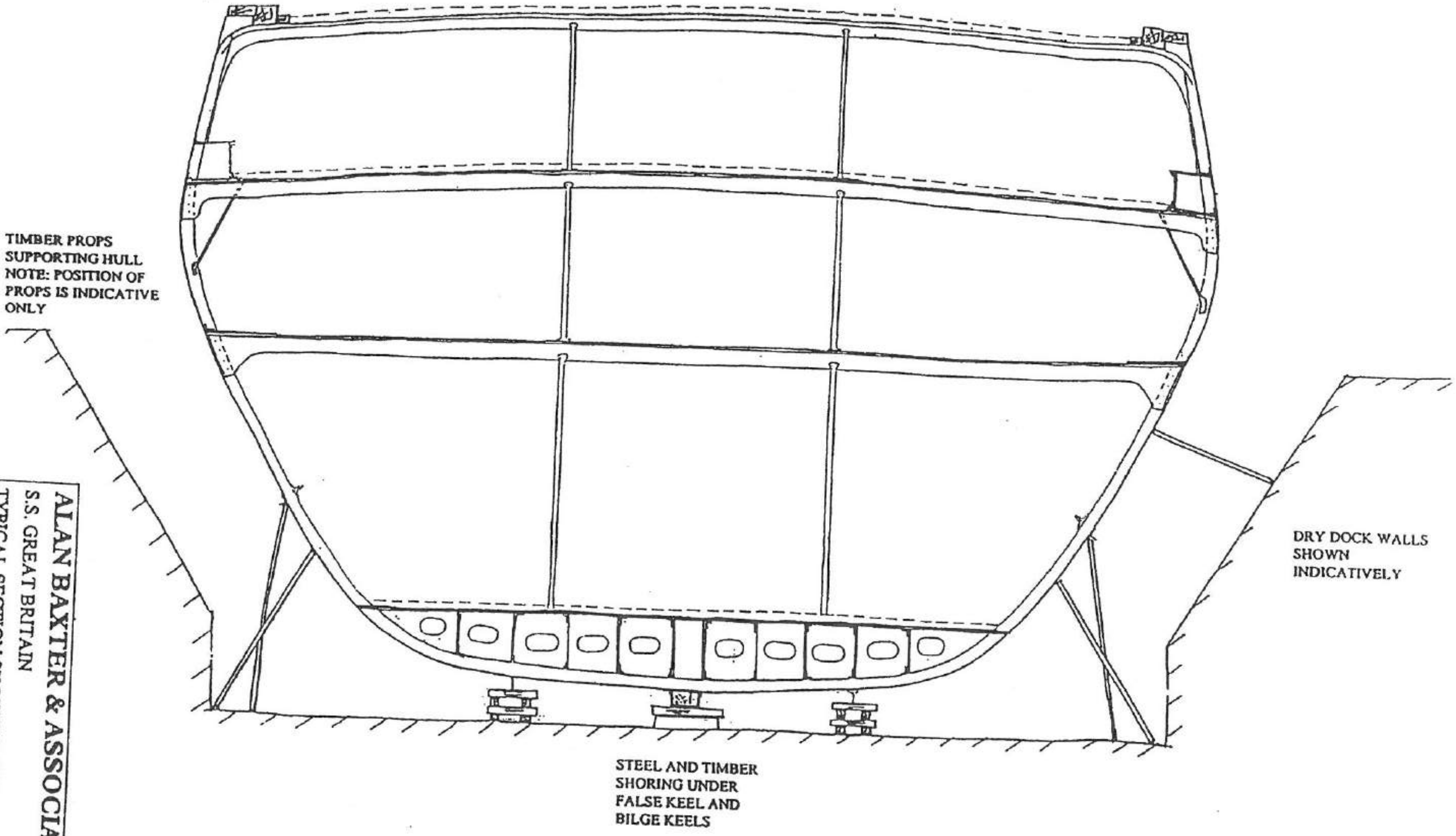
S.S. GREAT BRITAIN

ASSUMED TYPICAL SECTION SHOWING PRIMARY STRUCTURAL ELEMENTS c.1887

FIGURE 3 204



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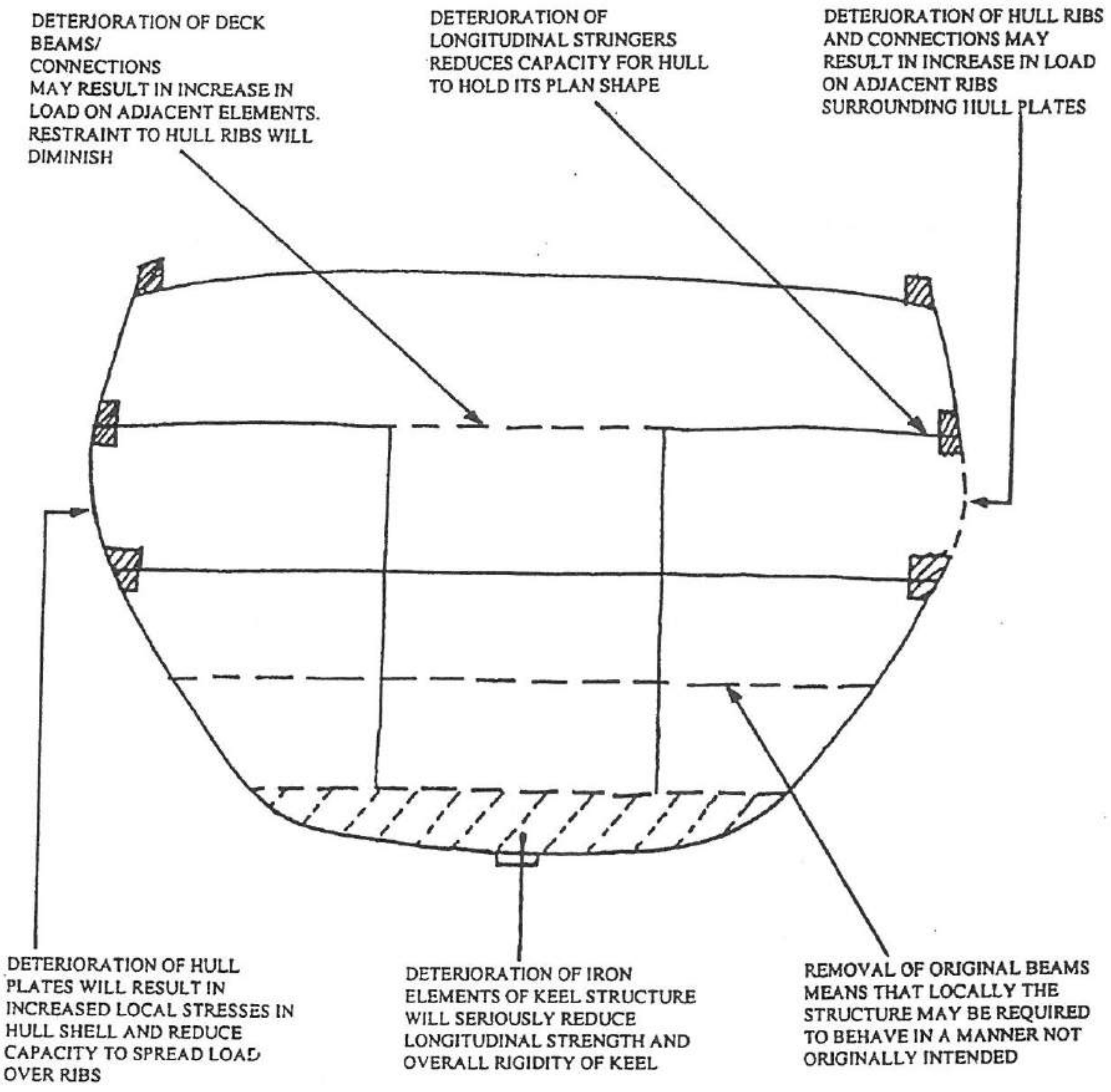
S.S. GREAT BRITAIN

TYPICAL SECTION SHOWING SYSTEM OF SUPPORT TO HULL

FIGURE 4



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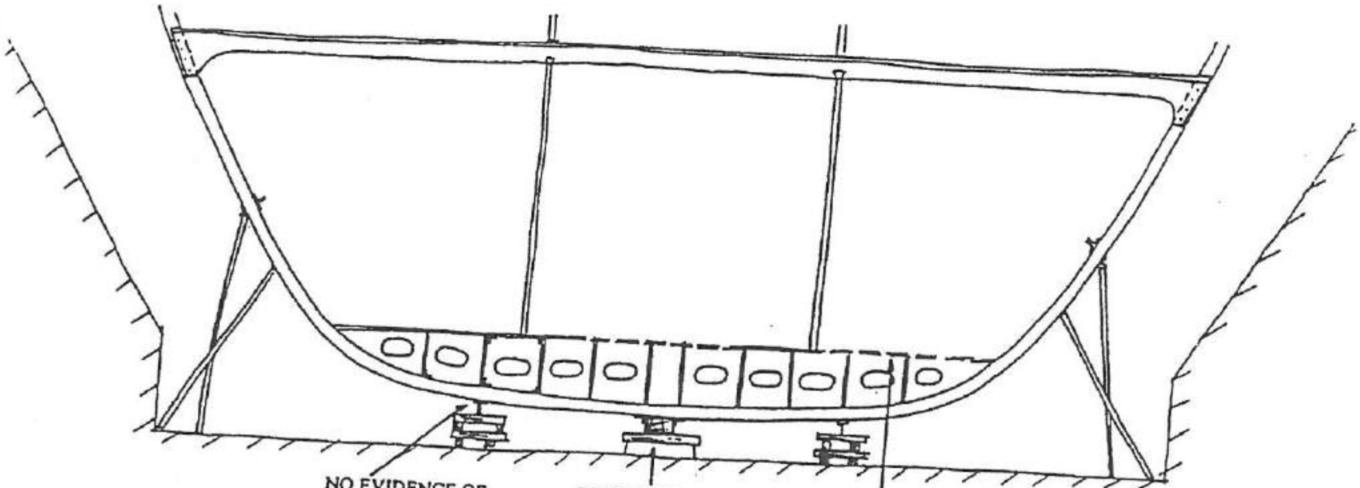
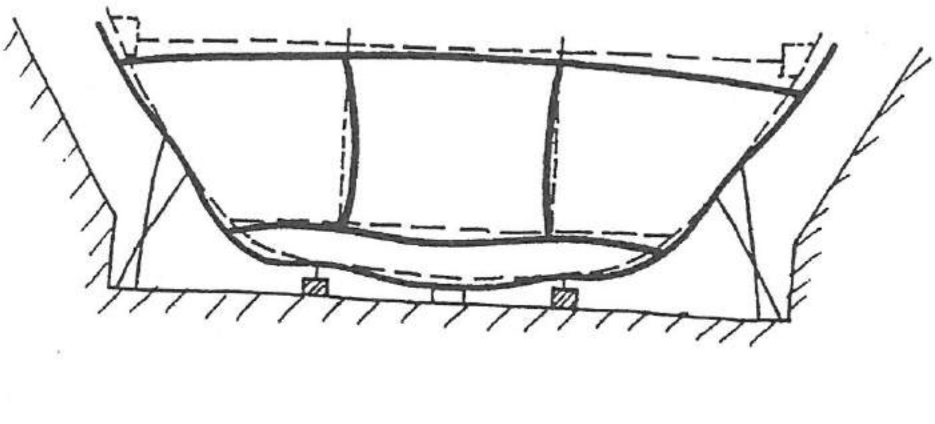
S.S. GREAT BRITAIN

ASPECTS OF THE PRESENT STRUCTURE (1)

FIGURE 5 206





TYPICAL SECTION THROUGH HULL SHOWING ASSUMED EFFECT OF DEFECTS ON HULL OVER TIME (EXAGGERATED)

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S.S. GREAT BRITAIN

ASPECTS OF THE PRESENT STRUCTURE (2)

FIGURE 6

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Appendix L

Report on the Hull, State and Status of the *ss Great Britain*
L F Porter, 29 December 1997

REPORT

ON THE

HULL STATE AND STATUS

OF THE

SS GREAT BRITAIN SHIP

by Eur. Ing. L.F.Porter, C.Eng., F.I.Mar.E. dated 29 December 1997

Aim.

This report accepts the importance of the ship SS GREAT BRITAIN in the maritime history of the United Kingdom and also in its own right as an unique historical artefact. There is still a great deal of information to be uncovered of the design, construction and various conversions therefore it is essential that she be properly conserved with the materials and structure stabilised, preserved and protected as far as is possible with modern technology.

Description.

The SS GREAT BRITAIN has had a long and honourable working life during which she was subjected to many changes. Each change in itself was worthy of note and will be investigated, documented and any surviving artefacts and records studied and displayed. However the most meaningful, long lived and original item is the SSGB hull which is still almost entire.

The survival of this massive and beautiful hull, which is so important in maritime history, is a minor miracle in itself. It incorporated so many firsts that the claim that it is the ancestor of the modern mercantile marine is no empty boast. The iron hull, the fine lines and the bilge keels are all relatively intact and can be viewed by interested persons and closely studied by academics, historians, engineers and scientists. The materials are also important and worthy of close study in that they have survived for so long in inhospitable conditions.

Discussion.

Whilst the SSGB has survived for so long some of the hull fabric has suffered from corrosion and stress and this is sadly beyond reclamation other than by replacing with similar or replica materials in the affected areas. It is understood that this is not to be an option as it would degrade the authenticity of the ship. Since returning to Bristol and settling in her original building dock she has been cleaned and preserved as far as possible within the limited knowledge and resources available.

The underwater hull, whilst still strong enough to support the ship, has suffered particularly from corrosion and is perforated in many places. Had the hull plating been mild steel rather than wrought iron there would have been nothing left to conserve but the actual material used has resisted oxidation well in sufficiently large areas to show the design, workmanship and clever use of the limited sizes and shapes of the materials of the time.

As the ship is so historically important it is understood that no action is to be permitted to remove or replace corroded areas, therefore many of the larger holes have been covered with glass reinforced plastic(GRP) to keep out the weather and to temporarily seal the plate. This does not in any way contribute to the strength of the hull. The hull was scraped and sealed with a commercial paint coat which has slowed down the rate of deterioration but has not stopped it and this treatment will need to be repeated shortly.

Also temporary and unsightly repairs have been made, particularly where the hull is cracked vertically on the starboard side almost to the keel. In this case the inside will be strengthened and the bolted plates removed. The crack can then be inspected and studied to determine its effect on the hull strength.

When funds are available it is intended to initiate a project to determine the metallurgical structure of the wrought iron and the mechanism of corrosion so that a non-destructive method of passivation and sealing can be devised to preserve and conserve the hull for posterity. This may be in conjunction with the Submarine Museum at Gosport which has a similar problem with the Holland Boat 1 which is presently sealed in a tank and flooded with a neutral chemical solution until a satisfactory treatment is produced. This expedient is not available to the SS GREAT BRITAIN PROJECT so it is essential that the ship be kept as clean and dry as possible with access to all the underwater parts for monitoring and working, in anticipation of the suitable treatment. Also, as previously stated, it is important that visitors are able to view the results of the skills and expertise of the craftsman, shipbuilders and engineers of the XIXth. century.

The weather deck planking was very decayed and unsafe when the ship was salvaged and this was cleared and replanked with pitchpine on her return to Bristol. Unfortunately this succumbed to wet rot within twenty years and has now been replaced with steel plate and covered with 50mm. Jarrah planking on angle iron bearers to allow for the circulation of air to discourage any form of rot. Whilst the wrought iron frames and deck bearers are generally sound and complete this form of decking adds significantly to the hull strength, protects the inside of the hull from deterioration due to weather and allows safe and comfortable access for visitors to view the beauty of the hull lines and rigging. Where possible any of the original parts that were salvageable have been incorporated in the renovation of the weather deck.

The inside of the hull is also being preserved and, where important sections have disappeared, an effort is being made to replicate them as closely as possible from the records available. This particularly includes the 1844 engine, the dining saloon and the first class accommodation, all of which were significant at the time and have been the subject of research and study in their own rights.

Conclusion.

With the necessity to preserve what is left of the original hull and for access to study it closely it is essential that the ship be kept in as clean, dry and protected an environment as is practicable. The bottom is perforated in many areas and little is yet known of a suitable corrosion preventative. This, combined with the effects of the stresses suffered during the time the ship spent aground and afloat (which led to the vertical cracking of the starboard side), precludes her being floated up without a massive sealing exercise which would severely degrade the original, existing hull plating and framing and destroy valuable historical material.

Recommendation.

That the SS GREAT BRITAIN drydock be sealed off and the ship maintained so that when suitable processes become available she can be safely preserved, studied and exhibited as a most important artefact of British Maritime History in the place where she was actually built.

L.R.Porter
Engineering Consultant

Appendix M

The wrought iron of the *ss Great Britain*.
An overview of properties in design and renovation
Dr J E Morgan, 1996

THE WROUGHT IRON OF THE *S.S. GREAT BRITAIN*, AN OVERVIEW OF PROPERTIES IN DESIGN AND RENOVATION

Dr J E Morgan, MIM MIMechE
Department of Mechanical Engineering,
Bristol University, Bristol, UK

SUMMARY

This paper considers the manufacturing processes, the characteristic internal structure , and the related mechanical properties of 19th century wrought iron components obtained from the S.S. Great Britain. In addition the paper considers the problems of renovating historic wrought iron structures using normal modern welding techniques.

AUTHOR'S BIOGRAPHY

Dr John Morgan is a senior lecturer in Materials Science at The University of Bristol. Over a number of years he has been involved in examining and testing a number of ferrous and non-ferrous components from historic sites around the UK. Recent work has involved carrying out a detailed metallographical analysis of the iron staircase in Christopher Wren's Monument in the City of London, built to commemorate the Great Fire of 1666.

1.0 INTRODUCTION

The International Festival of the Sea, celebrated in Bristol this year, will be one reason why even more people than usual will visit Brunel's famous steam ship the *S.S. Great Britain* and wonder at the technology and inventiveness of the 1840's which allowed such a landmark in ship construction to be completed at that time. It is of course erroneous to identify the *S.S. Great Britain* as either the first ship to be built of iron, or the first ship to be driven by screw propulsion. However, the first large sized, ocean-going ship to combine both iron construction and screw propulsion she certainly was. When Scrivenor (1) recorded in his History of the Iron Trade in 1854, " But the vessel which has generally attracted the most attention in Liverpool is the *Great Britain* iron screw steamer ", he could, with only a change of place-name of *Bristol* replacing that of *Liverpool*, surely have been writing for 1996.

Under the auspices of I.K.Brunel and the Great Western Steamship Company, the plans for the *S.S. Great Britain* were drawn up in 1838. However, at this date it was envisaged that she would be built in wood, powered by paddles, and named the *City of New York*. Her keel was laid in Bristol's Great Western Dock in 1839 (the same dry dock that she can be seen in today). However, even at this late stage, when designs had been more or less finalised and construction had begun, Brunel began to consider the possibility of building the *City of New York* in iron. A detailed report arguing the case for iron, rather than for wood construction, was drawn up by Brunel and his building committee and submitted to the company directors, hopefully for their approval. In retrospect, it must be considered surprising, and evidence of extreme far sightedness, faith, or foolishness, that the directors approved this radical change and as a result requested Brunel to draw up detailed plans for a ship in iron. Apparently not a subject that at the time he knew very much about (2). However, one problem that Brunel no longer had to contend with was that of the influence of his ship's ironwork on the accuracy of the ship's magnetic compass. It would appear that just in time (also in 1839) Sir George Airey and the Admiralty Compass Committee proved the use of magnets to correct magnetic deviations built into an iron ship. This discovery now meant that iron ships could safely venture from the sight of land but still be able to steer a known course. Construction in iron began in July 1839.

However, major changes to Brunel's latest plans were still to unfold. In May 1840 a small experimental ship called, appropriately, the *Archimedes*, visited Bristol and demonstrated the practicality of a ship being powered by the novel device of a screw propeller. Brunel was fascinated by this device, as evidenced by his comments, calculations and crossings-out to be seen in his personal calculation book (3), concerning the relative efficiencies of screw and paddle wheel propulsion. Looking at his hand written calculations, it is possible to almost sense the frantic surge of excitement that he must have felt while trying to determine whether this new form of ship propulsion was as good as it seemed.

Following his own trials aboard the *Archimedes*, Brunel yet again proposed a radical change in the design of his *Iron Ship*, and specifically that it would incorporate propulsion by screw rather than by paddle wheel. The directors again approved this fundamental and relatively unproven change in design, and at the same time agreed to rename the ship *Great Britain*. In 1843, The *S.S. Great Britain*, built according to a continuously changing series of designs, was launched from the Great Western dry-dock, exactly where she can be visited to-day.

2.0 WROUGHT IRON PRODUCTION

Only 50 years before the construction of the "iron" *S.S. Great Britain* commenced, the production of wrought iron was a grossly inefficient and time-consuming business. However, Henry Cort's invention of his puddling process in 1784 and Joseph Hall's further improvement of this process in 1839 meant that by the time the plans for the

Great Britain were finalised, not only was the price of wrought iron competitive with other construction materials, but sufficient quantities could be produced to allow engineers to contemplate using it on even the largest of projects. At the zenith of wrought iron production, before the Bessemer process made cheap steel a reality, Fairburn (4) recorded that production of cast iron containing 4% carbon, cost approximately £3 per ton. The value added contribution in refining cast iron into wrought iron, raised the cost of wrought iron to £8 per ton, while a 1% carbon steel could command a price of £50 per ton.

With slight variations, by 1840, the process of converting cast-iron into wrought iron followed a well established route. Cast-iron was placed in a furnace and remelted. By a process of oxidation the molten cast iron gave up its carbon and in so doing formed an iron-carbon alloy whose solidification/melting temperature gradually increased as the carbon content was reduced. The result of this was that the alloy mass in the furnace became less liquid and more pasty in texture. This pasty iron-slag mixture was stirred with a long iron rod to encourage final removal of the last traces of carbon and other impurities, again by oxidation.

After this final stirring a white-hot semi-solid spongy mass of malleable iron and partially molten slag would be removed from the furnace and processed in a shingling hammer. This "hammer" squeezed this mass of iron and slag, primarily to densify the spongy iron into the form of a solid iron bloom, while at the same time expelling a high proportion of the semi-molten slag (shingle). The bloom was then passed through mechanical rollers for hot rolling into rod, bar or billet. Typically, the bars or billets so produced would be cut up into short lengths, and piled on top of each other, before being reheated and rewelded under a steam hammer to produce a new bar or billet, this time of better quality in terms of slag dispersion and as a result also in tensile strength and ductility.

Throughout her working life the *S.S. Great Britain* underwent a number of refits, and in some cases extreme modifications, as a result of both accident, (such as running aground off the coast of Ireland) and design (such as when different owners modified her to make her more suitable for her changing rôles). For this reason, items of wrought iron existing on the ship today may have been fitted some years after her original construction. Even in 1854, only eleven years after her launching, Scrivenor (1) makes the comment "She was built at Bristol, although a Bristol man might have some difficulty in proving her identity" - a reference at this time to her totally altered appearance following her sale to Gibbs, Bright and Co in 1850.

3.0 *S.S. GREAT BRITAIN* COMPONENTS

In consultation with Capt. Chris Young (Director of the *S.S. Great Britain* Project) a number of wrought iron components were identified for metallographic examination, where the date of manufacture and fitting of these components has been confidently established. The wrought iron components examined included the following:

(a) Part from a stern plate - original 1843 construction.

(b) Part from a strengthening butt strap plate - original 1843 construction.

(c) Part from a stay supporting a platform around the main mast - fitted c.1857 during refitting.

(d) Part from a vertical member of the weather deck railing - fitted c. 1882 during refitting.

(e) Part from an internal column supporting the floor of the upper "tween deck"- fitted c. 1882 during refitting.

(f) Part from an I beam supporting the floor of the lower "tween deck" - fitted c. 1882

From all the components listed above, orthogonal metallographic sections were prepared in order to examine the microstructure of the wrought iron. All the components examined exhibited very similar structures comprising a three dimensional polygonal ferritic grain structure, heavily interspersed with slag fibres which had been elongated in the direction of final working of the components during manufacture. A three-dimensional composite micrograph of the observed structures, (after light etching), typically representative of all the components examined, is shown in Fig 1.

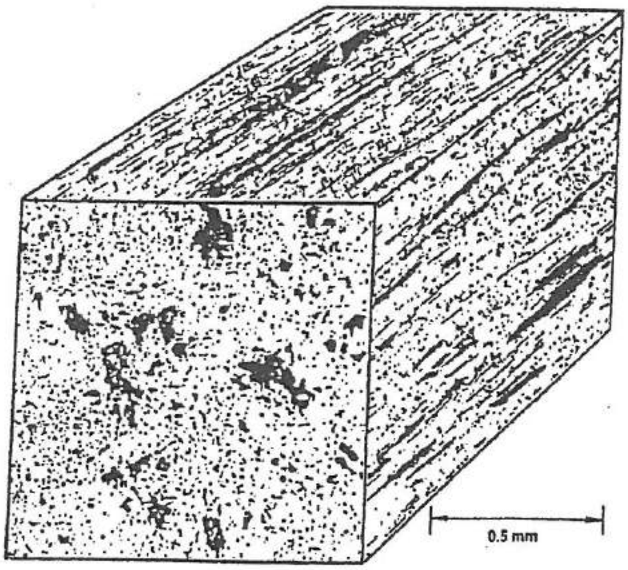


Fig. 1

For all of the components A - F, a series of hardness measurements, tensile tests and notched impact tests were carried out. Where appropriate, tests were carried out both in the direction of final working (i.e. with the applied load parallel to the slag inclusions) and also perpendicular to the direction of final working. For all these tests, mechanical property values close to those expected were obtained. Average values are shown below in Table 1.*

TABLE 1

Specimen	A	B	C	D	E	F	Average of A-F	Modern Mild Steel
Approximate date of manufacture	*1843*	*1843*	*1857*	*1882*	*1882*	*1882*	—	*1990*
Hardness HV20 kg/mm^2	136	129	119	125	135	137	130	225
Yield stress in direction of working N/mm^2	203	219	192	196	230	221	210	450
Maximum stress in direction of working N/mm^2	281	314	305	279	339	326	307	520
% elongation at failure	11	21	31	13	34	24	22	24

*For details of cross-grained strengths, see Ref. (5)

The results shown above are typically what one might expect to obtain from 19th century wrought iron and compare reasonably well with values quoted by other sources. For example, a CIRIA report on the structural renovation of traditional buildings (6) identifies the yield stress and maximum stress for wrought iron, manufactured between c. 1835 and 1900, as lying between 155 - 200 N/mm^2 and 280 - 370 N/mm^2 respectively.

In addition measurements by contemporary 19th century workers suggest that the higher end of the strength values reported by CIRIA tend to be obtained from later (c.1890) wrought iron, rather than earlier (c.1840) iron. However the CIRIA values are only guidelines and some 19th century wrought iron may well fall outside, and indeed below, these suggested values. For example, tests carried out on wrought iron from the roof of Paddington Station (7), designed by Brunel in 1850, only produced maximum strength values of 266 N/mm2 for the wrought iron used.

4.0 NOTCHED IMPACT TESTS

From the *S.S. Great Britain* results, however, the most interesting mechanical property values obtained have to be those from the notched impact tests. Notched impact testing is used to identify the susceptibility of metals, or other materials, to the possibility of instantaneous, catastrophic fracture occurring as a result of sudden impact loading. Surprisingly a number of materials that show good strength and ductility when tested in a standard tensile or compression test, (where a steadily increasing load is slowly applied to the test specimen), can, under certain conditions, fall apart as a result of receiving relatively small, sudden impacts. (One of the most convincing examples of these apparently contradictory mechanical properties is evidenced by the ability to totally support a large vehicle, for example, a double-decker bus, on only fragile porcelain tea cups - components which we know often fall apart at the slightest knock.). The notched impact test, which can identify the susceptibility to failure by impact, is usually carried out over a range of temperatures, since one of the objectives of the test is to identify any increased tendency to brittle fracture as a result of the metal being exposed to low temperatures.

The notched impact results for the components from the *S.S. Great Britain* (and for comparative purposes, those obtained from modern mild steel specimens) are shown in Fig 2. In this figure, the vertical axis identifies the amount of energy used to break the specimen, while the horizontal axis indicates the test temperature. The S shaped curve obtained for the modern mild steel specimens is exactly as expected.

This curve shows that mild steel is tough at normal working temperatures (~ +20°C) and at these temperatures can absorb very high impact energies before fracturing. As the temperature drops, however, say to -60°C, even modern mild steel becomes brittle and susceptible to fast fracture. The average temperature at which the transition from ductile to brittle behaviour occurs is known as the ductile-brittle transition temperature, which for mild steel is seen to be somewhere around -20°C. For the wrought iron of the *S.S. Great Britain*, however, the results are very different from those for mild steel.

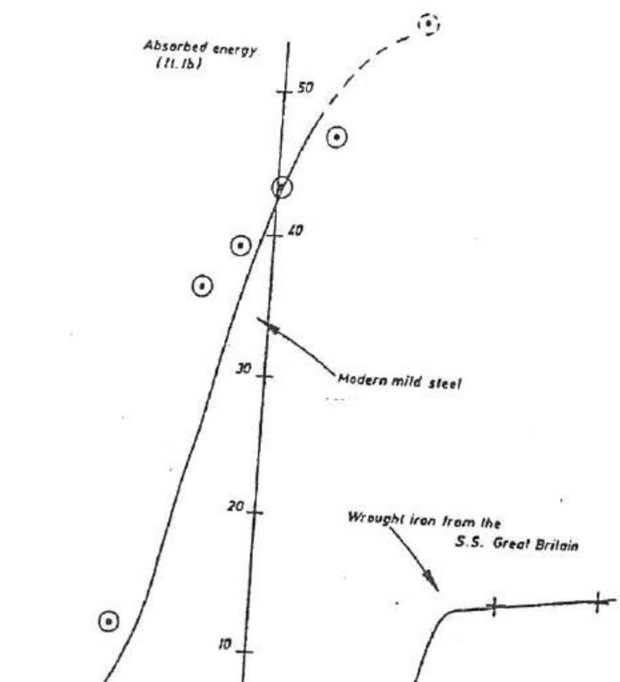


Fig. 2

Certainly the results show "upper shelf" and "lower shelf" values and also an identifiable transition temperature. However, even the upper shelf values are below 20 ft-lb, still relatively brittle, while the transition temperature is around about +40°C, well above the typical operating temperatures of the *S.S. Great Britain*. For a typical operating temperature of around +20°C it is seen that wrought iron is as brittle as mild steel is at - 60°C, in other words, very brittle indeed and as a result, extremely susceptible to fracture resulting from sudden impact.

5.0 BRITTLE FRACTURE

It is, of course, obvious to state that the susceptibility of wrought iron to brittle fracture is a well known phenomenon to those who have come across it before, but it appears that this particular property of wrought iron often comes as a total surprise to many people. For example, in 1987 Richard White in discussing the iron ship *HMS Warrior* (8), comments on results from a series of modern tests of Warrior's wrought iron, that: *"The surprise was in the impact strength tests. . "*. In a fascinating, recent paper co-authored by the eminent naval historian David Brown titled "the *Titanic* and *Lusitania: a final forensic analysis*"(9), the authors argue the case that the supposed 300 ft gash, supposedly ripped in the side of the *Titanic* by an iceberg, in fact never existed. Instead they restate the case argued at the Board of Trade's inquiry by the *Titanic's* designer, Edward Wilding, that the iceberg created only a 12 sq ft hole below the *Titanic's* water-line, but that at the prevailing low temperature increased flooding occurred as a result of brittle fracture of the wrought iron rivets securing the ship's side plates which were impacted by the passing iceberg and which subsequently opened up at their seams to allow ever more water to enter the hull.

In the 1840's when the *S.S. Great Britain* was built (or even in 1912 when the *Titanic* sunk) the science and understanding of fracture mechanics, notch sensitivity and ductile-brittle transition effects were as yet unknown. However, in their own way the Victorians had almost identified the susceptibility of wrought iron to fast brittle fracture without having quite realised the full importance of their observations. For example, in 1869, William Fairburn (4) wrote *"In determining tensile strength, the force employed to affect rupture is slowly applied; and results are obtained in this manner which may cease to be applicable in cases where impact takes place. . . "*. Similarly, William Greenwood writing in 1884 (10) stated that: *"The higher qualities of bar-iron present, when broken, a certain silky fibrous appearance. The fractured surfaces are, however, more or less deceptive, since specimens broken by progressively increasing stresses are invariably fibrous, whilst the same specimen broken by a sudden blow will exhibit a crystalline fracture. . . "*.

The susceptibility of wrought iron to brittle failure, especially at cold temperatures, must have increased the potential for disaster at sea for ships which were made from this material, and it might be fortunate that wrought iron was used as a preferred material for a relatively short period of time before the availability of cheap steel made this latter material standard for ship's construction. Some years ago the author suggested (5), rather tongue in cheek, that had the *S.S. Great Britain* regularly sailed in very cold waters and ever suffered impact damage to her main structure, then she could have suffered the same fate as the ill-fated liberty ships of the last war. It now appears that her fate could have even pre-empted that of the *Titanic*.

6.0 THE RENOVATION OF WROUGHT IRON STRUCTURES

Considering her chequered history, it is without doubt to some extent fortunate that the *S.S. Great Britain* is now back in Bristol safe and sound and in the process of being restored to her original condition. As well as replacing some components completely, some of the restoration naturally involves repair to the original wrought iron structure. However, once again, due to the inherent structure of wrought iron, even apparently straightforward repairs may prove more difficult to make than one might think. As more and more of our 18th and 19th Century historical monuments suffer the weakening effects of corrosion and old age, an increasing number of wrought iron structures are becoming in need of repair and renovation, not only to ensure their availability for future generations to enjoy, but also to ensure their present safety.

In 1935 The Iron and Steel Institute held a symposium which among other things considered possible inherent weakening as a result of welding wrought iron (11). This weakening, observed after electric welding, was attributed to slag spreading across the weld and producing layers of weakness perpendicular to the normal worked slag direction. Much more recently, some repairs to historic structures have involved welding steel or replacement, "second-hand", wrought iron onto existing wrought iron. Problems associated with this type of renovation are discussed by Connell (7) in his paper detailing recent renovations carried out to the roof of Paddington Station. (already identified as another of Brunel's designs).

Connell identifies, especially for fillet welds, the problems of attaching steel or new "second-hand" iron onto what may only actually be a thin outer coating of iron sitting on a weak slag layer. Connell suggests, however, that butt welds can give a satisfactory joining, if the weld attaches to all layers of the wrought iron. For the Paddington Station roof renovation, the soundness of butt welds were checked by experiment where trial welds were made and strength tests carried out on the trial joints. Experiments at Bristol have also tested welded joints of old wrought iron where the weld has been built up to try to ensure contact with most of the iron in the wrought Iron structure. Like the Paddington Station tests, the results from such trial welds generally indicated that a sound joint had been made. However, the author now thinks that if normal "modern" welding methods are used, then a good weld can not necessarily be guaranteed and that its formation, or otherwise, may well be more to do with luck than judgement.

Recent experiments have been carried out where a 1" diameter, 19th Century wrought iron bar was MIG welded using a mild steel filler rod and an argon shield. The two ends of the bar to be joined, were first machined to a point so that the weld metal would theoretically attach itself to all the exposed iron layers. After sectioning, polishing and lightly etching the welded bar, the new weld metal can clearly be identified, and although some non joining is evident in the centre of the weld, much of the rest of the weld seems to have fused into the original wrought iron with no obvious voids or lines of weakness.(Fig. 3).

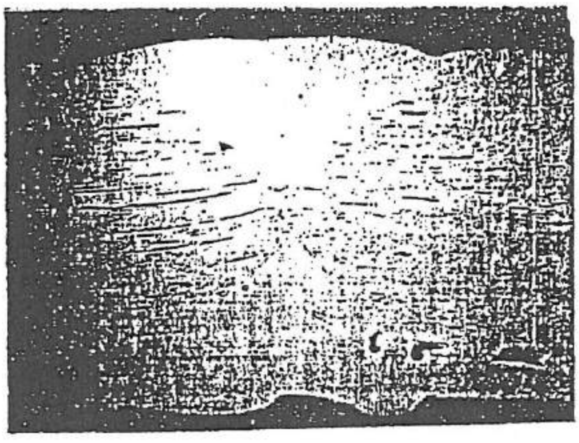


Fig. 3

A higher magnification micrograph showing where wrought iron and weld metal appear to have satisfactorily fused without problem is shown in Fig. 4.

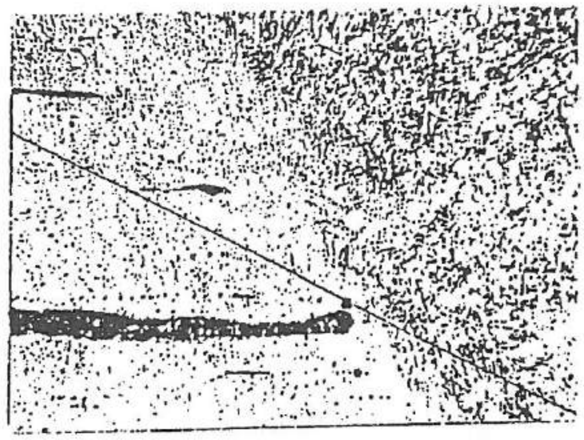


Fig 4

The bar seen in Fig 3. was subsequently machined into tensile specimens which were each tested in the normal way. Not surprisingly,the specimen from the centre of the bar, where some segregation had been previously seen, broke at a low stress in the welded region. Of the remaining two specimens, however, where the weld looked sound, one broke in the gauge length, initiated at a large slag inclusion, (Fig. 5) while the other, surprisingly, broke once again with a low stress at the weld interface (Fig. 6).

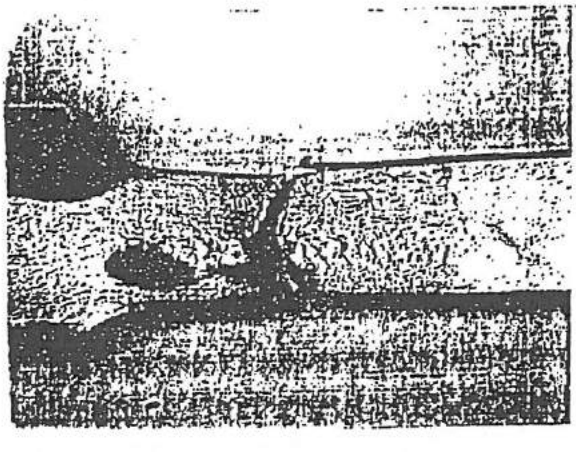
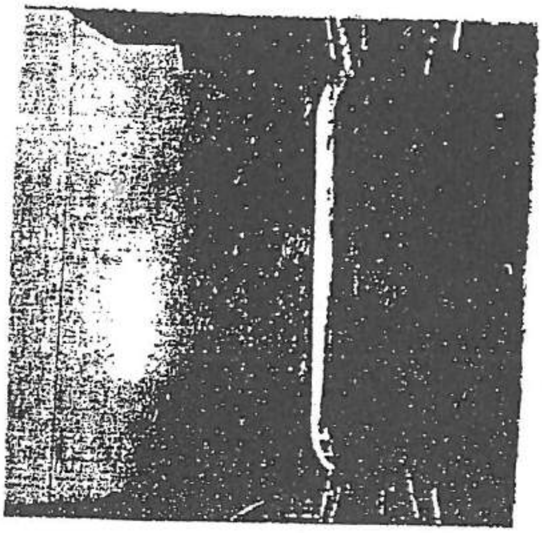


Fig. 5

Upon closer examination it appears that during the welding process, the slag in the wrought iron melts and can, as a matter of chance, resolidify in a position where it sits across the join between the weld metal and wrought iron (Fig. 7).



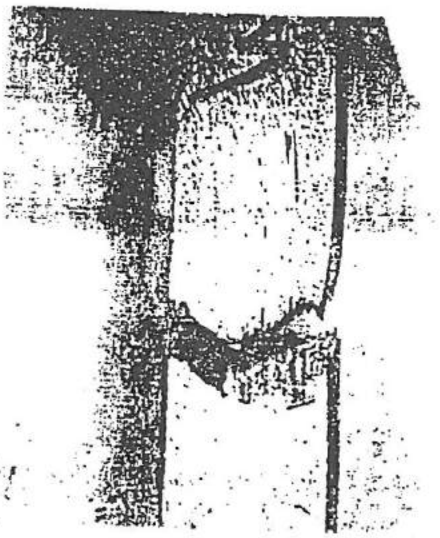


Fig. 6

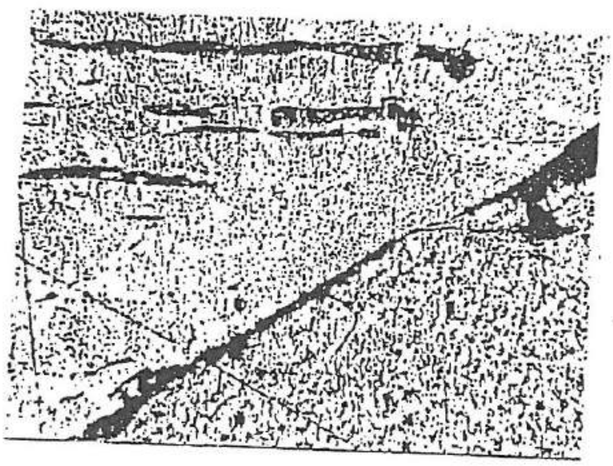


Fig. 7

In other words, the resolidified slag creates a weak layer almost exactly at right angles to the worked slag stringers in the original bar, and in so doing almost exactly replicates the weakening effect of the slag identified as harmful in electrically welded wrought iron in 1935.

Thus what appears at first sight to be a perfectly normal welding operation using standard techniques and filler rods, may end up producing a welded joint that is not at all as sound as it looks. Perhaps therefore, when considering joining wrought iron by welding, the adage that *old ways are the best*, is in this instance possibly correct. Traditional welding of wrought iron involves heating the iron to white heat and forging parts together, with a subsequent working of the joined area to reform the slag stringers in the direction of original working, thus eliminating the possibility of weak planes of slag existing at right angles to the primary stressed direction of the component. In the renovation of Paddington Station, it is reported that all the welds were subsequently inspected. In other repairs and renovations, however, it is not difficult to imagine that what might look like a perfect weld could be suspect if the weld was ever called on to provide the full strength of the original wrought iron.

7.0 CONCLUSIONS

The wrought iron of the *S.S. Great Britain* shows a typical slag stringer-iron matrix structure. The tensile strength of the iron is relatively low if judged by slightly later British Standards but is, nevertheless, representative of the strength expected of wrought iron made about 1840. The notch impact sensitivity of the iron is alarmingly low and therefore its susceptibility to fracture from impact damage must be considered to be high, especially if combined with low working temperatures. In terms of renovating wrought iron structures, the characteristic iron-slag mix in wrought iron may make its repair by conventional welding techniques questionable, especially if the component is ever called upon to provide its maximum design strength.

ACKNOWLEDGEMENTS

The author wishes to thank the *S.S. Great Britain* project and especially the project director Capt. Chris Young RN for his enthusiastic help and support. The author would also like to express his thanks to Dorothea Restorations Ltd who continue to provide him with specimens of early wrought iron.

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Conditions

This report is the companion volume to Volume 1 of the Conservation Plan for the Great Western Steamship Company Dockyard and the ss Great Britain which was prepared in January 1999. This Report has been prepared for use by the ss Great Britain Project and their professional advisers only.

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(Cover picture is 'The Return from Australia' by Francis Smitheman)

ss Great Britain Project December 1999
Text and research by Shane Casey and Matthew Tanner of the ss Great Britain Project, and Robert and Russell Turner of Eura Conservation Ltd.